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NOTRE DAME ROCKETRY TEAM
PRELIMINARY DESIGN REVIEW

NASA STUDENT LAUNCH 2022

LAUNCH VEHICLE IDENTIFICATION SYSTEM AND APOGEE CONTROL SYSTEM

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Table 1: Commonly-Used Acronyms

Acronym	Meaning
ACS	Apogee Control System
AGL	Above Ground Level
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CP	Center of Pressure
CPU	Central Processing Unit
FMEA	Failure Modes and Effects Analysis
FPS	Frames Per Second
FRR	Flight Readiness Review
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LED	Light Emitting Diode
LiPo	Lithium Polymer
LVIS	Launch Vehicle Identification System
NAR	National Association of Rocketry
NDRT	Notre Dame Rocketry Team
PCB	Printed Circuit Board
PID	Proportional-Integral-Derivative
PDR	Preliminary Design Review
PLA	Polylactic Acid
PRM	Primary Recovery Module
PWM	Pulse-Width Modulation
RF	Radio Frequency
SOP	Standard Operating Procedure
SRM	Secondary Recovery Module
TRA	Tripoli Rocketry Association
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
WNV	Weighted Normal Value

1 Summary of Report

1.1 Team Summary

Team Information:	Notre Dame Rocketry Team (NDRT) University of Notre Dame 365 Fitzpatrick Hall of Engineering Notre Dame, IN 46556
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1.2 Launch Vehicle Summary

A brief summary of the launch vehicle design is provided in Table 2.

Table 2: Summary of Launch Vehicle Design

Feature	Value
Target altitude (ft.)	4800
Selected Motor	Aerotech L2200G-18
Length (in.)	140
Outer diameter (in.)	6.17
Total Mass (oz)	846.4
Rail Size	12-foot 1515

The recovery system consists of the The primary recovery module (PRM) and secondary recovery module (SRM). The PRM deploys a 2 ft x 30 ft, .105 C_d drogue streamer at apogee, and a 12 ft diameter, 0.97 C_d parabolic main parachute at 680 ft AGL. The SRM separates the fin can and ACS bay at 450 ft AGL to decrease kinetic energy at impact. All four sections of the vehicle will meet NASA requirements (3.3), (3.10), (3.11).

1.3 Payload Summary

The Launch Vehicle Identification System (LVIS) will use an inertial navigation system (INS) throughout the entire flight to calculate the position of the vehicle given data from multiple sensors, meeting NASA requirements 4.1, 4.2.2.6, and 4.2.4.1.

2 Changes Made Since Proposal

2.1 Vehicle Criteria

The vehicle will no longer have a transition section from a 6 in. to an 8 in. diameter. This change is a result of the payload design change from an unmanned aircraft system (UAS) to an INS. The updated INS design requires less space, and thus the elimination of a transition section simplifies part procurement, manufacturing, and analysis.

A secondary recovery system was added to the vehicle to ensure that NASA Req. 3.3 would be met for higher descent rates. This system will be explained further in Section 4 of the report.

2.2 Payload Criteria

The payload has changed from a UAS to an INS. The ground station remains the same. The inertial navigation system will use precise, accurate sensors to calculate the vehicle's trajectory during all stages of flight. The on-board computer will still compute the vehicle's grid location and transmit back to the ground station. Moreover, the payload will retrieve a satellite aerial image instead of using a UAS to capture the image. The reason for this change is a decrease in complexity, due to the lack of payload jettison and additional separation, in favor of a non-jettisoning payload. NDRT concluded that an image or object recognition system would be equally, if not more, complicated than an inertial navigation system.

2.3 Project Plan

The team remains on track to meet all deadlines and milestones on time and within budget. The next milestone after PDR is the subscale test flight, planned for November 6 or 7 with backup dates on November 13, and 14. There are also opportunities on December 4 and 11 if needed. The budget, located in Section 9.3, reflects purchases made for this upcoming subscale test flight in addition to components for early prototyping and electronics testing. The team currently has enough funds to successfully complete the project, given the large amount of funds leftover from past years and a significant contribution from The Boeing Company.

3 Technical Design: Launch Vehicle

3.1 Mission Statement

The overall mission of the launch vehicle is to safely and reliably facilitate the mission goals of each payload. In pursuit of this goal, the vehicle design is driven by certain NASA-specified requirements as well as additional requirements identified by the team that are deemed necessary for mission success. The main NASA Requirements that drive the vehicle design are to reach apogee at an altitude between 4,000 feet and 6,000 feet (NASA Req. 2.1) with a maximum motor impulse of 5,120 Newton-seconds (NASA Req. 2.12) and to reach a minimum velocity of 52 feet per second (NASA Req. 2.17) with a static stability margin of at least 2.0 at launch rail exit.

The scoring payload, the LVIS system, requires that the vehicle performs close to nominally and is not overly-sensitive to wind gusts such that the vehicles drifts too far from the launch site. The non-scoring payload, the ACS system, requires that the vehicle be designed to reach an apogee that is sufficiently high as to allow the system to control the apogee by adding drag as designed. Additionally, all vehicle components must be designed such that they can withstand loads sustained during motor burn, recovery events, and landing.

A successful mission for the launch vehicle system includes meeting the following mission success criteria:

3.1.1 Mission Success Criteria

- Achieving design stability
- Achieving design rail-exit velocity
- Placing the vehicle on a trajectory to an apogee above the specified target apogee
- Separating vehicle sections during recovery events
- Landing without damage

3.2 System Alternative Designs

The team considered many different design layouts in order to determine the best design to achieve mission success. The primary systems that are required to be housed in the vehicle are the LVIS and the ACS payloads as well as all necessary recovery system hardware and parachutes. Three separate designs of the launch vehicle are described in detail in the following sections: the traditional layout, the MEGASLED layout, and a fin-can-split layout.

3.2.1 Traditional Layout

The first design was similar to what the team has done for the past two years. This design places the payload near the nosecone, a dual-deploy recovery system and two parachutes in the middle section, and the Apogee Control System and the motor in the fin can. An OpenRocket diagram of this design, indicating the black powder energetics locations (indicated in red) and separation points (indicated with green arrows), is shown in Figure 1.

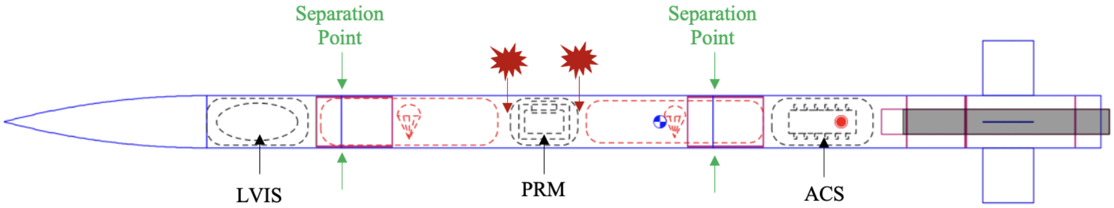


Figure 1: Traditional Layout with 2 Separation Points

Keeping the payload, recovery, and ACS systems separate in their own bays keeps the design an integration of each of these systems as simple as possible. With the recovery bay being in the middle, this design is able to eject the drogue parachute and main parachute from separate locations while only containing one recovery system. The separate separation points of the drogue and main parachutes prevents entanglement and leads to the best system reliability.

3.2.2 MEGASLED Layout

The second design option was very different from layouts that the team has previously chosen. Its distinguishing feature is the recovery bay section containing both the payload and the recovery system, combining them onto one sled. An OpenRocket diagram of this design, indicating the black powder energetics locations (indicated in red) and separation points (indicated with green arrows), is shown in Figure 2.

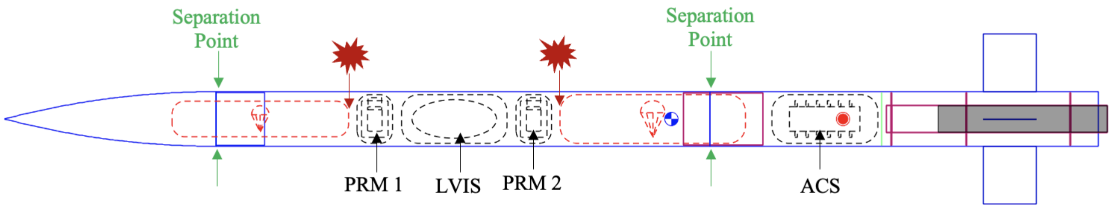


Figure 2: MEGASLED Layout with 2 Separation Points

Putting the payload and recovery systems on the same sled would make it possible to share components that each system shares. and decrease the overall system mass. This layout would also allow for quicker launch vehicle preparation time as it only involves inserting one system. However, because this layout combines the total mass of the payload and recovery systems, this creates a single section that has a higher mass than separate sections despite the total mass decrease. This section would limit the descent velocity of the vehicle to meet NASA Req. 3.3 which would allow for more drift from the launch pad. Furthermore, combining the recovery and payload systems presents potentially complicated integration issues due to the complexity of each system that are not otherwise present. The MEGASLED design was not chosen for these reasons.

3.2.3 Fin-Can-Split Layout

The final launch vehicle design that was evaluated consists of a single diameter body and includes three points of separation; ultimately, this results in four independent sections descending during the recovery phase of flight. This design is similar to the Traditional Layout discussed above with an added separation point within the fin can. An OpenRocket diagram of this design, including energetics locations (indicated in red) and separation points (indicated with green arrows), is shown in Figure 3.

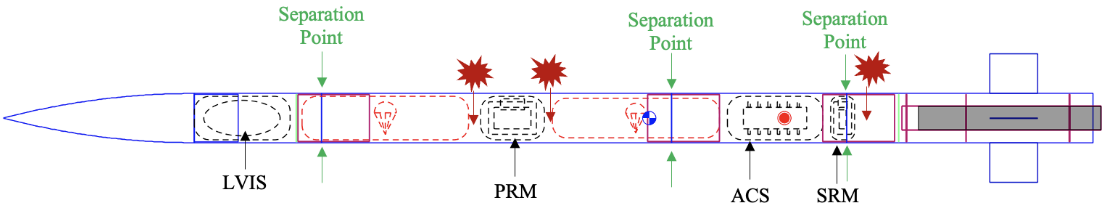


Figure 3: Fin-Can-Split Layout with 3 Separation Points

The additional separation point within the fin can, was deemed to be desirable in pursuit of ensuring that the launch vehicle will comply with maximum kinetic energy requirements for independent sections upon landing (NASA Req. 3.3). The fin can typically has the most mass out of all the sections upon descent as it contains both the Apogee Control System and the burned-out motor. The mass of each individual section is less than it would be as one combined section because the fin can is separated into two sections upon descent. This mass reduction allows each individual section to descend at a higher velocity while still staying within required kinetic energy bound of 75 ft-lbf since mass is directly proportional to kinetic energy ($KE = \frac{1}{2}mv^2$). This increased rate of descent will reduce the drift of the rocket from the initial launch location which will be favorable for the LVIS payload mission. This design was ultimately selected based on these reasons.

3.3 Component Level Design

With the general layout of the vehicle selected, trade studies were performed to document the process of choosing designs for the vehicle sub-components including the airframe, the motor mount, nosecone, tail cone, and fins. In all trade studies, criteria were determined, and units were selected such that higher assigned values of all criteria are optimal.

3.3.1 Airframe Material Selection

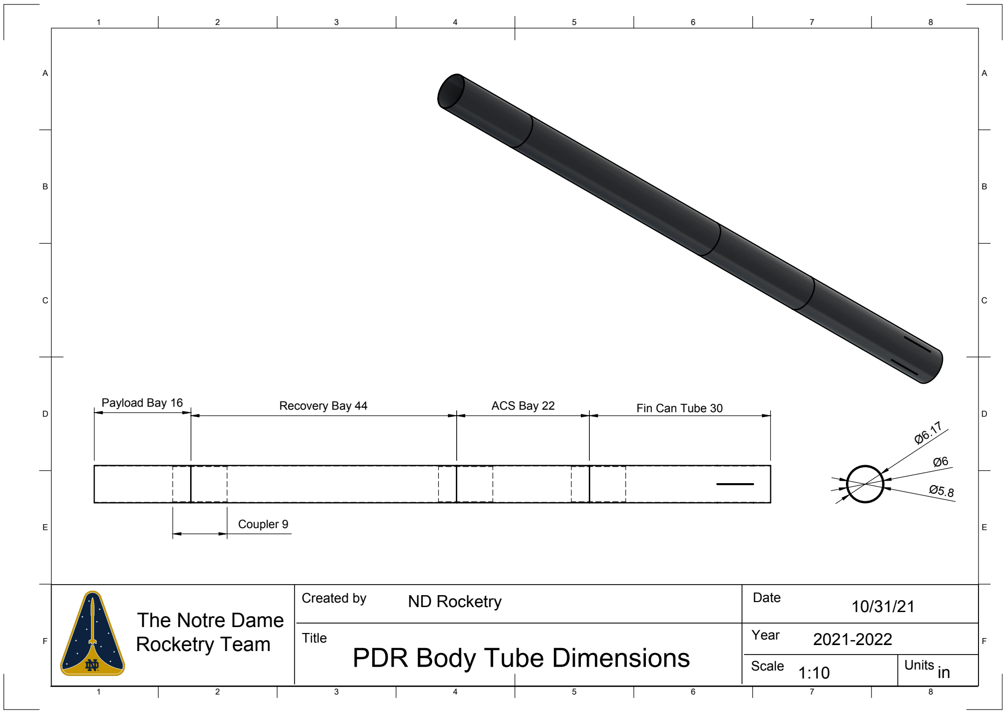
The body tubes make up the main airframe of the launch vehicle that contains the subsystems and holds the nosecone and fins in place. The couplers are internal tubes used to connect the airframe together. The team has chosen to restrict the study to commercially available body tubes to avoid the added complication and inaccuracy of in-house composite layups. The dimensions of the airframe are based on the dimensions necessary to house the payloads and recovery systems. The trade study in Table 3 presents the top three possible airframe materials that were traded.

Table 3: Airframe Material Trade Study

		Fiberglass		**Phenolic**		**Blue Tube**	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Yield Strength (psi)	40%	30000	0.28	8270	0.08	5076	0.05
Weight (ft/lb)	25%	2.61	0.07	3.968	0.10	3.968	0.08
Durability	25%	4	0.14	1	0.04	2	0.07
Cost (in./$)	10%	0.485	0.01	2.381	0.05	1.587	0.04
Total WNV		**0.50**		**0.27**		**0.23**	

Yield strength was the most important criteria analyzed for the vehicle to maintain its shape and have the maximum allowable load. Weight was also taken into account because lighter materials result in higher apogee and higher off-rail velocity. A lower importance was also given to weight and cost in the trade study. Durability was also considered since the launch vehicle must withstand multiple launches and a lot of handling in the transportation and testing throughout the year. Taking these design drivers into consideration, the yield strength, weight, durability, and cost were normalized and given weights of 40%, 25%, 25% and 10%, respectively.

The weight and yield strength of each material were based on research of commercially sold materials. Fiberglass has the highest weight and phenolic has the lowest weight. The team researched different tubes for each material to estimate the costs. Fiberglass has the highest cost and phenolic has the lowest cost. Durability was based on experience with past launch vehicles and values were assigned qualitatively. Fiberglass was determined to have the highest durability and phenolic was determined to have the lowest durability. Fiberglass was ultimately chosen due to its light weight, high yield strength, and high durability. Notably, carbon fiber was not included in this study due to its inability to allow radio transmission which is needed through the airframe. The cost of fiberglass is still within the budget, although this material is the most expensive. A CAD drawing of the body tube and coupler assembly for the launch vehicle can be seen in Figure 4.



The Notre Dame Rocketry Team
Created by ND Rocketry
Title PDR Body Tube Dimensions
Date 10/31/21
Year 2021-2022
Scale 1:10
Units in

Figure 4: Airframe Assembly CAD Drawing

3.3.2 Motor Mount Material

The function of the motor mount is to retain the motor within the airframe and to transfer the thrust force of the motor into the body of the vehicle. The motor mount is centered within the airframe using epoxied centering rings, which both center the motor mount and also transmit the thrust force of the motor into the airframe. The motor slides into the motor mount until it contacts the bottom edge. The dimensions of the motor mount are dependent on the dimensions of the selected motor. The following trade study examines the best material to be used and is based on commercially available tubes.

Table 4: Motor Mount Material Trade Study

		Carbon Fiber		Fiberglass		Phenolic	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Yield Strength (psi)	40%	360000	0.36	30000	0.03	8270	0.01
Weight (ft/lb)	20%	2.65	0.06	2.61	0.06	3.97	0.09
Durability	20%	5	0.09	4	0.07	2	0.04
Heat Tolerance	15%	5	0.07	4	0.05	2	0.03
Cost (in./$)	5%	0.22	0.00	0.49	0.01	2.38	0.04
Total WNV		**0.49**		**0.15**		**0.16**	

The yield strength was given the most weight (40%) as the most important function of the motor mount is to transfer the thrust loads to the vehicle. Carbon fiber and fiberglass have the highest yield strengths out of the materials considered. Additionally, a high heat tolerance in the material is desirable, as the motor generates heat. It was determined that the heat tolerances of all materials considered would be adequate to withstand the heat generated by the motor. As a result, heat tolerance was given a weight of 15%. Durability was assigned a weight of 20% for reuse across multiple launches. Carbon fiber and fiberglass were assigned the highest durability due to advantageous material properties. Weight was given a weight of 20% for considerations in the mass budget. Carbon fiber and fiberglass have a much larger weight than the other materials, and phenolic is the least heavy material considered. Finally, price was assigned a weight of 10%. Phenolic was the cheapest material and carbon fiber was the most expensive. Carbon fiber was ultimately chosen due to its high yield strength, light weight, durability, and heat tolerance. A CAD drawing of the motor mount can be seen in Figure 5.

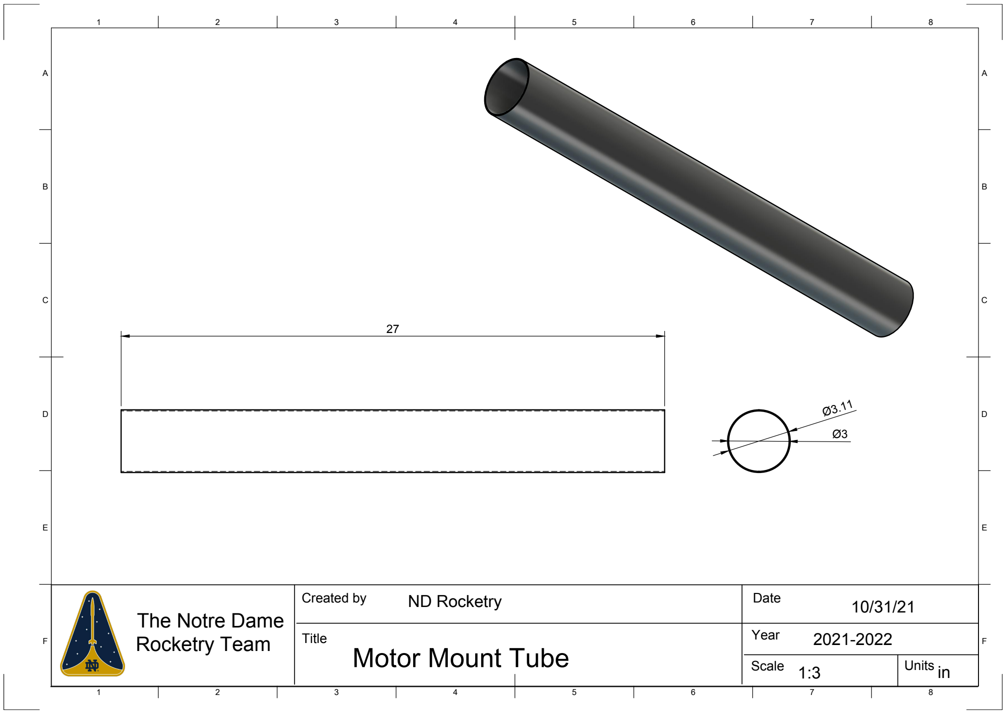


Figure 5: Motor Mount CAD Drawing

3.3.3 Nosecone Selection

The nosecone is the topmost section of the Launch Vehicle, and it plays a major role in reducing drag on the launch vehicle. The only design requirement for the nosecone was that it must have an outer shoulder diameter matching the payload bay's diameter. Five nosecones were identified that fit the design specifications above, and each was compared in a trade study. The five cones were split into two different groups initially: 3D-printed ABS nose cones and purchased fiberglass nosecones. The 3D-printed cones were separated by shapes: ogive, elliptical, and conical. The top three options from the trade study are shown in Table 5.

Table 5: Nosecone Trade Study

		Fiberglass Ogive (PML) 24"		**3D-Printed Elliptical 24"**		**3D-Printed Conical 24"**	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Altitude (ft)	35%	4909.30	0.12	4890.40	0.12	4807.00	0.12
Durability	35%	5	0.19	2	0.08	2	0.08
Mass (1/oz)	20%	0.03571	0.12	0.01136	0.04	0.01136	0.04
Cost (1/$)	10%	0.00834	0.04	0.00667	0.03	0.00667	0.03
Total WNV		**0.47**		**0.26**		**0.26**	

The trade study evaluated each of these nosecones on their simulated altitude, price, mass, and yield strength. A high yield strength was important in determining the nosecone so it will be able to withstand several launches. Mass and price minimization were also minor design criteria. Each nosecone was modeled in OpenRocket, and simulations were performed on each while keeping the Launch Vehicle mass and stability constant to find the altitude. The OpenRocket-calculated apogee for each was determined and the values were used for the altitude criteria in the trade study, which corresponds to drag. An analysis of the the length of the 3D-printed cones was also performed. This analysis showed that shortening the nose cone while keeping the mass and stability fixed led to increased apogees. However, the apogee increases were considered to be negligible compared to the added complexity of 3D-printing a nosecone.

The trade study determined that the best nosecone option is the Fiberglass Ogive Nosecone from Public Missiles. It satisfies the 6 inch outer shoulder diameter requirement and has the best combination of altitude, yield strength, minimized price, and minimized mass. The important parameters of the chosen nosecone are provided in the Table 6 and a CAD drawing with dimensions is shown in the Figure 6.

Table 6: Parameters of Selected Nosecone

Feature	Value
Exposed length (in.)	24
Shoulder length (in.)	5.5
Shape parameter	Ogive
Weight (oz)	28
Material	Fiberglass

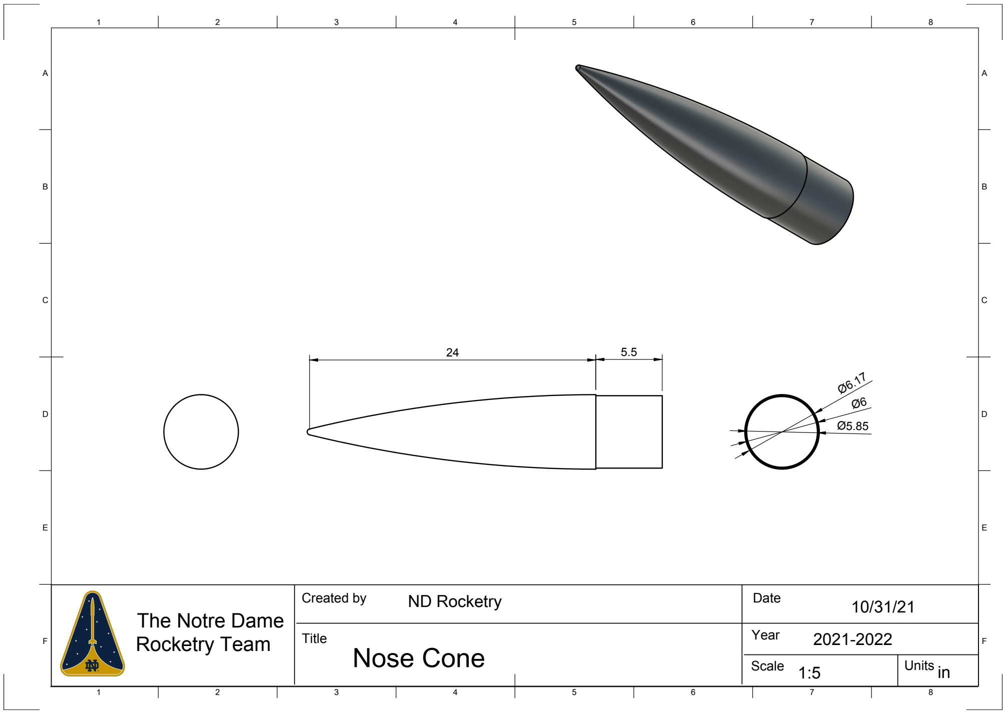


Figure 6: Nosecone CAD Drawing

3.3.4 Fin Shape Analysis

Fins provide stability to the launch vehicle's flight and control the location of the center of pressure. The exact scaling of the fins will be based on achieving the desired launch vehicle stability. The basic shape of the fin was analysed in a trade study. The options reviewed were elliptical, triangular, trapezoidal, and rectangular. These fin shapes were chosen because they represent a broad spectrum of fin shapes. Triangular fins represent the extreme for trapezoidal fin shape when the tip chord equals zero. Rectangular fins represent the opposite extreme for trapezoidal fin shape, which is when the root chord is equal to the tip chord. Finally, elliptical was also considered due to it being the most ideal in terms of limiting lift induced drag. The trade study is included in Table 7

Table 7: Fin Shape Trade Study

		Elliptical		Triangular		Trapezoidal		Rectangular	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Center of Lift (in.)	60%	2.12	0.15	1.67	0.12	2.2	0.16	2.5	0.18
Profile Drag (1/in.^{2})	30%	0.05	0.07	0.08	0.11	0.05	0.07	0.04	0.05
Induced Drag Apogee (ft)	10%	4980	0.03	4986	0.03	4977	0.02	4975	0.02
Total WNV		**0.24**		**0.25**		**0.25**		**0.26**	

The three criteria examined in this study were the induced drag, profile drag, and the location of the center of lift for each fin shape. The center of lift was given the most weight (60%) because the tip of the fin is most effective at creating lift to restore the vehicle to vertical when perturbed. Center of lift was calculated by finding the centroid of the fin shape, and the distance from the root chord was recorded in the trade study. Induced drag was given a weight of 10% because the lift-induced drag force created is minimal. Induced drag was compared using an OpenRocket simulation. Simulations were run with each fin shape while keeping the total vehicle mass, stability, fin height, and fin area constant, and the apogee of each fin shape was recorded in the table to represent the difference in induced drag. Profile drag increases when area increases because of the friction between the air and the surface and was given a weight of 30%. Area was calculated based on each fin having a root chord, tip chord, and height of 5 inches. The trade study determined that the rectangular fin is ideal due to its high center of lift.

Sweep length was also analyzed having chosen the rectangular fin design. The analysis was first performed on a rectangular fin with no sweep, a 5in. root chord, 5in. tip chord, and a 5in. height. Successive tests were then performed by increasing the sweep length of the base rectangular fin while keeping mass, root chord, tip chord, and height constant. The apogee was recorded for each successive test. The analysis showed that as sweep length was increased, the apogee also increased. Therefore, a sweep distance of half the root chord was selected to balance this decreased drag and to keep the design practical to manufacture. A CAD drawing of the fins is included in Figure 7.

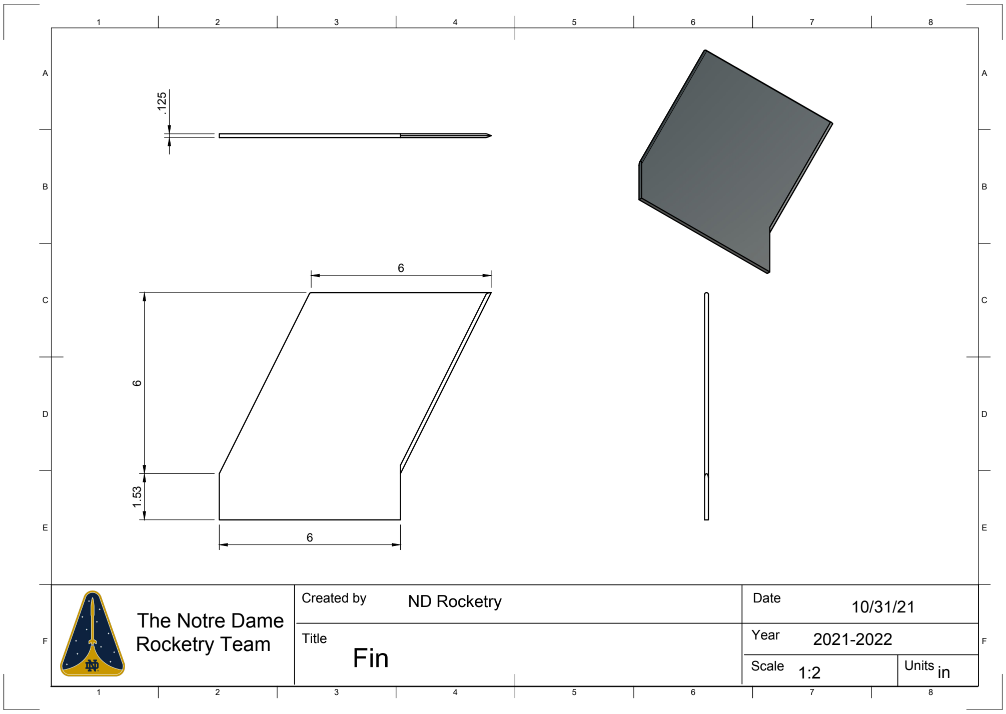


Figure 7: Fin CAD Drawing

3.3.5 Tail Cone

The tail cone is the bottom most section of the launch vehicle and is important for reducing base drag. The only restrictions for the tail cone is that the fore diameter must match the airframe and the aft diameter must match the motor mount to fit properly on the launch vehicle. A trade study was conducted to compare four different tail cone options including a commercially available fiberglass ogive cone and various 3D-printed tail cone shapes including conical, ogive, and elliptical. The top three options in this study are compared below in Table 8.

Table 8: Tail Cone Trade Study

		Fiberglass Ogive 6.0-3.9, 14"		ABS Conical 6.0-3.0, 3"		ABS Ogive 6.0-3.0, 3"	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Apogee (ft)	30%	4839	0.10	4950	0.10	4944	0.10
Ease of Integration	30%	1	0.03	5	0.14	5	0.14
Mass (1/oz)	20%	0.05	0.02	0.25	0.09	0.25	0.09
Cost (1/$)	10%	0.00752	0.02	0.02000	0.04	0.02000	0.04
Durability	10%	5	0.06	2	0.02	2	0.02
Total WNV		**0.19**		**0.26**		**0.26**	

The different tail cones were evaluated based on their simulated apogee, cost, mass, durability, and ease of integration. Simulations were performed with each tail cone while keeping stability and mass constant to determine which caused the least drag. It is important for the tail cone to be durable for reuse across several launches. Ease of integration was also considered a key variable due to the difference in length between the commercial fiberglass boattail (14.75in.) and the possible shorter lengths of 3D-printed tail cones. A longer length tail cone results in a higher altitude but decreases the structural integrity of the launch vehicle near the fin can, where the primary thrust loads are transferred.

It was determined that the best tail cone design would be a 3D printed option such that the dimensions can be fully controlled. The ogive and the conical options had the same score but it was decided that the ogive option would lead to the least flow separation over the aft end of the vehicle. The parameters of the chosen tail cone option are shown below in Table 9 and a CAD drawing is shown in Figure 8.

Table 9: Tail Cone Parameters

Feature	Value
Exposed length (in.)	3
Forward diameter (in.)	6.17
Aft diameter (in.)	3.11
Shape parameter	Ogive
Weight (oz)	3.22

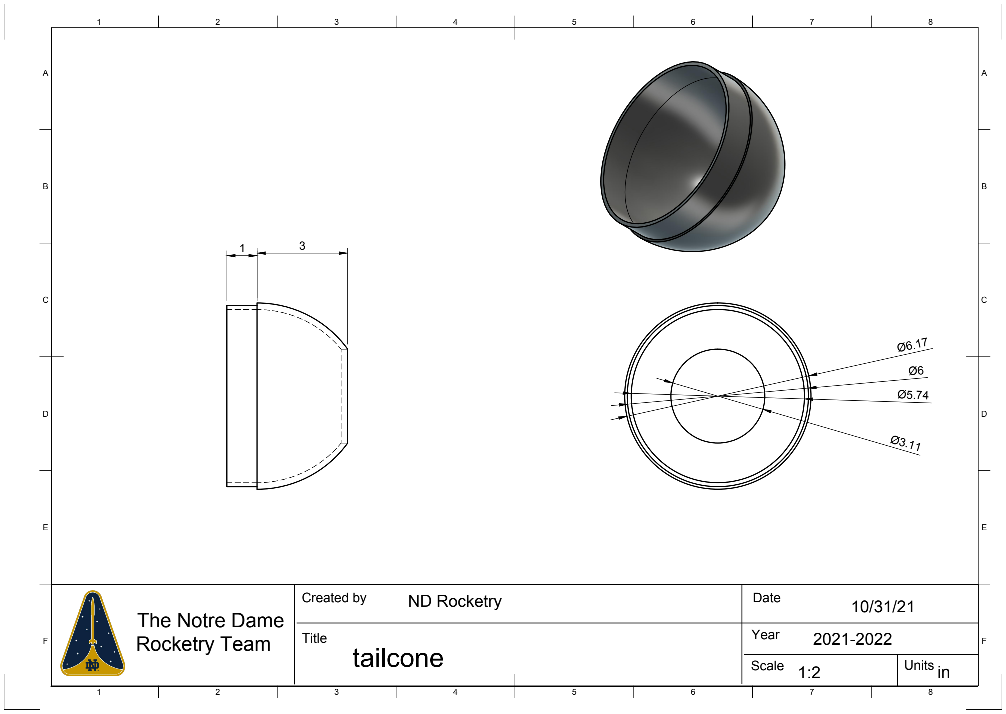


Figure 8: Tail Cone CAD Drawing

3.4 Propulsion System Design

The following sections detail the selection process and specifications of the motor to be used for the launch vehicle, as well as the planned assembly of the motor mount and its subcomponents.

3.4.1 Motor Selection

The team conducted a brief study to select the ideal motor for this year's launch vehicle design. The motor had to be capable of propelling the launch vehicle to a trajectory altitude above 5,000 ft in order to give the ACS system amble ability to add drag while also abiding by NASA Req. 2.12. OpenRocket simulations were used to project the apogees of 17 different motors that fit the impulse requirement. Motors with projected apogees below 5,000 ft were discarded and ultimately the field was narrowed to three motor types: the Cesaroni L2375-WT-P, the Aerotech L2200G-P, and Aerotech L1500T-P. The cost for each motor was similar enough that cost was not taken into account for this comparison.

Table 10: Cesaroni L1115 Classic Motor Specifications

Motor	Cesaroni L2375-WT-P	Aerotech L2200G-P	Aerotech L1500T-P
Highest Apogee	5085	5226	5025
Diameter (in.)	2.95	2.95	3.86
Length (in.)	24.45	26.80	17.44
Loaded Weight (oz)	146.77	168.72	164.34
Propellant Weight (oz)	81.89	88.82	87.87
Burnout Weight (oz)	64.89	79.90	76.47
Impulse (N-s)	4864.00	5104.00	5089.00
Average Thrust (N)	2451.00	2200.00	1500.00
Maximum Thrust (N)	2798.00	3114.00	1690.00
Burn Time (s)	1.90	2.32	3.47
Cost ($)	347.89	322.99	365.99

The team decided to select the Aerotech L2200G-P based on the data in Table 10 and because it produces the highest apogee of the three compared. The motor specifications for the Cesaroni L2200G-P are provided in Table 10, and the motor thrust curve is shown in Figure 9. It was determined that the highest apogee would be beneficial to allow the necessary distance for the Apogee Control System to add drag and control the apogee as designed.

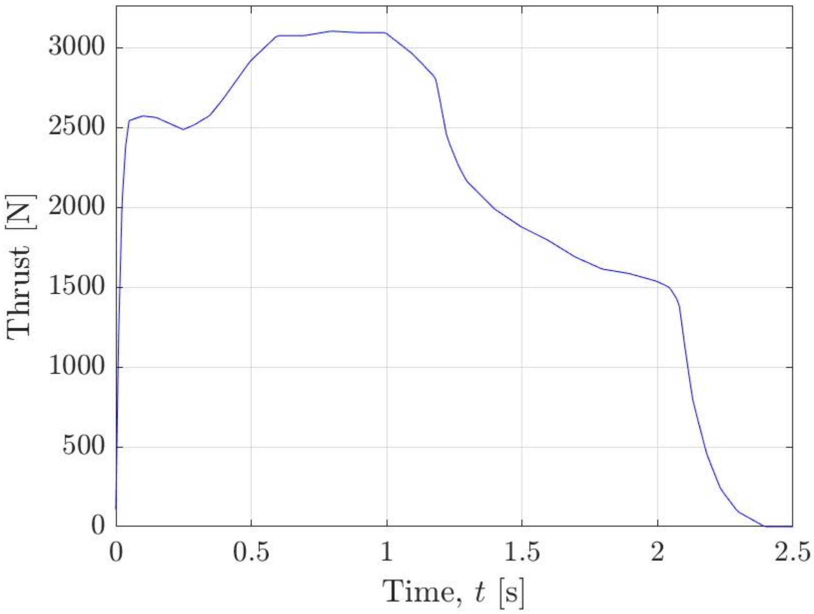


Figure 9: Motor Thrust Curve

3.4.2 Motor Retention

The motor will be restrained within the launch vehicle using a motor mount and a motor retaining ring. The motor mount will contain the motor laterally, while the retaining ring will constrain the motor axially. The motor mount will be attached to the fin can via three centering rings. These rings align the thrust line to the center of the vehicle, as well as transfer the thrust load to the rest of the vehicle. A CAD drawing of these centering rings is shown in Figure 10. Structural analysis will determine the final thickness of the centering rings and the epoxy thickness used to attach the centering rings to the inside wall of the fin can.

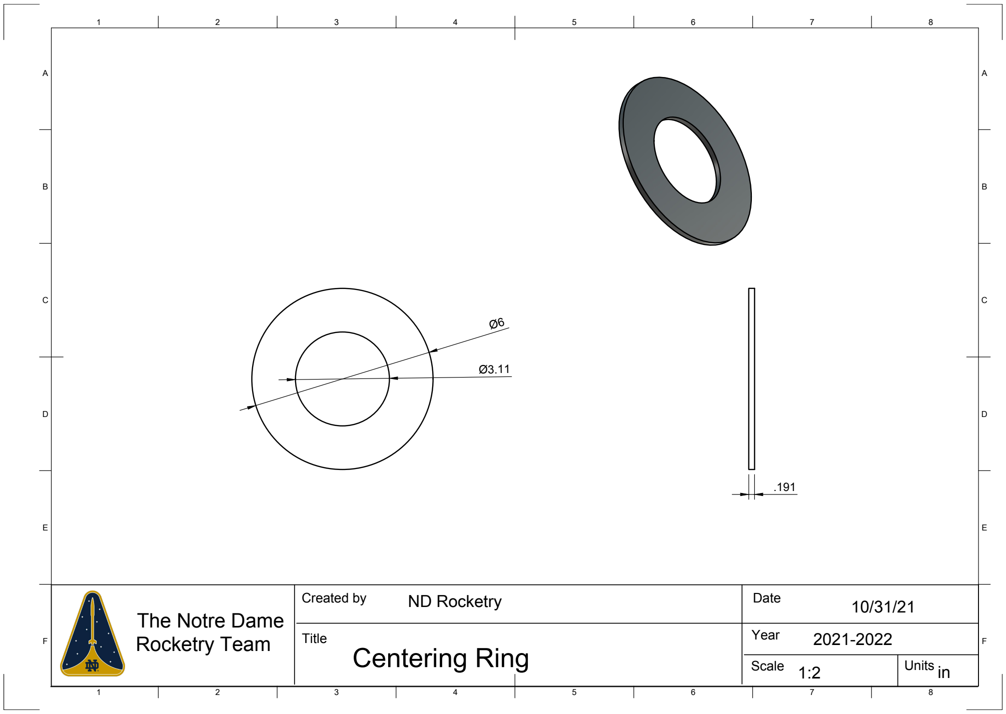


Figure 10: Centering Ring CAD Drawing

The motor mount assembly includes the fins, which will be epoxied to the motor mount structure for added fin structure. A CAD drawing of this assembly is shown in Figure 11.

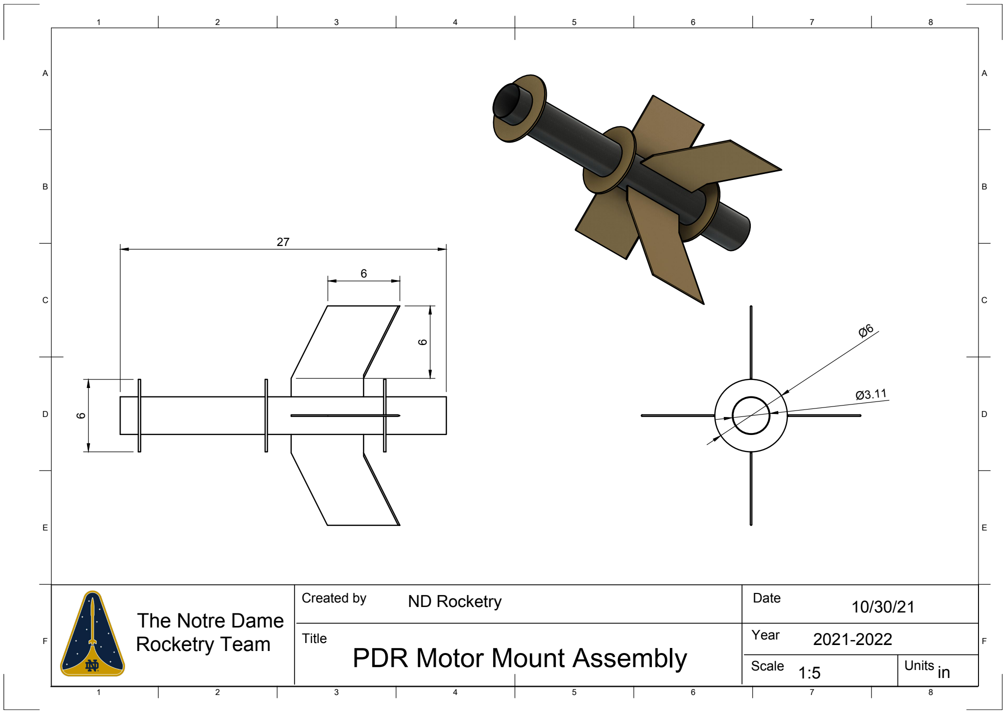


Figure 11: Motor Retention System CAD Drawing

3.5 Vehicle Design Summary

The designed launch vehicle has a length of 140 inches and a single inner diameter of 6 inches. It has a design stability margin of 2.75 and its target apogee is 4,800 ft, which it will achieve with the help of the ACS. It has three separation points and four independent sections, all of which will remain tethered to one another on descent. The vehicle sections as well as the CP and CG locations can be seen in Figure 12, and the subsystem locations, separation points, and energetics locations can be seen in Figure 13.

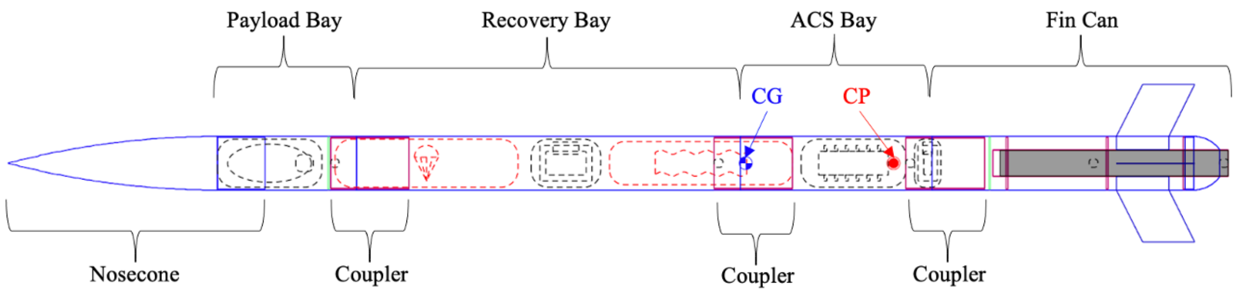


Figure 12: Launch Vehicle Design Outline

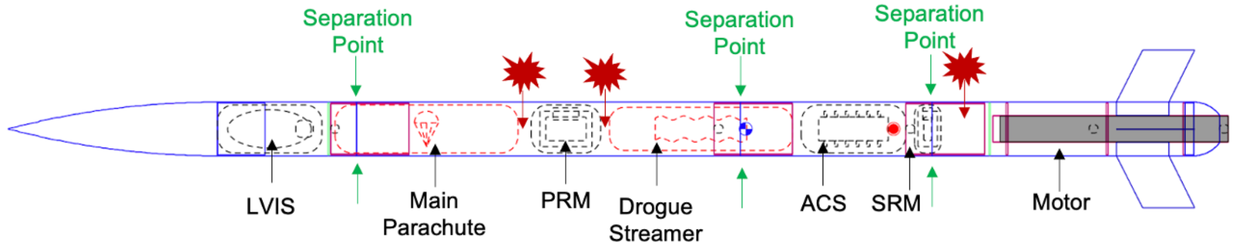


Figure 13: Launch Vehicle Design Outline

A summary of each vehicle section and its contained subsystems, overall length, and weight can be seen in Table 11.

Table 11: Launch Vehicle Section Outline

Section	Integrated Components	Length (in.)	Section Weight (oz)
Nose Cone and Payload Bay	LVIS, GPS	LVIS, GPS	166.08
Recovery Bay	PRM, Main Parachute, Drogue Streamer	44	124.40
ACS Bay	ACS, SRM	22	147.90
Fin Can	Motor	34	191.76

A summary of the relevant parameters to vehicle stability can be seen in Table 12, and a summary of airframe materials can be seen in Table 13.

Table 12: Launch Vehicle Overall Measurements

Parameter	Value
CG Location (in.)	84.6
CP Location (in.)	102
Static Stability Margin (calibers)	2.75
Overall Length (in.)	140
Outer diameter (in.)	6.17

Table 13: Summary of Vehicle Materials

Component	Material
Nose Cone	Fiberglass
Airframe	Fiberglass
Tail Cone	ABS Plastic
Fins	Fiberglass
Motor Mount	Carbon Fiber
Centering Rings	Fiberglass
Payload Bulkhead	Fiberglass

3.5.1 Updated Mass Estimate

NDRT has adopted the mass control method given by AIAA Standard S-120A, titled "Mass Properties Control for Space Systems" to track system mass estimates and budgets throughout the year. Each system thus gets an allowable mass. This is the maximum mass the system can contain while remaining within specifications. Each system begins tracking estimated component weights beginning at the preliminary design phase. This estimate is the basic mass. Each component is then given a mass growth percentage depending on the component type and design maturity level. This estimates the growth of the mass of each system as the design matures, and is applied to the basic mass estimate to get a predicted mass. The predicted mass is the mass the system is expected to grow to by the end of the design and fabrication process. Mass margin percentage is used to gauge how the predicted mass compares to the allowable mass. The basic mass, predicted mass, margin percentage, and allowable mass for each system is reported in Table 14.

Table 14: Updated Mass Estimate

System	Basic Mass Estimate (oz.)	Predicted Mass (oz.)	Margin (%)	Allowable Mass (oz.)
Launch Vehicle	469.98	489.96	0.008	490
Recovery (main)	140.50	153.17	1.30	155
Recovery (secondary)	52.80	58.77	2.34	60
Payload	69.65	76.18	19.84	90
ACS	48.18	53.09	35.10	70
Total	801.27	852.41	1.57	865

3.6 Launch Vehicle Preliminary Testing Plan

NDRT has developed a preliminary testing plan to properly verify the design, fabrication, and integration of the launch vehicle. The systems team will continue developing each of the tests described in Table 15 and provide full detailed test plans for CDR.

Table 15: Launch Vehicle Preliminary Testing Plan

Test Name	Description	Success Criteria
Vibration Test	Vibrate launch vehicle and integrated systems to test security of fastenings and physical connections	All components and systems are fully secured throughout vibration
Launch Vehicle Component Impact Test	Subject individual launch vehicle sections to expected landing load to validate the structural design	No cracks or damages are detectable after impact
Launch Vehicle Static Loading Test	Subject structural bulkheads and motor mount tube to constant load corresponding to maximum thrust to simulate load due to motor burn	Bulkheads able to withstand the applied load without showing any detectable cracks or damage

Table 15: Launch Vehicle Preliminary Testing Plan (continued)

Test Name	Description	Success Criteria
Bulkhead Impulse Test	Subject bulkhead to expected impulse load due to main parachute deployment to validate the impact strength of recovery harness points	Bulkhead is able to withstand the force without showing any signs of detectable damage
Motor Mount Strength Test	Subject motor mount to expected load due to upward motor force	The motor mount withstands the applied force without showing any signs of detectable damage
Subscale Flight	Launch and recover a subscale version of the launch vehicle to test the stability of the overall design	The team successfully launches and recovers a subscale model of the launch vehicle
Launch Vehicle Demonstration Flight	Launch full-scale vehicle with integrated recovery system and ACS and payload systems either integrated or replaced by a mass substitute	Launch vehicle performs as expected based on flight simulations and is not damaged from launch, recovery, or landing
Payload Demonstration Flight	Launch full-scale vehicle with all systems active	Launch vehicle performs as-expected based on flight simulations and is not damaged from launch, recovery, or landing

3.7 Subscale

The team will design, construct, and launch a subscale vehicle to critically examine how the full-scale vehicle and subsystems are likely to perform at a fraction of the cost.

3.7.1 Subscale Sizing

The subscale vehicle will be a 50%-scaled version of the full-scale version in order to allow ample internal volume for subsystem testing prototypes while remaining simple and cost effective. The subscale vehicle will include all the critical components of the full-scale, such as the nosecone, tail cone, payload bay, couplers, recovery bay, fin can, and fins. The effectiveness of all these components will be analyzed during the subscale launch. The components and subsystems will be analyzed during the test to determine if any modifications are needed. A comparison of the dimensions of the full-scale components and the subscale counterparts can be seen in Table 16, and a CAD drawing for the subscale vehicle can be seen in Figure 14.

Table 16: Subscale Vehicle Size and Material Comparison

Components	Full-Scale Material	Subscale Material	Full-Scale Dimensions	Subscale Dimensions
Nose Cone	Fiberglass	Fiberglass	L = 24 in., D = 6.17 in.	L = 12 in., D = 3.112 in.
Payload Bay	Fiberglass	Fiberglass	L = 16 in., D = 6.17 in.	L = 8 in., D = 3.112 in.
Recovery Bay	Fiberglass	Fiberglass	L = 44 in., D = 6.17 in.	L = 22 in., D = 3.112 in.
ACS Bay	Fiberglass	Fiberglass	L = 22 in., D = 6.17 in.	L = 11 in., D = 3.112 in.
Fin Can	Fiberglass	Fiberglass	L = 34 in., D = 6.17 in.	L = 17 in., D = 3.112 in.
Tail Cone	ABS Plastic	ABS Plastic	L = 3 in., D = 6.17 in.	L = 1.5 in., D = 3.112 in.
Motor Mount	Carbon Fiber	Carbon Fiber	L = 27 in., D = 3.112 in.	L = 13.5 in., D = 1.556 in.

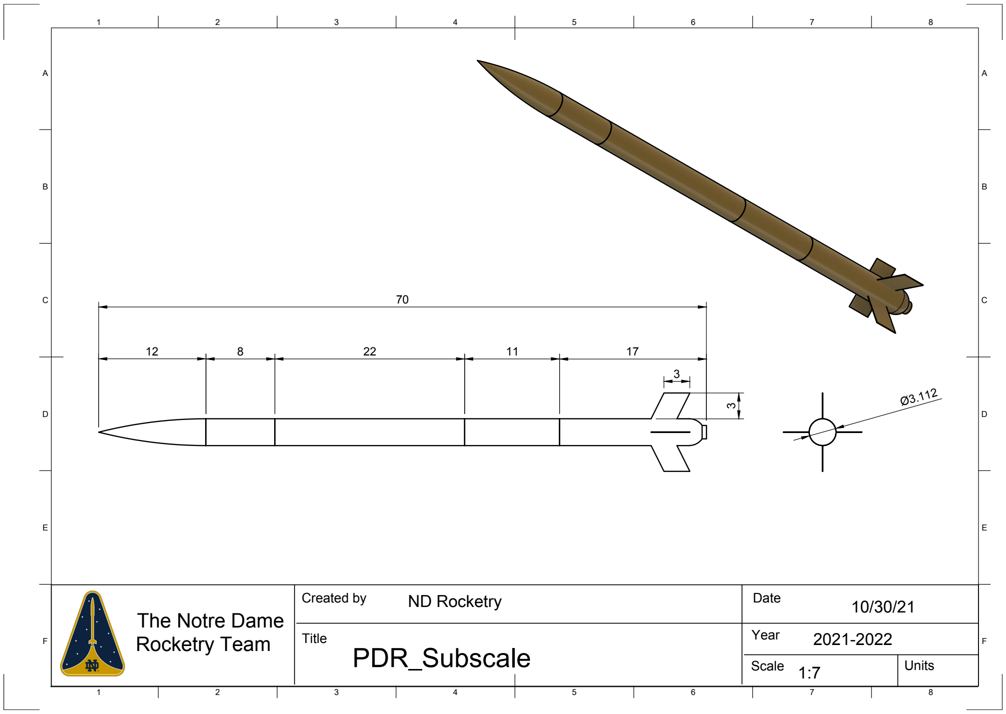


Figure 14: Sub-scale Vehicle Drawing

3.7.2 Subscale Motor Selection

In selecting a motor for the subscale vehicle, the main priority was to match the thrust to weight ratio of the subscale vehicle to that of full-scale in order to most accurately simulate the behavior of the full-scale vehicle. The selected motor for the subscale rocket is the I300T. The final motor specs can be referenced in Table 17. The maximum simulated apogee with this motor is 1974 feet.

Table 17: I300T-10 Subscale Motor Specifications

Feature	Value
Weight (oz)	15.5
Length (in.)	9.5
Diameter (in.)	1.5
Max Thrust (N)	284.4
Burn Time (s)	1.5
Total Impluse (N-s)	440.0
Cost ($)	62

3.7.3 Subscale Flight Simulations

Simulations were performed to analyse the expected performance of of the subscale vehicle. Table 18, Table 19, and Table 20 below, describe the velocity off the rod (ft/s), the apogee (ft), the max velocity (ft/s), and max acceleration (ft/s^2) of the subscale launch vehicle for varying wind speeds (0 - 20 mph in increments of 5 mph) using OpenRocket simulations. Table 18 has a launch angle of 5°, Table 19 has a launch angle of 7°, and Table 20 has a launch angle of 10°. The predicted apogees range from 1960 to 1792 feet.

Table 18: 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	73.6	1960	362	398
5	73.6	1945	362	398
10	73.6	1922	361	398
15	73.6	1900	360	398
20	73.6	1876	359	398

Table 19: 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	73.6	1945	362	398
5	73.6	1930	362	398
10	73.6	1907	362	398
15	73.6	1872	360	398
20	73.6	1840	359	398

Table 20: 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	73.7	1912	362	399
5	73.7	1887	362	399
10	73.6	1861	362	399
15	73.6	1831	361	399
20	73.6	1792	360	399

3.7.4 Subscale Test Plan

The main purpose of the subscale test is to simulate the full-scale launch as much as possible in order to gather data that will assist in the design of the full-scale vehicle and to predict and prevent potential issues that could occur with the full-scale launch. Each subsystem will identify test priorities for the subscale vehicle tests. The main priority for the vehicle design during subscale is testing various launch vehicle stability values to determine which leads to the highest apogee.

4 Technical Design: Vehicle Recovery System

4.1 System Overview

The recovery system will reliably reduce the kinetic energy of the launch vehicle with a streamer and parachute deployment system so that the launch vehicle lands within the kinetic energy requirements while also well within the required drift radius. The recovery system will deploy a streamer which functions as a drogue parachute at apogee. The recovery system will deploy the main parachute at 680 ft AGL, and the fin can will separate from the ACS bay at 450 ft AGL. The two sections will remain tethered with a recovery harness but no parachute will be deployed. Black powder ejections will be used for each of these separation events. The main parachute will be protected from ejection debris and gases with a deployment bag, and the streamer will be protected with a fire-retardant blanket. Both the main parachute and the streamer will be attached to the vehicle via shock cords, quicklinks, and u-bolts. Three redundant altimeters will be used to deploy the streamer and main parachute and will be housed in the Primary Recovery Module (PRM). The Secondary Recovery Module (SRM) will house the three redundant altimeters used to eject the motor mount from the launch vehicle. The GPS system will be mounted on the bulkhead between the payload and recovery bays. All of the altimeters are independently redundant and completely isolated from the payload system.

4.1.1 Mission Success Criteria

The following criteria will be used to evaluate a successful mission for the recovery system:

- All components of the tethered launch vehicle will land with maximum kinetic energies of 75 ft-lbf.
- The launch vehicle will drift no more than 2500 ft in radius from the launch pad.
- The launch vehicle will land within 90 seconds of reaching apogee.
- Battery powered altimeters housed within the recovery system will collect official altitude readings as proof of flight.
- The GPS system within the recovery system will transmit the location of the landed launch vehicle to a ground receiver to verify the results of the payload mission.

4.2 Separation and Deployment

Each vehicle separation will be initiated by a separation event. The following sections detail the separation methods used, the overall redundancy, and the black powder housing scheme for each of events.

4.2.1 Separation Method

Black powder charges will be used for all separation events. Other deployment methods, such as a mechanical separation system or compressed carbon dioxide, were originally considered, but black powder is favorable due to its simplicity, reliability, low weight, and low cost.This method has added benefits of familiarity and time savings in design and construction given the team's past success with black powder deployments.

4.2.2 Ejection Module Redundancy

All planned separations of the launch vehicle this year are flight critical, including the fin can separation event. The team relies on the success of this event to reduce the maximum mass of each landing section and to ensure safe kinetic energy at landing. The other separation events allow for the deployment of the main parachute and the drogue streamer, which are also flight critical events. Each separation event will therefore have two redundant ejection modules to ensure complete separation.

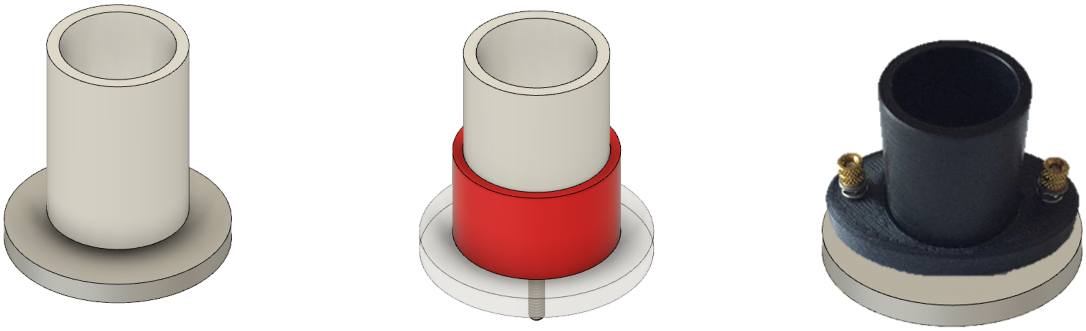
4.2.3 Ejection Charge Housing

Each of the black powder charges will be housed in a charge well. Epoxy has historically been used to secure PVC charge wells to aluminum recovery bulkheads. However, epoxied charge wells detached from bulkheads during flight on multiple occasions last year, potentially due to temperature effects or bulkhead surface smoothness weakening adhesion. Alternative methods for fastening charge wells to recovery bulkheads were thus examined and a trade study was conducted, shown in Table 21. Effectiveness in Table 9 refers to the method's ability to secure the charge well to the bulkhead. Effectiveness and simplicity are evaluated on a scale of one to five and are weighted the most due to the importance of these factors during flight and construction, respectively. Weight per charge well is given the least weight since all three methods have a similarly low weight per well.

Table 21: Charge Well Connection Trade Study

		Epoxy		In-House Bolting Scheme		Dog House Rocketry Ejection Charge Mount Kit	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Effectiveness	0.4	3	0.09	5	0.11	5	0.15
Simplicity	0.4	5	0.15	5	0.15	3	0.09
Weight per Well (oz)	0.2	0.91	0.08	0.99	0.07	1.23	0.06
Total WNV		**0.32**		**0.33**		**0.30**	

Figure 15 shows each of the charge well connection methods included in Table 21. Each method is pictured with the well attached to a small bulkhead section.



(a) Epoxy (b) In-House Bolting Scheme (c) Ejection Charge Mount Kit

Figure 15: Charge Well Connection Methods

The results in Table 21 determined that the charge wells will be fastened to recovery bulkheads using an in-house bolting scheme. This will include inserting a PVC charge well into a PVC end cap screwed into the bulkhead. This method will be advantageous in terms of simplicity due to low cost and availability. It is expected that each end cap will require only one screw to secure the well to the bulkhead, meaning minimal additional machining to the bulkhead. The Dog House Rocketry mounting kit would effectively accomplish the desired task in a similar manner, but the kit configuration would call for superfluous efforts in machining, tolerancing, and assemblage of the included hardware. The selected in-house bolting scheme will reduce the likelihood of charge well detachment while reducing additional labor.

4.3 Laundry

The following sections outline the design of the various recovery devices.

4.3.1 Parachute Selection and Sizing

Each section of the vehicle has to land with a kinetic energy of less than 75 ft-lb to comply with NASA Req. 3.3. A minimum size and drag coefficient can be determined for the main parachute with this upper bound:

$$v_{\text{max}} = \frac{2KE_{\text{max}}}{m_{\text{max}}} \tag{1}$$

$$(C_d A)_{\text{min}} = \frac{2m_{\text{max}}g}{\rho v_{\text{max}}^2} = 108.3 \text{ ft}^2 \tag{2}$$

where $m_{\max}$ is the maximum section mass, shown by Table 22. All parachutes in the main parachute trade study met this minimum requirement. The criteria then used to compare the parachutes were: cost, weight, drag parameter $C_d A$, and packing volume, where the drag parameter was desired to be minimized. The parachute trade study is shown in Table 23.

Table 22: Section Masses, Excluding Laundry Mass

	Payload Bay	Recovery Bay	ACS Bay	Fin Can
Mass (oz)	166	124	147	192

Table 23: Main Parachute Trade Study

		Rocketman Standard (D=12',C_d=.97)		Rocketman Ultra Light (D=12',C_d=.97)		Rocketman Inspired (D=10',C_d=1.27)		Rocketman Ultra Light (D=8',C_d=2.2)	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Weight (oz)	10%	17	0.02	8.37	0.03	28.3	0.01	7.30	0.04
$C_d A$ (ft^2)	45%	109.7	0.11	109.7	0.11	99.75	0.12	110.58	0.11
Cost ($)	40%	155	0.16	310	0.08	210	0.11	470	.05
Packing Vol. (in.^{3})	5%	138.2	0.00	49.1	0.01	164.8	0.00	24.3	0.03
Total WNV		**0.287**		**0.236**		**0.250**		**0.227**	

The parameters of the selected main parachute, the Rocketman Standard Parachute, are shown in Table 24.

Table 24: Main Parachute Parameters

Parameter	Value
Brand	Rocketman
Shape	Parabolic
Material	1.1 oz Ripstop Nylon
No. Shroud Lines	4
C_d	0.97
Diameter (ft)	12
Weight (oz)	17.0
Cost ($)	$155.00
Packing Volume [in^3]	138.2

There are a range of acceptable drag parameters for the drogue based on the main parachute selected was determined by the descent time and drift requirements (NASA Req. 3.10 and NASA Req. 3.11), as well as an upper limit on the acceleration at main deployment of 25g.

$$v_{\text{min}} = \frac{h_{\text{apo}} - h_{\text{dep}}}{t_{\text{req}} - h_{\text{dep}}/v_{\text{wind}}} \tag{3}$$

$$(C_d A)_{\text{max}} = \frac{2mg}{\rho v_{\text{min}}^2} = 7.72 \text{ ft}^2 \tag{4}$$

$$v_{\text{max}} = \sqrt{\frac{2mg(n+1)}{\rho (C_d A)_{\text{main}}}} \tag{5}$$

$$(C_d A)_{\text{min}} = \frac{2mg}{\rho v_{\text{max}}^2} = 3.73 \text{ ft}^2 \tag{6}$$

where h_{apo} is the highest possible apogee, h_{dep} is the altitude at main deployment, n is the maximum acceleration at main deployment, and m is the total vehicle mass. The main deployment altitude is desired to be 500 ft, in order to reduce the drift, but it cannot be set to this exact altitude because of the delay on the redundant altimeters. The maximum delay is 2 seconds, meaning that the deployment altitude can be calculated:

$$h_{\text{dep}} = 2v_{\text{drogue}} \tag{7}$$

Drogue parachutes and streamers were selected for the trade study using this range of $C_d A$ values. The trade study criteria were cost, weight, drag parameter, and packing volume. Additional weights were added to account for the streamer's ability to reduce drift and the flexibility in sizing. The area can be set to whatever is desired since the streamer is custom. The streamer can be shortened using a hot knife after purchase in addition to flexibility in ordering. The drogue trade study is shown in Table 25.

Table 25: Drogue Trade Study

		Rocketman 2' x 30' Streamer (C_d=.105)		Rocketman Elliptical Parachute (D=24",C_d=1.6)		Fruity Chutes Compact Parachute (D=24",C_d=1.55)		Fruity Chutes Elliptical Parachute (D=24",C_d=1.55)	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Weight (oz)	15%	12	0.01	2.1	0.06	1.6	0.08	2.2	0.04
$C_d A$ (ft^2)	10%	5.66	0.03	5.03	0.03	4.87	0.04	4.87	0.04
Cost ($)	40%	70	0.12	50	0.17	72.03	0.12	64	0.13
Packing Vol. (in^3)	15%	30	0.02	12.16	0.04	8.8	0.05	12.2	0.04
Drift Reduction	10%	1	0.10	0	0	0	0	0	0
Sizing Flexibility	10%	1	0.10	0	0	0	0	0	0
Total WNV		**0.3757**		**0.3003**		**0.2846**		**0.2449**	

Table 25 determined the streamer to be the best method to slow the descent rate before main deployment, mainly due to the additional flexibility and drift benefits with similar cost. The coefficient of drag for the streamer was obtained from the manufacturer for a streamer of the same area, but the team will perform testing to calculate the drag coefficient of the streamer empirically. The parameters for the streamer are shown in Table 26.

Table 26: Drogue Parameters

Parameter	Value
Brand	Rocketman
Shape	Streamer
Material	1.1 oz Ripstop Nylon
No. Shroud Lines	4
C_d	0.105
Length (ft)	30
Width (ft)	2
Weight (oz)	12.0
Cost ($)	$70.00
Packing Volume [in^3]	30

4.3.2 Parachute Protection

The parachutes of the launch vehicle will be located in the chamber where the black powder will combust and the emitted gasses can cause serious damage to the material of the parachute. Therefore, the parachutes will need protection from these combustion charges so parachute protectors were analyzed with trade studies to determine the most optimal choice. The two main criteria that fit a desired parachute protector were cost and weight. Cost was the driving factor since weight is relatively small for each product. Sizing was not considered as no additional benefit comes from a larger fabric, as long as the minimum (12x12 inch) was considered as it will cover the parachute entirely. Table 27 determined that the best parachute protector is the ApogeeRockets product, which had the lowest cost and a weight of 1.16 oz.

Table 27: Parachute Protection Trade Study

		ApogeeRockets (A=144 in^2)		**Rocketry Works (A=324 in^2)**		**Rocketman (A=324 in^2)**	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Weight (oz)	10%	1.16	0.05	2.26	0.024	2	0.03
Cost ($)	90%	8.09	0.144	10.95	0.325	26.5	0.13
Total WNV		**0.49**		**0.35**		**0.16**	

4.4 Avionics Design

Each of the separation events will be controlled by commercially available altimeters. These altimeters will be powered by batteries and armed using mechanical arming switches. The following sections detail the selection of these components.

4.4.1 Altimeter Selection

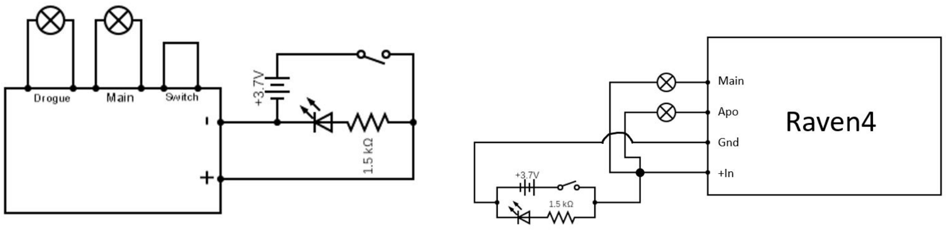
Six total altimeters will be necessary for fully redundant primary and secondary recovery modules, with three altimeters allocated to each module. Five altimeters are currently in the team's inventory, making them cost effective and reliable choices for five of the six altimeters to be used. The altimeters currently in inventory include one Featherweight Raven4, two StratoLogger SL100, and two StratoLogger CF altimeters. The final altimeter was chosen considering the cost, size, and weight of the device. The ability of the altimeter to act as a GPS system, noted as "dual use" in Table 28, was also considered. Table 28 shows the results of the trade study conducted to choose the final altimeter.

Table 28: Altimeter Selection Trade Study

		StratoLogger CF		Raven4		Telemini		Telemetrum	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Cost	42%	69.95	0.156	160	0.127	152	0.130	363.46	0.062
Area (in^2)	25%	1.68	0.055	1.44	0.059	0.835	0.070	2.94	0.034
Weight (oz)	25%	0.38	0.061	0.233	0.073	0.25	0.072	0.71	0.034
Dual Use	8%	1	0	0	0	0	0	1	0.020
Total WNV		**0.272**		**0.260**		**0.271**		**0.149**	

The StratoLogger CF altimeter was ultimately chosen due to its low cost, relatively compact size and low weight. The second choice altimeter, the Telemini, was very close in score to the StratoLogger CF, but the StratoLogger CF has been used in the past by the team, verifying its reliability and increasing its ease of use over the Telemini. Additionally, the StratoLogger CF has a low power draw, allowing for a small battery.

The electrical schematics for the chosen altimeters are shown in Figure 16.



(a) Perfectflite StratoLogger (b) Featherweight Raven

Figure 16: Recovery Electrical Schematics

4.4.2 GPS Selection

One GPS transmitter will be mounted to the bulkhead separating the payload and recovery bays to fulfill NASA requirement (3.12) and verify the results of the payload mission. The Featherweight GPS Tracker was chosen due to its reliability and ease in assembly along with other criteria listed in Table 29. The reliability of the system is imperative as it will verify the results of the payload mission. The chosen GPS tracker has a range of 300,000 ft and can simultaneously receive signals from GPS and GLONASS which, coupled with highly positive reviews and recommendations, indicates a reliable system. The Featherweight GPS tracker needs no soldering to be an active and reliable device and can connect to an iPhone to transmit location information, increasing its ease of assembly and use. The Telemetrum and

Telemega GPS systems also serve as altimeters, indicated by the dual use criteria. While this is an attractive quality, the Teletrum and Telemega do not have the same reliability as the Featherweight GPS Tracker and do not have considerable size benefits to outweigh other deficits. NDRT has used the Eggfinder Mini GPS Transmitter in the past but found difficulties with soldering the device correctly which impacted the reliability and ease of assembly of the system. This year, the Featherweight GPS tracker will be used to mitigate unreliable GPS information issues from prior years.

Table 29: GPS Selection Trade Study

		Featherweight Tracker		Eggfinder Mini		Telemetrum		Telemega	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Cost ($)	17%	350	0.028	75	0.065	365.49	0.026	484.62	0.010
Major Assembly	25%	0	0.100	1	0.025	0	0.050	0	0.075
Reliability	30%	1	0.120	4	0.030	3	0.060	2	0.090
Weight (oz)	10%	0.529	0.029	0.35	0.036	0.71	0.021	0.88	0.014
Area (in^2)	10%	3.28	0.316	2.28	0.324	2.94	0.319	4.06	0.310
Dual Use	8%	1	0	0	0	1	0.040	1	0.040
Total WNV		**0.743**		**0.48**		**0.716**		**0.715**	

4.4.3 Other Electrical Components

Switch selections were evaluated based on their reliability and safety, cost, and ease of use. The switches must not be able to be activated or disarmed unintentionally, must be easily accessible from outside the launch vehicle, and must be reasonably cost effective. The keyed rotary switch was chosen for both the PRM and SRM due its high performance in the above mentioned categories. Additionally, an LED light will be lit when each key switch is activated to further increase the safety of the system and clarify the state of the switches. The trade study table is shown in Table 30.

Table 30: Switch Selection Trade Study

		Keyed Rotary		Pin-Pull		Push Button		Eggtimer Wifi Switch	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Cost ($)	25%	6	0.100	6.95	0.096	7.15	0.096	28	0.021
Ease of Use	10%	1	0.033	1	0.033	2	0.017	1	0.033
Reliability	30%	1	0.136	3	0.082	5	0.027	1	0.136
Weight (oz)	15%	5	0.014	2	0.055	1	0.068	2	0.055
Area (in^2)	10%	1	0.022	0.5	0.040	0.062	0.057	1.58	0.001
Ease of Assembly	10%	1	0.038	1	0.038	4	0.015	5	0.008
Total WNV		**0.356**		**0.351**		**0.280**		**0.273**	

4.5 Integration

The avionics and energetics for both the main and drogue deployments will be housed in the PRM, shown in Figure 17. The PRM will be located in the recovery bay. It contains six charge wells, two U-bolts, and three altimeters to provide independent redundancies to ensure that the streamer and main parachute will be deployed at the correct altitudes. The SRM, shown in Figure 18, will house the avionics and energetics responsible for the separation of the fin can from the airframe of the launch vehicle and is located fore of the fin can. The SRM is identical to the PRM is design with the only difference being the absence of charge wells, mounting blocks, and a U-Bolt on the bottom bulkhead. The SRM controls only one separation event, rendering the extra material unnecessary.

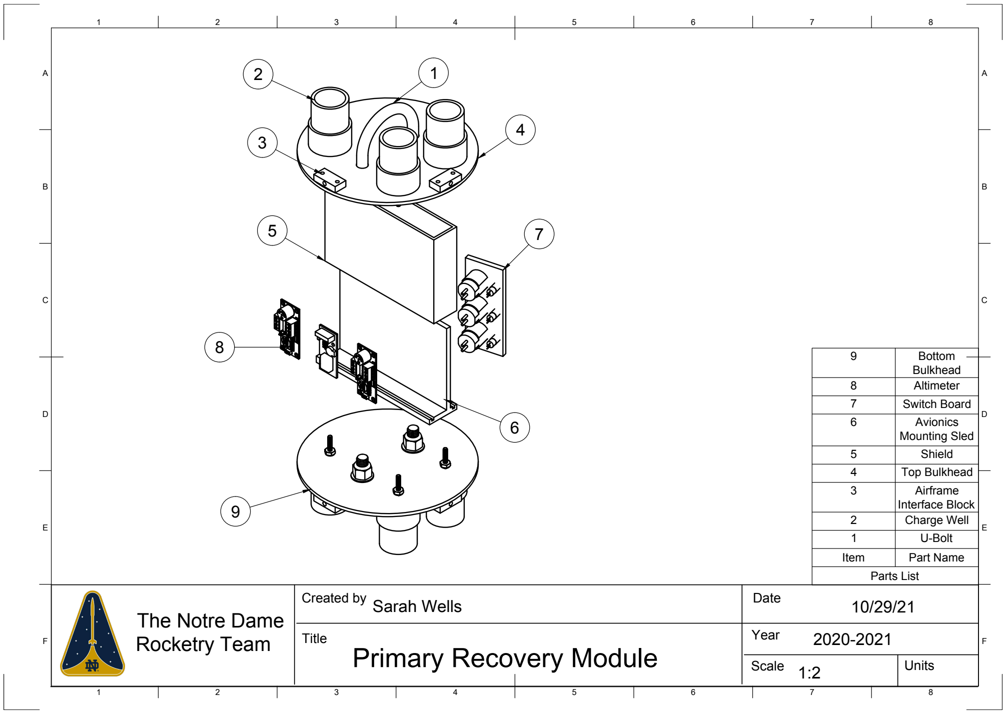


Figure 17: Primary Recovery Module Drawing

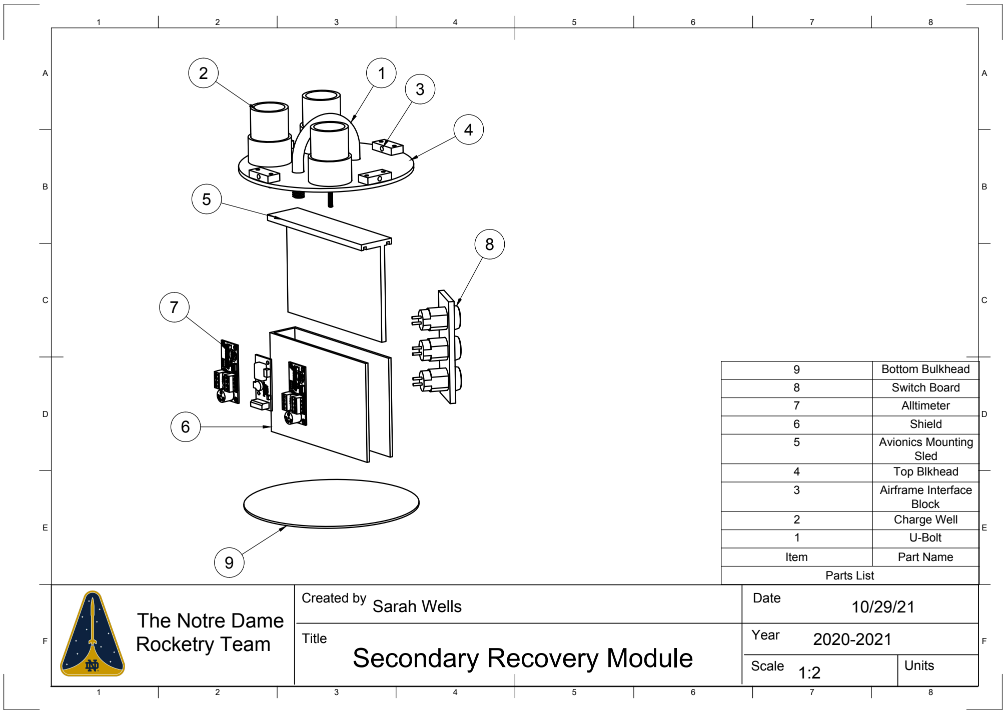


Figure 18: Secondary Recovery Module Drawing

The altimeters will be mounted on the avionics mounting sled and shielded from electromagnetic interference by a carbon-fiber inlaid 3D-printed shield. The shield slides into grooves on the avionics mounting sled as shown in figure 19.

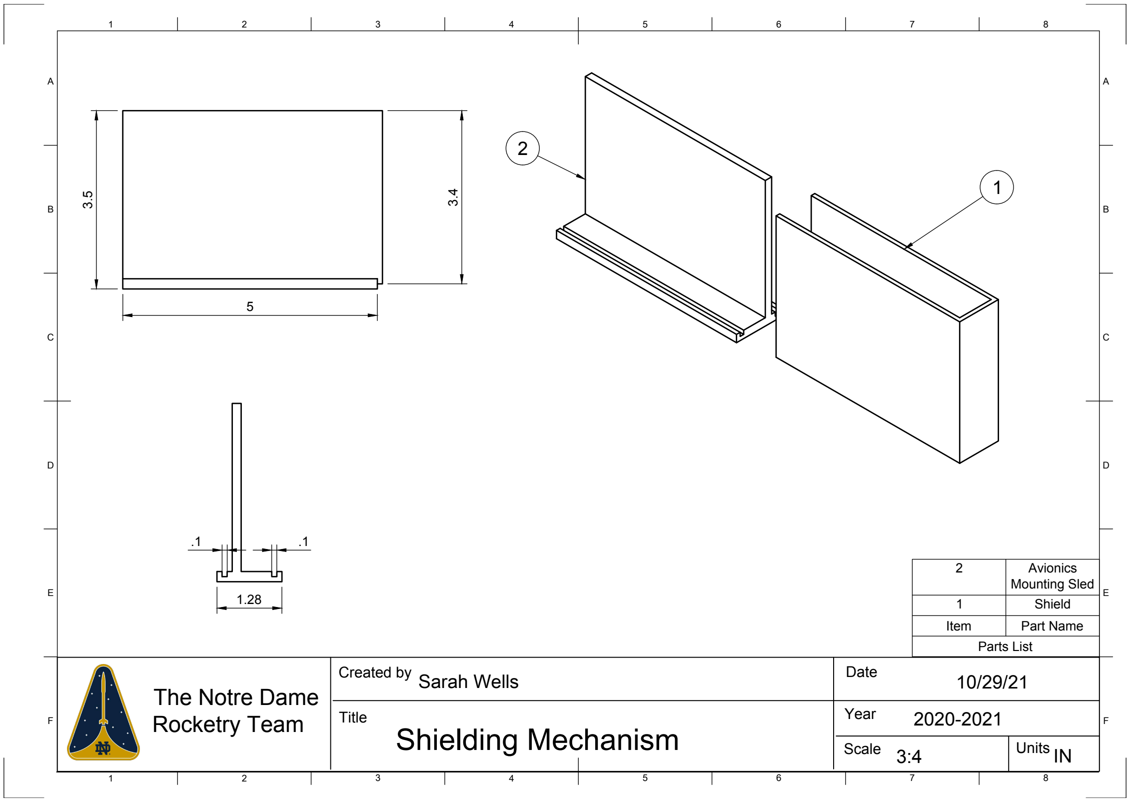


Figure 19: Shielding Mechanism Drawing

Both the PRM and SRM house three keyed rotary switches to control the respective integrated avionics packages.

The main load bearing elements of the PRM and SRM are the bulkheads, which transmit in-flight loads to the air frame. The material selection for both the bulkheads and the altimeter mounting board are shown in the following sections.

4.5.1 Bulkhead Material Selection

The bulkhead material for the recovery module was chosen based on four criteria: tensile strength, density, cost, and machinability. A high tensile strength is necessary because the bulkhead transfers the load from the parachute to the vehicle body, a low density is desired to reduce mass, and the material must be affordable and able to be machined without difficulty. The trade study is shown in Table 31 and the chosen material is Garolite G-10.

Table 31: Bulkhead Trade Study

		Garolite G-10		HDPE		Aluminum 6061	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Tensile Strength (psi)	0.45	50,000	0.234	4,000	0.019	42,000	0.197
Density (lb/in^3)	0.2	0.69	0.054	0.035	0.107	.0975	0.038
Cost	0.2	44.88	0.058	27	0.097	59.07	0.044
Machinability	0.15	2	0.043	3	0.064	2	0.043
Total WNV		**0.390**		**0.287**		**0.323**	

4.5.2 Altimeter Mounting Sled Material Selection

The material selection for the altimeter mounting sled was based on the maximum service temperature, tensile strength of material, weight, density of material, and cost. The density and cost were the two highest drivers in material selection, as the mounting sled is minimally load bearing. The trade study, shown in Table 32, determined that the altimeter mounting sled material will be made of 3D printed ASA.

Table 32: Altimeter Mounting Sled Material Trade Study

		ASA		ABS		Nylon	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Max. Temp (°C)	0.05	95	0.02	98	0.02	87.5	0.02
Tensile Strength (MPa)	0.15	42.75	0.05	6.90	0.01	80	0.09
Density (g/cm^3)	0.40	1.07	0.14	1.07	0.14	1.14	0.13
Cost	0.40	0.04	0.29	0.15	0.08	0.30	0.04
Total WNV		**0.48**		**0.27**		**0.26**	

4.6 Recovery Preliminary Testing Plan

NDRT has developed a preliminary testing plan to properly verify the design, fabrication, and integration of the recovery system. The systems team will continue developing each of the tests described in Figure 33 and provide full detailed test plans for CDR.

Table 33: Recovery System Preliminary Testing Plan

Test Name	Description	Success Criteria
Ground Test	Activate black powder ejection charges within horizontally integrated launch vehicle to simulate in-flight separation events	All vehicle sections separate fully using calculated amount of black powder
Altimeter Simulated Flight	Use computer generated flight data and LEDs connected to altimeter ejection output terminal blocks to simulate expected separation event timeline	LEDs corresponding to appropriate altimeters illuminate at expected altitudes
Battery Duration Test	Activate system with fully charged battery and leave in cold environment to simulate launch delay in extreme limit of launch temperature window.	System remains active for 3 hours, fulfilling battery duration requirement
GPS Transmitter Field Test	Connect GPS to computer software to observe data transmission from GPS to computer	GPS transmits accurate location to computer
Altimeter Disarming Test	Power on altimeters with LEDs connected to altimeter ejection output terminal blocks and disarm altimeters with switches to ensure all LEDs turn off	All altimeters/LEDs power down completely when switches are turned into the off position
Parachute/Streamer Opening Test	Release a weight from a balcony to ensure that parachutes and streamers open without the cords tangling	Parachute and streamer escape deployment bags and open unhindered by shock cord entanglement

Table 33: Recovery System Preliminary Testing Plan (continued)

Test Name	Description	Success Criteria
Drogue Streamer C_D Determination Test	Release drogue streamer connected to a known weight from a predetermined height to calculate the drag coefficient	Sufficient data is collected for the calculation of drogue streamer C_D
Launch Vehicle Demonstration Flight	Integrate full system into launch vehicle to test parachute deployment and safe recovery of launch vehicle	All separation events occur as designed, parachutes open without tangling, and launch vehicle is safely recovered
Payload Demonstration Flight	Integrate full system into launch vehicle to test parachute deployment and safe recovery of launch vehicle	All separation events occur as designed, parachutes open without tangling, and launch vehicle is safely recovered

5 Vehicle Mission Performance

5.1 Simulation Methods

The team used three methods to assess the performance of the vehicle: OpenRocket, RockSim, and hand calculations. OpenRocket and RockSim are both full flight simulators, which output flight profiles for a range of inputs. Hand calculations were used for a preliminary verification of the vehicle's structural integrity and as the primary assessment of the vehicle's descent performance.

The OpenRocket simulation can contain error for many reasons, including:

- Mismatch in weather conditions on launch day to simulation such as wind speed, direction, air density
- Performance of real world components under stress such as fin flutter
- Differences in the real texture of surface components compared to simulated surface

- Shift in wind speed during flight due to altitude change, direction change, or gusts
- Manufacturer variations in components such as the motor, body tubes, etc

OpenRocket uses the Barrowan method with a correction term for determining the aerodynamic characteristics of the vehicle and makes several assumptions including

- Small angle of attack
- Steady and irrotational flow under parachutes
- Rocket body is rigid and axially symmetric
- Nose is sharp
- Fins are flat plates, rocket body is axially symmetric

Tumbling during descent is modeled using an average drag coefficient that was empirically determined. However, this model did not account for the effect of fins, and an additional 3-14% error is introduced for. OpenRocket uses fourth-order Runge-Kutta to numerically integrate the equations of motion for the vehicle, which introduces additional error into the calculation. Overall, the creators of OpenRocket estimate the simulation over-approximates apogee by about 29%, though it may be up to 43%.

It can be more difficult to asses sources of error in RockSim outside of model inaccuracies since it is a proprietary software. The authors of OpenRocket performed many comparisons between the two software programs and found that RockSim generally produces apogees 5-10% higher than OpenRocket, but it is unclear which is more accurate. OpenRocket is generally used as the primary simulation method because it is open source, allowing for a more informed view of the introduction of error into the predictions.

The hand calculations used in the descent performance predictions made many assumptions, including the following:

- Instantaneous parachute opening and velocity change
- Worst-case scenario apogee (ACS does not deploy)
- Constant wind velocity
- Streamer reduces drift by 25% compared to drogue parachute
- No weathercocking

The following equations were used to calculate the performance parameters:

$$v = \sqrt{(2mg)/(\rho C_d A)} \tag{8}$$

$$KE = 0.5mv^2 \tag{9}$$

$$T = \frac{\delta h}{v} \tag{10}$$

$$D = F_d T v_{\text{wind}} \tag{11}$$

where F_d is the drift factor, which allows for more accurate calculation of the drift reduction of a streamer.

5.2 Simulated Flight Profiles

The team conducted a series of flight simulations using OpenRocket to predict a range of flight profiles within the possible launch rail cant angles of 5 - 10° and wind speeds of 0 - 20 mph . The results of those simulations are provided in Table 34, Table 35, and Table 36, which include the velocity off the rod (ft/s), apogee altitude (ft), max velocity (ft/s), and max acceleration (ft/s^2) of the launch vehicle for varying wind speeds.

Table 34: 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	87.6	5228	621	397
5	87.6	5203	621	397
10	87.6	5173	621	397
15	87.6	5139	620	397
20	87.6	5109	620	397

Table 35: 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	87.7	5186	622	397
5	87.7	5310	621	397
10	87.7	5210	621	397
15	87.7	5151	621	397
20	87.6	5010	620	397

Table 36: 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	87.7	5096	622	397
5	87.7	5051	622	398
10	87.7	5005	622	398
15	87.7	4955	621	398
20	87.7	4901	620	398

The accompanying flight profiles for the three tables above are provided in Figure 20, Figure 21, and Figure 22.

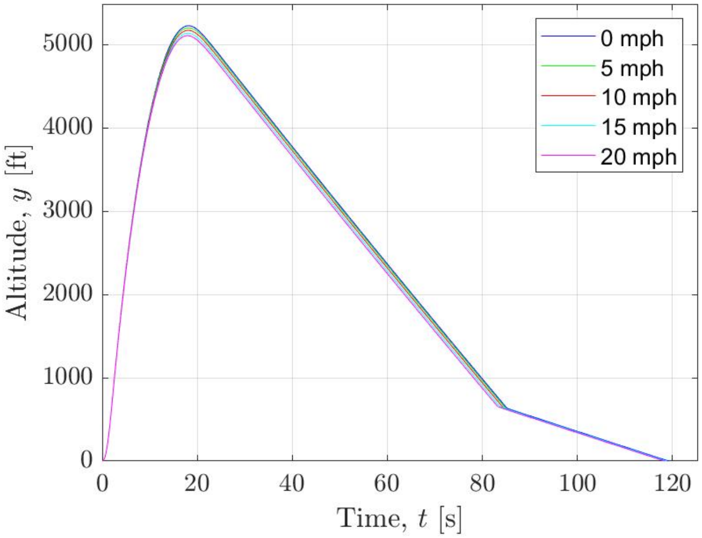


Figure 20: Flight profiles from OpenRocket simulations for Launch Angle of 5°

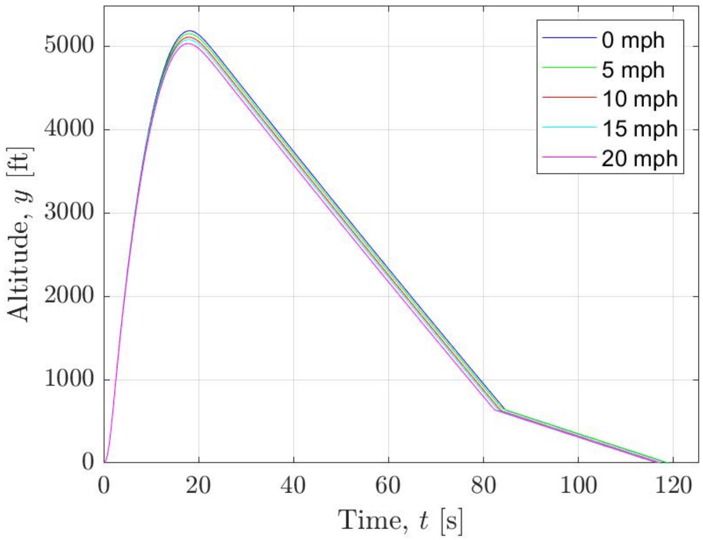


Figure 21: Flight profiles from OpenRocket simulations for Launch Angle of 7°

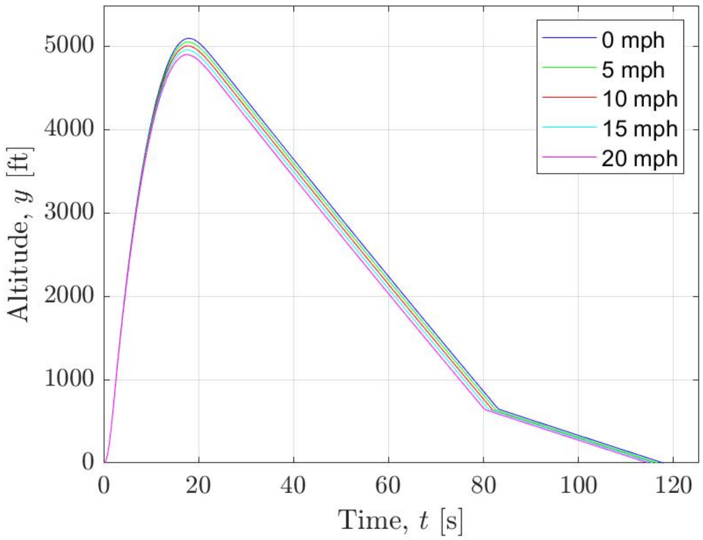


Figure 22: Flight profiles from OpenRocket simulations for Launch Angle of 10°

A model of the launch vehicle was also generated in RockSim, and the same setup conditions were applied to cross-verify the validity of the OpenRocket simulations provided above. The results of the RockSim simulations are provided in Table 37, Table 38, and 39.

Table 37: 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	92.9	5577	625.7	400.9
5	92.9	5596	625.5	400.9
10	92.9	5609	625.1	400.8
15	92.9	5611	624.5	400.8
20	92.9	5606	624.0	400.8

Table 38: 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	92.9	5531	625.9	401.1
5	92.9	5559	625.7	400.9
10	92.9	5582	625.3	400.9
15	92.9	5590	625.0	400.8
20	92.9	5596	624.2	400.8

Table 39: 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	92.9	5433	626.5	401.4
5	92.9	5479	626.2	401.2
10	92.9	5504	625.9	401.1
15	92.9	5538	625.1	400.9
20	92.9	5546	624.7	400.9

5.2.1 Launch Target Altitude

The main priority for determining an official target apogee is to select and apogee that enables the ACS system to be effective in adding drag to control the apogee altitude. The team's priority is to select a target that is below the lowest simulated apogee, although the simulations from OpenRocket and RockSim varied by about 300 feet. The worst case apogee scenario is that the vehicle is on a trajectory to an apogee less than the target apogee such that the ACS system is completely unable to affect apogee. For this reason, with simulated apogees between 5578 feet and 4900 feet, the team will select 4800 feet as the official target apogee.

5.2.2 Stability

The OpenRocket and RockSim models were used to check the static stability margin of the launch vehicle at the launch rail exit to satisfy NASA Req. 2.14. In each case, the CP was calculated using the Barrowman equations, and the stability in calibers was calculated using Equation 12 in which CP is the location of the CP measured from the nose cone tip, CG is the location of the CG measured from the nosecone tip, and d is the launch vehicle outer diameter.

$$\text{Stability} = \frac{CP - CG}{d} \tag{12}$$

The static stability measured by the OpenRocket model is 2.75 calibers, and the static stability measured by the RockSim model is 2.67 calibers (NASA Req. 2.14). Based on research done on past model rocket launches, it was determined that a stability around 2.75 will be ideal for a vehicle of this aspect ratio

Further analysis will be done using CFD to generate a pressure profile around the launch vehicle airframe in attempt to better estimate of the CP location at the off-rail velocity when cross-winds are present.

5.3 Flight Descent Predictions

The following sections outline the performance predictions for vehicle descent.

5.3.1 Terminal Kinetic Energy

The kinetic energy values at main deployment from both the MATLAB simulation and the OpenRocket are shown in the Table 40:

Table 40: Kinetic Energy of Vehicle Sections at Main Deployment

Section	MATLAB K.E. (ft-lb)	OpenRocket K.E. (ft-lb)
Payload and Recovery Bay	2132.2488	2395.0713
ACS and Fin Can	2101.6208	2800.5342

The kinetic energy values at landing from both the MATLAB simulation and the OpenRocket are shown in Table 41.

Table 41: Kinetic Energy of Vehicle Sections at Landing

Section	OpenRocket K.E. (ft-lb)	MATLAB K.E. (ft-lb)
Payload Bay	56.4	63.9
Recovery Bay	42.3	47.7
ACS Bay	50.2	56.9
Fin Can	65.1	73.9

The difference in values for the kinetic energies can be attributed to the different landing velocities calculated by hand and obtained from OpenRocket. There was a 6% difference in these velocities, which is becomes almost 12% because velocity is squared in the equation for kinetic energy.

5.3.2 Descent Time

The estimated descent time from apogee as calculated by both the MATLAB and OpenRocket Simulations is shown in Table 42:

Table 42: Descent Time from Apogee

	OpenRocket (s)	MATLAB (s)
Descent Time	88.1	82.7

The difference in descent times is likely due to OpenRocket's more advanced calculation methods. The OpenRocket simulation steps through time so it can account for the continuous change in velocity due to parachute deployment, even while assuming instantaneous parachute opening. This would have contributed to the increase in descent time that was seen.

5.3.3 Drift Radius

The estimated drift radius as calculated by both the MATLAB and OpenRocket Simulations is shown in Table 43:

Table 43: Drift Radius

Wind Speed (mph)	MATLAB (ft)	OpenRocket (ft)
0	0	0
5	517.3382	591.15
10	1034.6764	1218.04
15	1552.0145	1814.72
20	2069.3527	2389.94

Figure 23 shows the drift curve from OpenRocket.

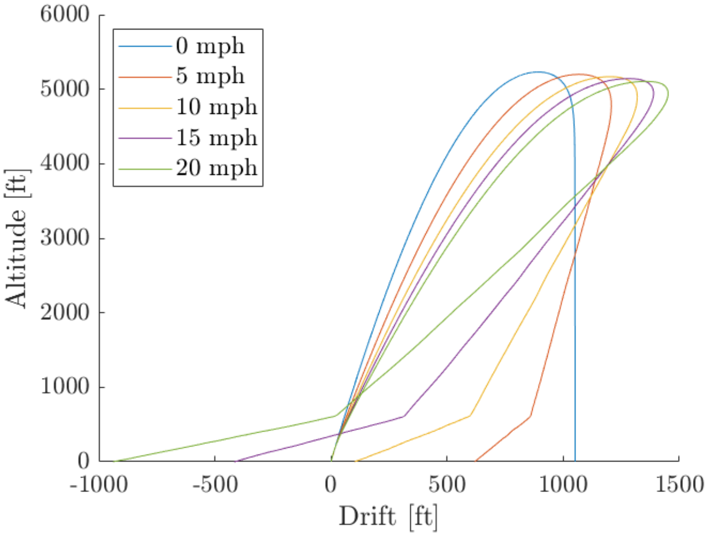


Figure 23: OpenRocket Drift

The differences between the two calculations are likely due to OpenRocket's wind model, which includes turbulent variation in wind speed and direction and weathercocking. These differences become more pronounced as the wind speed increases, as expected. Additionally, the drift obtained using hand calculations was subject to an initial estimate for the drift factor, which was the team's way of accounting for a streamer's drift-reducing properties. It is unclear how OpenRocket models this same property, but this did not concern the team, as the drift value assuming no benefits from a streamer (2484 ft with 20mph winds) was also under the value set by NASA Requirement 3.10.

5.4 Structural Verification

The highest loads during flight are expected at peak thrust and at main deployment. The expected accelerations at these events are listed in Table 44. The acceleration at peak thrust was determined using an OpenRocket simulation, and the acceleration at main deployment was calculated as shown in Equation 13:

$$a_{\text{max}} = \frac{\rho (C_d A)_{\text{main}} v_{\text{drogue}}^2}{2mg} - 1 \tag{13}$$

where m is the total vehicle mass. This is a very conservative estimate, since the model assumes that the main parachute will open instantaneously.

Table 44: Acceleration during Various Flight Events

Event	Expected Acceleration (g)
Peak Thrust	12.3
Main Deployment	18.84

The expected forces on various vehicle components can be calculated using these accelerations:

$$F = (a_{\text{max}} + 1)mg \tag{14}$$

where m is either the total vehicle mass, for peak thrust, or the combined mass of the sections supported on each side of the main separation point. The expected loads during each high-acceleration event are shown in Table 45.

Table 45: Loads during High-Acceleration Flight Events

Event	Component	Expected Load (lb)
Peak Thrust	Motor Mount	626
Peak Thrust	Centering Rings	215
Main Deployment	Payload Bay Eyebolt/Bulkhead	206
Main Deployment	Main Recovery Harness	782
Main Deployment	Drogue Recovery Harness	421
Main Deployment	Fin Can Recovery Harness	238
Main Deployment	PRM Fore U-Bolt/Bulkhead	576
Main Deployment	PRM Aft U-Bolt/Bulkhead	421
Main Deployment	ACS Eyebolt/Bulkhead	421
Main Deployment	SRM U-bolt/Bulkhead	238
Main Deployment	Fin Can Eyebolt/Bulkhead	238

The recovery harnesses, U-bolts, and eyebolts were all sized to to withstand the expected loads at main deployment. The recovery hardware for the SRM will also be designed to withstand main deployment to ensure safe vehicle recovery in all potential scenarios even though the fin can separation is slated to occur after main deployment. The bulkheads, motor mount, and centering rings were all designed with high strength materials and FEA will be used to determine that bulkhead thickness required for a minimum Factor of Safety of 1.5 (LV.2).

6 Technical Design: Launch Vehicle Identification System

6.1 System Objective and Mission Success Criteria

The Launch Vehicle Identification System, consisting of a strap-down inertial navigation system (INS), is the Notre Dame Rocketry Team's payload for the 2021-2022 NASA Student Launch Initiative. This year's payload remains inside the launch vehicle for the duration of the flight and uses an INS to track and calculate the launch vehicle's landing location. The LVIS will record data from three independent inertial measurement units (IMUs) and three independent accelerometers, filter the data, calculate the exact landing position, and assign a grid value. The LVIS layout as well as the design options currently under consideration are detailed in the following sections.

The LVIS is composed of multiple subsystems designed to satisfy multiple aspects of the payload mission. The LVIS can be broken down into three main subsystems: mechanical, electrical and software. The structure of the payload and its subsystems are seen in Table 46.

Table 46: LVIS Subsystems Overview

System	Description
Mechanical	Includes the physical structure of the payload including bulkhead material selection and overall structure of the payload system.
Electrical	Includes the selection and integration of each sensor in the overall LVIS system.Includes microcontroller selection, battery selection to meet requirement 2.7, and wireless data transmission.
Software	Includes the overall control algorithms from launch to landing of the LVIS system to determine the launch vehicle location, data filters to fuse sensor information, and software testing.

Trade studies were conducted to evaluate design alternatives for each payload subsystem and the design alternative with the highest value was selected as the leading design for that subsystem.

6.1.1 Mission Success Criteria

The following criteria will be used to evaluate the success of the payload system:

- The payload system correctly identifies and transmits the grid square in which the rocket lands and depicts the launch rail in the gridded image.

- The payload system collects relevant data throughout the entire flight and processes it through a sensor fusion algorithm to complete the task of identifying and transmitting the grid square after landing.
- The payload system is rigidly fixed to the launch vehicle, and the sensors are rigidly fixed inside the payload system, such that movement relative to the rest of the launch vehicle is minimized.
- The payload system and each of the parts inside are easily accessible for modification during tests and competition.

6.2 Functional System Designs

It is necessary to define the various design considerations for LVIS in order to effectively answer this year's mission. These design considerations provide criteria that allow the team to conduct trade studies to evaluate system alternative designs relative to one another as well as demonstrate functional design.

6.2.1 Design Considerations

The primary and secondary design considerations for LVIS are accuracy and ease of implementation, respectively. System accuracy is the primary driver of the system design decisions due to this year's system objective to locate the launch vehicle. The secondary driver ensures that the team is able to successfully design and implement the system within the timeline and to minimize any delays in schedule. Additionally, the design must accommodate the team derived requirements limiting the weight of LVIS to 80 oz, have a maximum length of 16 in., and have a maximum diameter of 6 in. according to the payload bay dimensions. The weight was allocated based on the need of the payload to have redundant systems to ensure the accurate identification of the launch vehicle upon landing and the relationship between the launch vehicles performance (NDRT Req. LVIS.1, NASA Req. 2.16). The team derived requirements focus on the longevity and strength of the system since the system does not have any moving or jettisoning components. LVIS power supplies must have at least 3 hours of operation (NDRT Req. LVIS.14) because of all of the electrical equipment. Moreover, the structural components must be able to withstand maximum loads of launch and landing with a factor of safety of 1.5. (NDRT Req. LVIS.2).

6.2.2 System Alternatives

The payload in the launch vehicle must be able to determine the location of the launch and landing site of the vehicle. The team considered utilizing an unmanned aerial vehicle (UAV), an INS, or glider computer imaging. The team envisioned the payload ejecting a UAV either mid-flight, or after the launch vehicle landed, that would take an image of the entire launch area. The INS would relay the payload's motion and orientation by using accelerometers, gyroscopes, and magnetometers that record acceleration, rotation, and magnetic field measurements. The sensors would calculate the distance the payload traveled relative to the launch position in order to complete the task. The glider computer imaging would jettison from the payload and use a passive flight method with active imaging detection software. The team weighted three factors as the most important to determine which system design would work best: mechanical simplicity, precision, and accuracy. Mechanical simplicity and accuracy were allocated the most weight because the method of determining location must be feasible and reliable. Table 47 showed that the INS had the highest total weighted normalized value becoming the leading design. The INS considered would be a strapdown INS which drastically reduces the mechanical simplicity since there would be no jettisoning event. Therefore, it scored the highest value amongst the three systems considered in that category. The other two systems would have to be designed for launch, landing, and ejection. The number of mechanical parts decreases by avoiding the deployment of a survey drone, decreasing the cost. The UAV and glider imaging system would have a mechanical and computation complexity outweighing its effectiveness and dividing the team to pursue two complex aspects of the design. Therefore, the team opted to use an INS composed of sensor arrays to complete the mission.

Table 47: System Level Alternatives

		Inertial Navigation System		UAV Computer Imaging		Glider Computer Imaging	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Mechanical Simplicity	30%	9	0.18	2	0.04	4	.08
Accuracy	30%	6	0.11	7	0.12	4	0.07
Precision	25%	8	0.01	3	0.05	3	0.05
Computational Simplicity	10%	1	0.01	3	0.03	5	0.06
Cost Effectiveness	5%	9	0.03	4	0.01	2	0.01
Total WNV		**0.47**		**0.26**		**0.27**	

6.3 Current System Design

LVIS is made of both mechanical and electrical components necessary to demonstrate functional design and safety within the launch vehicle. The current mechanical design of LVIS involved a trade study to determine the retention system and preliminary CAD designs for system layout. The electrical and software components of LVIS were designed through multiple trade studies relating to different components of the subsystem, including the various sensors, electronics, and data processing mechanisms all required to meet a functional design.

6.3.1 Mechanical

The mechanical system must safely retain itself within the payload bay of the launch vehicle. The team designed a mechanical subsystem that was chosen for ease of manufacturing, ease of mounting for sensors, and cost, among other factors. It must also not interfere with the transmission of the various electronic components as well as be reusable for multiple launches.

The team considered several options for overall LVIS layouts. Each option was evaluated for its positive and negative aspects on several factors, including implementation and ease of use. The first design consisted of layered bulkheads. Each bulkhead holds one of the three identical sensor assemblies. These bulkheads are stacked along the length of the launch vehicle and connected using spacers. The positive aspects of this design are that it allows for easy manipulation of the separate sensor assemblies. One negative aspect of the design is the need to separate the sensor assemblies in order to work on them. This issue will be resolved by attaching the spacers at 45 degree rotations from each other so that the levels are easy to access in order to detach.

The team also considered using flat plates connected to bulkheads at the fore and aft section of the payload module to hold all of the sensors as seen in Figure 24. This design was attractive to the team because each of the sensor plates would be accessible and it would be a simple design. However, this option was ultimately discarded because it would pose a challenge in wiring and connecting the multiple electronics. In addition, this design does not allow for the identical systems to be detached from each other in order to work on multiple sensor assemblies at the same time.

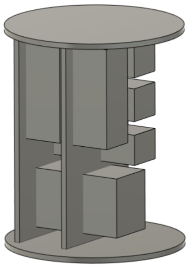


Figure 24: Alternative Payload Layout

6.3.1.1 System Layout

The team also considered a MEGASLED system design. This design was one module consisting of both the payload and recovery subsystems to integrate into the launch vehicle. The team concluded that this connection would complicate both the building and assembly processes. Ultimately, the team decided that the complexity of the system outweighed the benefit of integrated building.

Overall, the team selected the layered bulkhead system because it was less complex than the MEGASLED option, due to not needing to interface with the recovery system. Additionally, the layered bulkhead system provided more accessibility in terms of building and assembly than the flat plate system.

Once the team decided to use a tiered bulkhead design for LVIS, the team considered several options of materials to be used for the sensor bulkheads. These options included Aluminum 6061, fiberglass, plywood, and high-density polyethylene (HDPE). The criteria used to determine which material would be ideal for the bulkheads were ease of manufacturing, ease of mounting sensors, cost, specific volume, and loss factor, a measure of the dampening capability of each material. Ease of manufacturing was weighted the highest (35%), followed by ease of mounting sensors (30%), cost (15%), specific volume (10%), and loss factor (10%). The team decided that being able to easily work with the material and manipulate the placement of the sensors were the most important factors because the framework of the payload has to be stable in order for everything else to work smoothly. Cost was also weighted very heavily due to the allotted budget. The specific volume was deemed important because of the mass limit set for the payload. Finally, the loss factor was important because a dampening material was desired in order to reduce vibrations during flight and noise in the sensors. Plywood was the best option of the four because its ease of manufacturing and mounting sensors were very similar to that of Aluminum 6061 and fiberglass, but it comes at a much lower cost. Moreover, wood has natural dampening properties which will help counteract against sensor noise due to vibrations.

Table 48: Bulkhead Material Trade Study

		Aluminum 6061		Fiberglass		Plywood		HDPE	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Ease of manufacturing	35%	5	0.13	4	0.10	3	0.08	0	0.05
Ease of mounting sensors	30%	3	0.08	4	0.10	3	0.08	2	0.05
Cost ($)	15%	35.61	0.00	22.65	0.05	8.88	0.10	9.00	0.10
Specific Volume (cm^3/g)	10%	0.369	0.01	0.385	0.011	1.613	0.047	1.03	0.03
Loss factor	10%	0.0001	0.0002	0.020	0.038	0.013	0.024	0.02	0.04
Total WNV		**0.211**		**0.278**		**0.282**		**0.228**	

The leading system configuration with the selected bulkhead material for the sensors is seen in Figure 25.

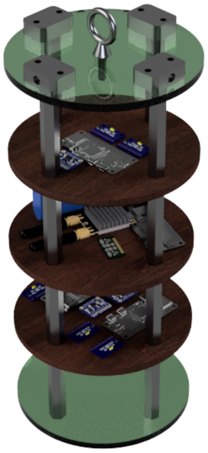


Figure 25: Payload Layout

6.3.2 Electrical

The electrical components of the LVIS are paramount to executing the payload mission successfully. The sensors for each redundant bulkhead system consist of two IMUs and an accelerometer that is able to operate in higher g ranges connected to a microcontroller. The three bulkhead subunits are connected to a central microcontroller which handles data processing and transmission via the radio subsystem. A battery will be used to power a power distribution board to properly supply voltage and current to the individual systems alongside a buck converter and a voltage regulator. The team will be using printed circuit boards (PCB) to improve connections and mechanical stability for the sensors and explore designs to reduce noise and electromagnetic effects. Figure 26 presents a preliminary wiring diagram.

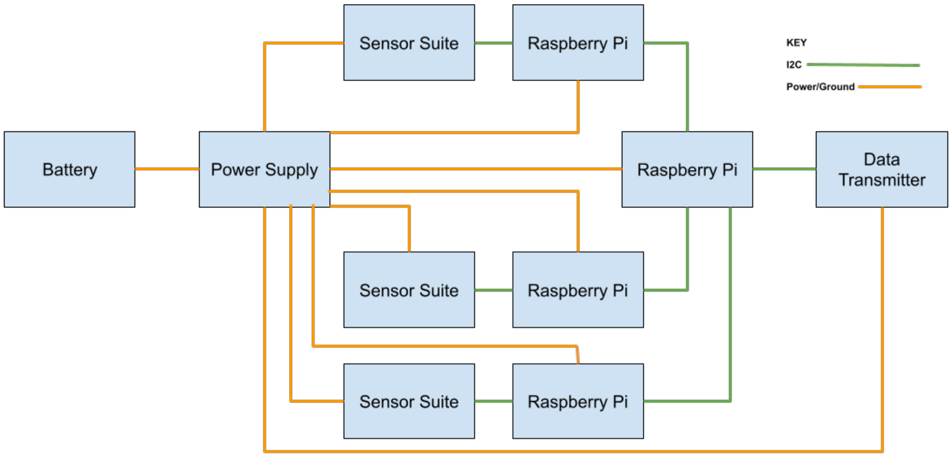


Figure 26: Preliminary Wiring Diagram

6.3.2.1 Sensors

The team will be using two IMUs and an accelerometer that operates in the higher g points of the launch vehicles trajectory (HiG accelerometer) to compose the INS. Two IMUs were selected to effectively balance the sensitivity and the range during the launch and landing of the launch vehicle. Moreover, the HiG accelerometer ensures that the microcontroller has more accurate readings during the highest acceleration points of the launch vehicle's trajectory. Trade studies were conducted to determine the proper sensors and are detailed in the sections below.

6.3.2.2 IMU

The LVIS will use an Inertial Measurement Unit (IMU) to determine the motion and orientation of the rocket at any given moment by providing acceleration, rotation, and magnetic field measurements with the end goal of determining the rocket's touchdown location. The team considered three different IMU sensors: Adafruit BNO055, HiLetgo MPU9250, and the SparkFun ICM-20948. The team rated the sensors based on factors such as maximum sampling rate, sensitivity, range, and resolution of their accelerometer, gyroscope, and magnetometer, as well as the cost and ease of implementation. The gyroscope specifications were weighed more heavily than the other sensors because it is critical to the payload team that the angular velocity and orientation of the rocket is accurate. The max sampling rate and sensitivity of each device were weighted heavier than the range because of the plan to use different sensors that will specialize in certain ranges. It is ideal that all IMUs considered can operate with an input voltage of 5 V; anything over will decrease its ease of implementation score. The BNO055, as specified by its data sheet, used the following equations to calculate the maximum sampling rates for the gyroscope and the accelerometer:

$$\text{Max Gyro Sampling Rate} = 4 f_s \ \text{[Hz]} \tag{15}$$

$$\text{Max Accelerometer Sampling Rate} = 2bw \ \text{[Hz]} \tag{16}$$

where f_s is the max update rate (2000 Hz) and bw is the max bandwidth (2000 Hz).

Table 49: IMU Trade Study

		Adafruit 9-DOF BNO055		HiLetgo MPU9250		SparkFun ICM-20948	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Cost ($)	20%	19.95	0.00	8.99	0.16	16.95	0.04
Max Sampling Rate of Gyro (Hz)	12%	8000	0.04	8000	0.04	9000	0.04
Sensitivity of Gyro (LSB/dps)	12%	16	0.01	131	0.06	131	0.06
Sensitivity of Accelerometer (LSB/g)	10%	2000	0.01	32000	0.08	4500	0.01
Max Sampling Rate of Accelerometer (Hz)	10%	1000	0.00	16384	0.05	16384	0.05
Max Sampling Rate of Magnetometer (Hz)	10%	30	0.00	1000	0.09	100	0.01
Sensitivity of Magnetometer (μT/LSB)	10%	0.15	0.02	0.60	0.07	0.15	0.02
Ease of Implementing	10%	5	0.02	8	0.04	8	0.04
Range of Accelerometer (g)	2%	16	0.01	16	0.01	16	0.01
Range of Gyro (dps)	2%	2000	0.01	2000	0.01	2000	0.01
Range of Magnetometer (μT)	2%	1300	0.00	4800	0.01	4900	0.01
Total WNV		**0.09**		**0.56**		**0.25**	

6.3.2.3 Accelerometer

The team will be utilizing a high-g accelerometer to determine the launch vehicle's location by measuring its acceleration in three directions. It is imperative to have a high-g accelerometer along with the IMUs to properly measure acceleration during moments of high forces on the vehicle during flight, such as the main parachute deployment. The team conducted a trade study to determine the best option of 3 different accelerometers. The options were the

Adafruit ADXL377, the DFRobot Gravity 12C H3LIS200DL, and the Adafruit ADXL375-EP. The three accelerometers were judged on their cost, sampling rate, maximum acceleration, accuracy, and availability. Accuracy was weighted the highest, since correctly determining the vehicle's position is paramount to the success of the LVIS. Availability and sampling rate were both weighted the same and as the next most important in order for ease of obtaining the accelerometer and for ensuring that the most data is obtained during the vehicle's flight. The trade study is shown in Table 50.

Table 50: Accelerometer Trade Study

		Adafruit ADXL377		DFRobot Gravity 12C		Adafruit ADXL375-EP	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Accuracy	30%	1	0.06	3	0.18	1	0.06
Availability	25%	1	0.05	3	0.15	1	0.05
Sampling rate	25%	1.00	0.05	1.00	0.05	3.20	0.15
Max acceleration (g)	10%	200.00	0.03	200.00	0.03	200.00	0.03
Cost ($)	10%	24.95	0.00	13.90	0.03	24.95	0.00
Total WNV		**0.19**		**0.44**		**0.30**	

The trade study determined that the best option for the LVIS is the DFRobot Gravity 12C H3LIS200DL, shown in Figure 27. The three accelerometers were very similar, but the DFRobot Gravity 12C was the most cost effective, easily available, and most accurate.

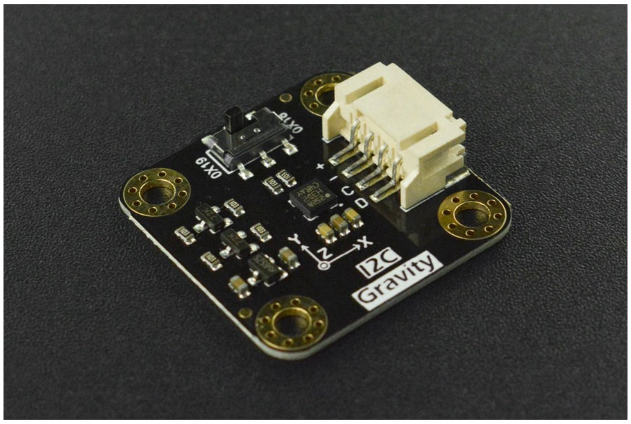


Figure 27: The team will use a DFRobot Gravity 12C High-G Accelerometer

6.3.2.4 Microcontroller

The microcontrollers perform one of two purposes. Each subunit microcontroller is part of an embedded system that receives data from IMUs and accelerometers, filters incoming data, computes displacements, and sends the resultant information. The main microprocessor then must take the calculated displacements from the three sensor-microcontroller units to determine the presence of outliers and transmit the final averaged location of the payload to a ground station. The microcontroller used must meet the following requirements in Table 51. It must be sufficiently small to fit into the payload container, have sufficient processing capabilities to complete the described task as determined by memory and clock speed, use minimal power due to limited battery capacity, and be available at a low cost. The Raspberry Pi 0W most adequately meet these requirements as it was the cheapest microprocessor with a high processing capability (1 Ghz single-core CPU). Additionally, it has a small footprint of only 1950 mm^2 and similar voltage inputs to other competing microcontrollers.

Table 51: Microcontroller Trade Study

		Raspberry Pi (0W)		Arduino (Maker 0)		Beaglebone	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Size (mm^2)	30%	1950	0.24	1538	0.25	5625	0.11
Processing Power (GHz)	20%	1	0.08	0	0.04	1	0.08
Availability	20%	7	0.07	7	0.07	7	0.07
Voltage Input (V)	20%	5	0.07	5	0.07	5	0.07
Cost ($)	10%	12.5	0.09	29	0.07	60	0.11
Total WNV		**0.54**		**0.49**		**0.37**	

Figure 28: Raspberry Pi Zero W

It is difficult to predict the availability of microcontrollers due to a worldwide shortage of chips and supply chain issues. Therefore, every microcontroller in the trade study received the same value. The team has begun early procurement of microcontrollers from a variety of suppliers and plans to use leftover microcontrollers from previous years for initial testing to mitigate this problem. Moreover, the team has an alternative configuration for the microcontrollers and sensors that utilizes 3 microcontrollers instead of 4. One of the three microcontrollers will take the responsibilities of calculating grid location and transmission after landing. This alternative configuration is detailed in Figure 29.

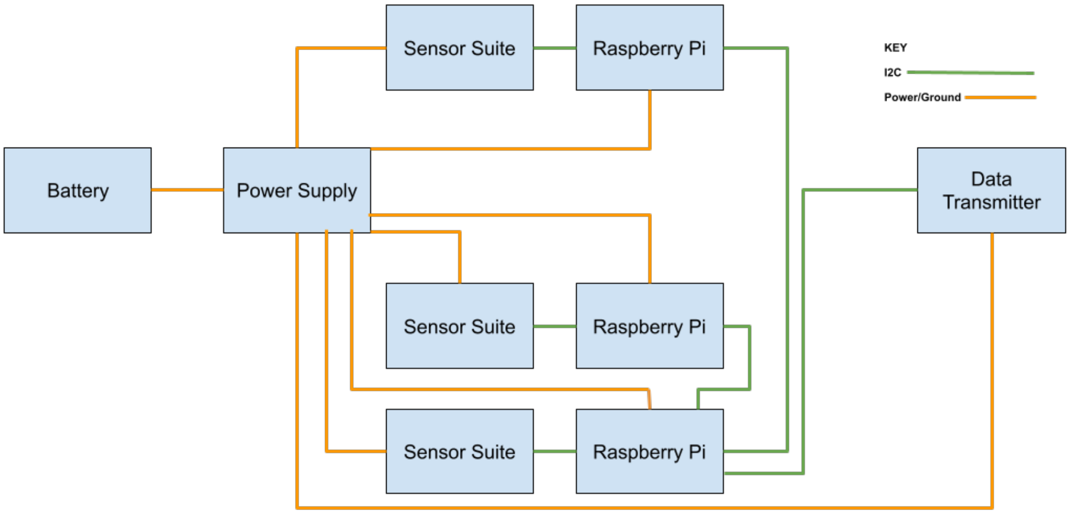


Figure 29: Alternative Preliminary Wiring Diagram

6.3.2.5 Battery

The team will have one battery to supply a power distribution board. The power distribution board regulates the voltage down to the supply levels for each of the subunits consisting of the Raspberry Pis, IMUs, and accelerometers in addition to the transceiver and the central Raspberry Pi Zero W. The 7.4 V will go through a buck converter and a LDO (low dropout) regulator to regulate down to 5 V and 3.3 V and any other operating voltages required by the microcontrollers and sensors. This topology takes advantage of the buck regulator's power efficiency and the linear regulator's low noise output which helps reduce noise for the INS. Additionally, the battery will need to have sufficient capacity for a life span long enough to provide power to the microcontrollers for the duration of the launch sequence including pre-launch, in-flight, and post-launch time intervals. Lastly, the battery must meet certain physical constraints such as size, and weight limits that have been set for the larger payload system. Table 52 compares the different batteries the team considered.

Table 52: Battery Trade Study

		Streamlight 18650 USB Li-ion Battery		Adafruit Lithium Ion battery Pack (2 cells)		Adafruit Lithium Ion Battery Pack (3 cells)	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Capacity (mAh)	25%	2600	0.05	4400	0.08	6600	0.12
Cost ($)	20%	25	0.13	19.95	0.14	24.50	0.13
Voltage (V)	20%	3.7	0.03	7.40	0.07	11.10	0.10
Mass (g)	20%	48	0.17	95	0.14	155	0.10
Size (mm^3)	15%	19634	0.13	45954	0.10	67068	0.07
Total WNV		**0.5**		**0.524**		**0.521**	

The battery that best meets these requirements was the Adafruit Lithium ion battery pack which consists of two, 18650 sized cells. This pack meets the requirement of supplying 7.4 V, a high enough voltage to be regulated down to 5 V and 3.3 V and low enough to minimize power consumed by a voltage regulator. Furthermore, this pack provides a total maximum capacity of 4400 mAh which will ensure a sufficiently long lifespan even in the case of time delays during launch. Ultimately, this battery was selected because it meets the voltage and capacity requirements while a single cell battery does not. Additionally, because a two cell battery meets the voltage and capacity requirements and has a lower cost and weight than a three cell battery pack the team decided to select the Adafruit 2 cell lithium ion battery pack.

Figure 30: Adafruit Lithium Ion Battery Pack - 3.7 V 4400 mAh

6.3.2.6 Wireless Data Transmission

The wireless transmission system of the payload will transmit the grid square where the rocket lands to the ground station. It will consist of two transceivers, one on board the rocket and another on the ground station. The payload bay will be fiberglass allowing radio frequency (RF) signals to pass through. The payload transceiver will interface with the locating system to receive the grid square upon landing and the ground station transceiver will output the location to a terminal. The maximum transmission range must exceed the radius of the launch field to allow for signal reception from any landing location. The team first considered the RFD900x 915 MHz transceiver module. This device is commonly used in hobby-grade remote control systems with a maximum range of up to 40 km line-of-sight. It operates on 5 V and 800 mA, which makes it ideal for battery-powered applications. A lower power version, the RFD900u, operates on 5 V and 300 mA with a 20 km max range. Also considered was the Adafruit RFM95 Low-Power Radio (LoRa) module. This module operates on very low power and also transmits on the 915 MHz band. It draws a max peak current of 120 mA and is advertised to have up to 20 km range with directional antennas. A trade study (Table 53) was conducted to evaluate the system options according to their range, cost effectiveness, hardware and software simplicity, and power consumption. The RFD900x was selected based on the trade study results. Specifically, the RFD900x has the highest value for range ensuring that transmission is successful over large distances and has the highest value for hardware simplicity leading to its selection.

Table 53: Wireless Transmission Trade Study

		RFD900u		**RFD900x**		**RFM95 LoRa (Adafruit)**	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Range	30%	5	0.09	10	0.19	1	0.02
Low power consumption	30%	7	0.10	5	0.07	10	0.14
Hardware simplicity	20%	7	0.08	7	0.08	3	0.04
Cost effectiveness	10%	6	0.03	5	0.03	8	0.04
Software simplicity	10%	5	0.03	5	0.03	5	0.03
Total WNV		**0.34**		**0.40**		**0.27**	

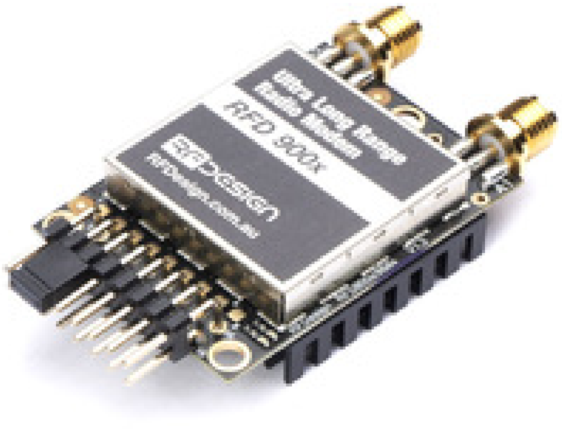


Figure 31: Long Range Telemetry Module

6.3.3 Software

Control flow is an integral part of effectively acquiring and processing the data from LVIS. The process is subdivided into data filtration and software testing portions, both necessary to test and demonstrate a functional design.

6.3.3.1 Overall Control Flow

Each subunit microcontroller on LVIS will perform the same sequence of tasks. They will start by calibrating each IMU and accelerometer and collecting data that is filtered using a Kalman filter while an unfiltered copy is saved for later analysis and displacement calculation. The real-time filtered data is used to determine launch through velocity, acceleration, and altitude readings. This filtered data set with minimal noise is then used to determine landing, at which point data collection stops. The unfiltered data is then filtered using a Gauss-Newton filter and used to calculate the overall displacement of the payload container on a grid using only data collected between the launch and landing timestamps determined by the real-time filtered data. This location is then sent to the main microcontroller for final calculations. This process is shown in Figure 32.

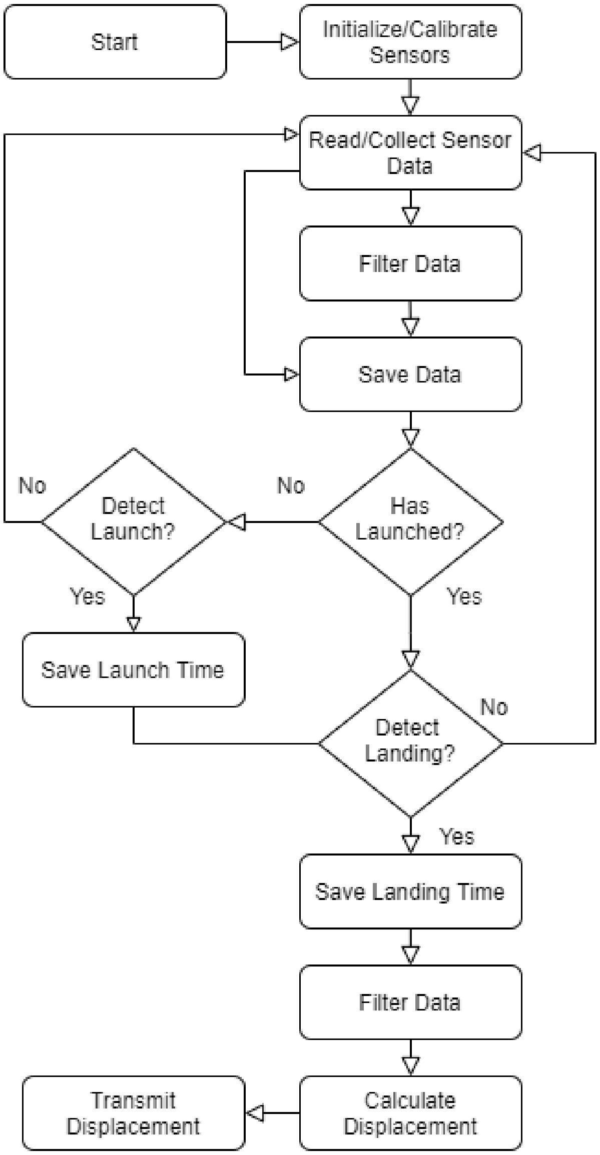


Figure 32: Overall Control Flow

The main microcontroller first receives the three displacement values from each subunit controller. The relative spacing of each displacement is compared to the others to determine if there is a significant difference. Any outliers detected in the set is eliminated. The remaining data points are then averaged to determine the final displacement of the payload. This value on the launch grid is then transmitted to the ground station. This process is shown in Figure 33.

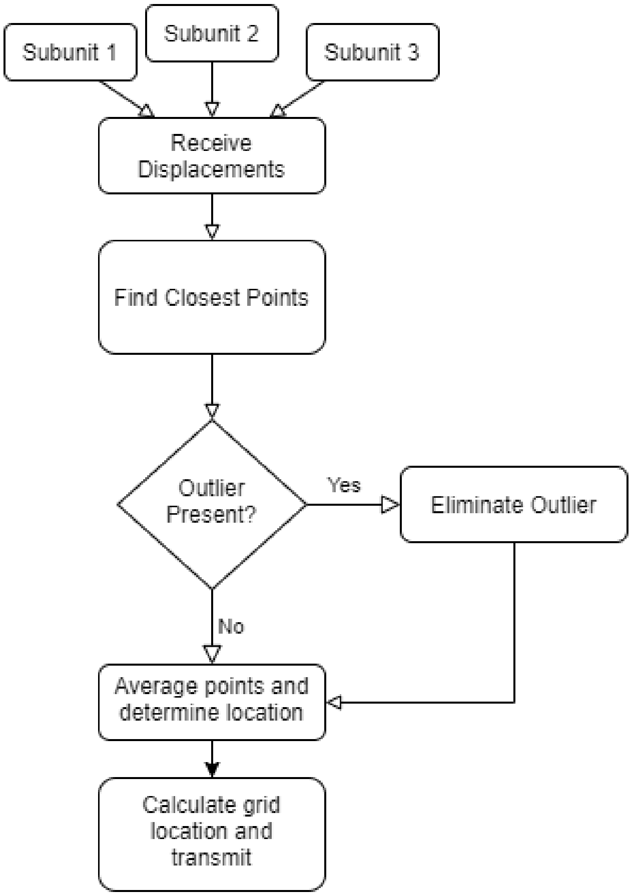


Figure 33: Primary Microcontroller Control Flow

The position will be correlated to the gridded image once the main unit has established a location for the launch vehicle. The aerial image of the launch field will be satellite-retrieved with the launch rail GPS coordinates as permitted through NASA Req. 4.2.3.1 . A grid with an appropriate scale will then be superimposed upon the image. The determined location will be calculated using the fact that all of the grids are 250 ft by 250 ft with the launch rail as the center. The on-board GPS from the recovery system will be used to verify the launch vehicle's location after the software has determined a landing site grid number as expressed in NASA Req. 4.2.3.1.

6.3.3.2 Data Filters

Data filters will need to aggregate the various raw data measurements from each sensor of the IMUs into a single, more accurate, and de-noised measurement to have an accurate measurement of the launch vehicle's state of system. The various data filters considered by the team were the recursive Gauss-Newton filter, the Kalman filter, the Madgwick complementary filter, and the Mahony complementary filter. These various filters were examined with two purposes in mind: one for analyzing the vehicle mid-flight and one for analyzing the vehicle once it has landed.

The recursive Gauss-Newton filter was found to be the most accurate in computing the state of the vehicle and relatively easy to conceptually grasp, but computationally very demanding and not quite as efficient as other filters. The Kalman filter was found to be effective in responding to quick changes in the system and in accurately eliminating noise from the data, but was not quite as accurate as the Gauss-Newton filter. The Kalman filter is also easy to implement due to being a popular choice for sensor fusion. The Mahony complementary filter was found to be roughly as accurate as the Kalman and more computationally efficient but more difficult to implement. The Madgwick complementary filter, similar in concept and implementation to the Mahony filter, was found to be more accurate for 9 DoF systems but with more processing time required.

Tables 54 and 55 show the trade studies performed for the above filters, the former for mid-flight analysis and the latter for post-flight analysis. Each filter was examined with five criteria in mind. Accuracy measures how effective the filter is in fusing raw, noisy data from multiple sensors into the state of the launch vehicle. Memory efficiency represents how much data the filter requires in order to perform its computation. Performance speed measures how many samples the filter can run through in a certain time interval. Ease of implementation deals with the complexity of the algorithm and with the resources available to implement it, and ease of testing deals with the complexity of verifying the algorithm's accuracy.

Table 54: Mid-Flight Data Filter Trade Study

		Kalman		**Recursive Gauss Newton**		**Madgwick**		**Mahony**	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Performance Speed	30%	7	0.09	4	0.05	6	0.08	7	0.09
Accuracy	25%	7	0.05	10	0.08	8	0.06	7	0.05
Ease of implementation	15%	8	0.04	7	0.04	6	0.03	6	0.03
Memory	15%	7	0.04	5	0.03	6	0.04	6	0.04
Ease of Testing	15%	6	0.03	8	0.05	6	0.03	6	0.03
Total WNV		**0.26**		**0.24**		**0.24**		**0.25**	

Table 55: Post-Flight Data Filter Trade Study

		Kalman		Recursive Gauss Newton		Madgwick		Mahony	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Accuracy	45%	7	0.10	10	0.14	8	0.11	7	0.10
Ease of implementation	20%	8	0.06	7	0.05	6	0.04	6	0.04
Ease of Testing	20%	6	0.05	8	0.06	6	0.05	6	0.05
Memory Efficiency	10%	7	0.03	5	0.02	6	0.03	6	0.03
Performance Speed	5%	7	0.01	4	0.01	6	0.01	7	0.01
Total WNV		**0.25**		**0.28**		**0.24**		**0.23**	

The different weights for each criteria between Table 54 and Table 55 represent the different needs between mid-flight analysis and post-flight analysis, wherein the former speed is most important followed by accuracy while in the latter accuracy is by far the most important with speed not an important consideration. The trade studies resulted in the Kalman filter being favored for mid-flight analysis and in the recursive Gauss-Newton filter favored for post-flight analysis. The team will examine and explore these algorithms for their respective purposes, but still will consider and test other possibilities.

6.3.3.3 Software Testing

The team plans to perform tests on each component to ensure each component of the software system performs as expected. Unit testing will be performed on as many sections of the code as possible. Each sensor will be tested independently, placing them in controlled environments to ensure their output matches the expected result. The integrated software system will be tested in multiple ways. Legacy data from previous years will be inputted into the system to calculate the position and compare it to the confirmed position. The ACS data from last year's launches will be sufficient for this test since it also utilized IMUs with nine degrees of freedom. Both subscale and full scale launches will also provide valuable data, regardless of whether LVIS is fully operational on the flight. The upcoming subscale launch will carry one of the planned three microcontroller subunits to collect data for this exact purpose. Simulations will be run to verify that the filter is appropriately removing noise and helping to compute the true system displacement. Any problems arising during launch will be isolated and addressed to ensure nothing similar happens during subsequent launches.

6.4 Launch Vehicle Interfaces

The primary launch vehicle interface is the retention system. The retention system for the payload is especially important as it provides stability to limit movement during flight, which minimizes forces and potential damage to the payload, as well as allowing for more precise sensor measurements to determine the location of the launch vehicle upon landing. The team was initially considering an integrated Payload and Recovery system, nicknamed the "MEGASLED", where the payload assembly would be firmly attached to the Recovery system, and the two retained inside the rocket together. However, this idea was rejected after further consideration due to the unnecessary complexity of the design and difficulty of integrating the two subsystems.

The team compared on three ideas to retain the payload: twist and lock mechanism, internal bolting to a bulkhead, and bolting to the outside of the payload bay. The twist and lock mechanism would allow for easy insertion and removal from the payload bay, but is a complicated mechanism and would be difficult to fabricate. Bolting to an inside bulkhead would give an adequate level of stability and not impact the design of the launch vehicle, but would also be harder to access and the connectors on the bulkhead would have to be sealed due to the location of the charges needed for separation of the rocket stages during recovery. Finally, bolting to the outside of the payload bay allows for the same high level of stability (in both lateral and rotational movement) as the former idea, but allows for easier access of the screws to remove the payload. The latter idea was also discussed with the launch vehicle squad as well to ensure that bolts on the exterior of the rocket would not significantly impact the launch vehicle, flight path, or simulations for the rocket itself. There will be two fiberglass retention bulkheads forward and aft of the payload system with aluminum retention blocks that directly interface with the payload bay. A trade study, as shown in Table 56, was conducted to evaluate the three design ideas based on relative stability, complexity, ease of access, machinability, cost, and weight.

Table 56: Retention Trade Study

		Bolt to Airframe		Bolt to Bulkhead		Twist and Lock	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Stability	40%	5	14.29	5	14.29	4	11.43
Complexity	20%	4	8.89	4	8.8	1	2.22
Ease of Access	15%	4	6.00	1	1.5	5	7.50
Machinability	10%	3	3.33	5	5.56	1	1.11
Weight	10%	2	2.86	2	2.86	3	4.29
Cost	5%	3	1.67	4	2.22	2	1.11
Total WNV		**37.03**		**35.31**		**27.66**	

6.5 Preliminary Mass Statement

A preliminary mass for the payload system was calculated after evaluating all design alternatives for each subsystem of LVIS and selecting the leading design for each. A mass growth allowance was also calculated based on the maturity and type of component; the total weight of the LVIS should not exceed 80 oz. Table 57 shows a breakdown of each component, the component maturity and type, the basic mass estimate and mass growth allowance percentage for each component, the total system basic mass, and the total system predicted mass.

Table 57: LVIS Mass Breakdown

Component	Maturity	Type	Basic Mass (oz)	MGA (%)	Predicted Mass (oz)
Raspberry Pi 0W	5	SENS	1.27	2	1.2954
Lithium Ion Battery Pack - 3.7 V 4400mAh	5	BAT	5	2	5.1
RFD900x	5	SENS	0.51	2	0.52
HiLetgo MPU 9250	5	SENS	0.576	2	0.58752
Wood Sensor Bulkheads	3	PRIM	7.60	10	8.36
Eyebolt	5	SEC	1.63	3	1.6789
Aluminum Retention Blocks	3	PRIM	4.212	10	4.6332
Threaded Hex Standoff	3	PRIM	32.28	10	35.508
DFRobot Gravity I2C H3LIS200D	5	SENS	0.317	2	0.324
Wiring	3	WIRE	3	18	3.54
Fiberglass Retention Bulkheads	3	PRIM	9.755	10	10.730
Power Board	3	ELEC	1.5	14	1.71
Screws/Nuts	3	PRIM	2	10	2.2

6.6 Payload Preliminary Testing Plan

NDRT has developed a preliminary testing plan to properly verify the design, fabrication, and integration of the payload system. The systems team will continue developing each of the tests described in Table 58 and provide full detailed test plans for CDR.

Table 58: Payload Preliminary Testing Plan

Test Name	Description	Success Criteria
Electronics Unit Tests	Connect each sensor to a computer to print real time data from the sensor and ensure each sensor can accurately read physical input data	Each sensor accurately records physical input data within sensor specifications
LVIS Module Integration Test	Connect each LVIS module to a computer to print real time data from the module and ensure each module can accurately read physical input data.	Each module accurately records physical input data
Transmission Module Test	Activate transmission module with command to transmit arbitrary information to simulate transmission to ground station	Ground station receives arbitrary data given to transmission module
Full System Integration Test	After full system integration, use computer generated flight data to simulate full-scale flight and observe expected output	Integrated electronic system works as intended, and payload system yields an expected output
Range Test	Transmit calculated launch vehicle location to ground station over the maximum allowable drift radius of 2,500 ft	LVIS is able to transmit the calculated location over this distance

Table 58: Payload Preliminary Testing Plan (continued)

Test Name	Description	Success Criteria
Battery Duration Test	Activate system with fully charged battery and leave in cold environment to simulate launch delay in extreme limit of launch temperature window.	System remains active for 3 hours, fulfilling battery duration requirement
Main Parachute Deployment Event Test	Subject payload bay with integrated system to simulated main parachute deployment event	Sensor suite registers perturbation due to high-g event
Algorithm Drift Test	Compare the algorithm predicted location vs real time location when the launch vehicle is moved around over time	Algorithm accurately predicts the launch vehicle location
Subscale Test Flight	Integrate single data collection module into vehicle to record all flight data necessary to perform the Algorithm Drift Test and the Full System Integration Test	Necessary data is successfully collected during flight
Payload Demonstration Flight	Integrate full system into Launch Vehicle for Payload Demonstration Flight to test system performance	System accurately determines grid location of landed launch vehicle

6.7 Subscale

One of the LVIS subunits will be included in the subscale vehicle. It will consist of the two IMUs, the accelerometer, a battery, and a microcontroller. The subunit will collect launch data and will serve as a point of reference for the development of the LVIS algorithm. The raw data will be fed through the Kalman filter and then compared to measure the filter's effectiveness.

7 Technical Design: Apogee Control System

7.1 System Overview and Mission Success Criteria

The Notre Dame Rocketry Team's Apogee Control System (ACS) squad focuses on designing a system that will help control the altitude of the launch vehicle during flight. The ACS system slows the launch vehicle down so that it reaches its required altitude without overshooting it based on the specifications for the altitude requirement. This is done by mechanically extending a set of drag surfaces from the body of the launch vehicle to generate drag. The ACS computer system decides how far to extend the surfaces by filtering data supplied by an altimeter, an accelerometer, and two IMUs. The ACS retracts the drag surfaces back into the body of the launch vehicle and deactivates for the remainder of the flight after they have slowed down the launch vehicle sufficiently and apogee has been achieved. The ACS subsystem must adhere to a variety of success criteria, listed below:

- System shall be located aft of launch vehicle burnout center of gravity (2.16)
- System shall not negatively impact the stability margin of the launch vehicle
- System shall not actuate until launch vehicle burnout stage has been reached
- System shall not change the pitch or yaw of the launch vehicle
- System shall accurately read in, filter, and actuate according to data corresponding to launch vehicle trajectory
- System shall ensure launch vehicle does not exceed target apogee by greater than 25 ft.
- System shall retract and enter a dormant phase once apogee has been achieved
- System shall retract if a jam is detected
- System shall be able to be fully integrated into the launch vehicle in 30 minutes or less and remain on launch pad for up to two hours prior to launch

7.2 Aerodynamic Considerations

It is necessary to consider effects of ACS actuation on other systems or the trajectory of the flight itself because the ACS actively manipulates the flow field around the launch vehicle. The requirement that the ACS does not deploy fore of the center of pressure of the launch vehicle is of primary importance, as it would decrease the stability of the vehicle. Drag surfaces will deploy aft of the launch vehicle center of pressure to satisfy NASA Req. 2.16 and NDRT Req. ACS.6. Additionally, the team will be conducting a variety of tests to understand the behavior of the flow field surrounding the ACS bay as it has an effect on barometric pressure data both as a static and dynamic system. These tests include wind tunnel testing, subscale flight testing with static fins, and CFD analysis.

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

$$F_{\text{drag}} = \frac{1}{2}\rho C_d A v^2 \tag{17}$$

where ρ is the density of air, C_d is the coefficient of drag, A is the effective area, and v is airspeed. It is assumed that the density of air remains constant because the target apogee is approximately a mile above ground level. The drag coefficient C_d will be determined for the launch vehicle body and tabs separately using CFD.

7.3 Mechanical Design

The drag surface actuation mechanism (DSAM) will be responsible for deploying tabs that induce drag and control the velocity and acceleration of the launch vehicle so that it achieves the predicted apogee of 4800 feet. The drag surfaces are designed to be controllable, meaning they can be moved to a specific position and held in that position. Maximizing the surface area of the mechanism will allow the DSAM to induce the greatest amount of drag and thus increase effectiveness. The DSAM will also be designed to fit within a 6-inch diameter and 12-inch length inside the launch vehicle. The DSAM will be designed so that it can withstand the highest demands of launch by a safety factor of 1.5, per requirements 11, 12, and 13. Additionally, the DSAM will be placed so that its effect on the stability of the launch vehicle is neutral or positive, per Requirement 8.

7.3.1 Mechanism Selection

It is first necessary to undergo a system level design of the mechanism itself to select the motor and materials of the tab actuation mechanism. Several mechanisms were proposed and trade in the ideation design phase. The team downselected to the following three mechanisms after weighing the relative pros and cons of each design.

7.3.1.1 Umbrella Flap Design

The first drag surface actuation mechanism that was examined utilizes the preexisting airframe to create drag-inducing flaps which deploy at an angle to the surface of the launch vehicle. It has been named the Umbrella Flaps Design (UFD) due to the resemblance of the flaps to an umbrella being opened. A picture of the mechanism of the UFD integrated into the airframe is shown in Figure 34.

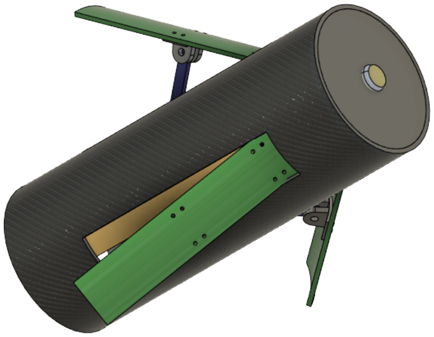


Figure 34: Mechanism Option 1 - Umbrella Flaps

The three drag flaps are deployed using pushrods attached to a lead screw controlled by a servo motor. The pushrods extend and deploy the flaps radially. As the motor turns the screw. Limit switches will be used at the fully retracted and fully extended position of the lead screw. The limit switch will turn the motor off once the lead screw reaches either the fully extended or the fully retracted position. The internal mechanism of the UFD is shown in Figure 35.

Figure 35: Internal Mechanism of the UFD

The UFD offers a wide range of motion, allowing flaps to be extended at an angle of nearly 90 degrees which makes the system extremely adaptable to situations that require varying amounts of drag.

An internal supporting bracket will be installed that couples both ends of the ACS system cavity to maintain the structural integrity of the launch vehicle and mitigate weak points that may result from the removal of material to create the flaps. The pushrods will be able to interact with the brake flaps through slits in the said bracket.

This surface area is significantly larger than the other two designs considered. The UFD also deploys vertically upward, meaning it must overcome air resistance during flight to deploy. Such a feature puts additional demands on the motor and could lead to a reduced number of higher drag-inducing positions, or require a more expensive motor. The UFD, however, promises the highest possible functionality over all three designs mainly due to its large surface area and adaptability to different in-flight scenarios.

7.3.1.2 Pizza Slice Design

The overall concept of this design is to make an airbrake by extending small tabs perpendicular to the launch vehicle. These tabs then have smaller sub-flaps which extend to the sides in order to increase the area and drag created by the air brake. These flaps in their extended state roughly resemble triangle pizza slices.

The actuation of the larger tabs is accomplished by turning the rotational motion of a servo motor into translational motion using rods connected to the tabs. Each of these larger tabs have two smaller flaps which are hinged to the tab. The smaller flaps are actuated from each side of the main tab by a pin attached to each flap that guides the flaps through a curved slot cut in the base. The slot path forces the pin outwards and the tabs rotate along with the pin as the main tab extend. The design is displayed in Figure 36.

(a) Pizza Slices Mechanism - Retracted (b) Pizza Slices Mechanism - Extended

Figure 36: Mechanism Option 2 - Pizza Slices

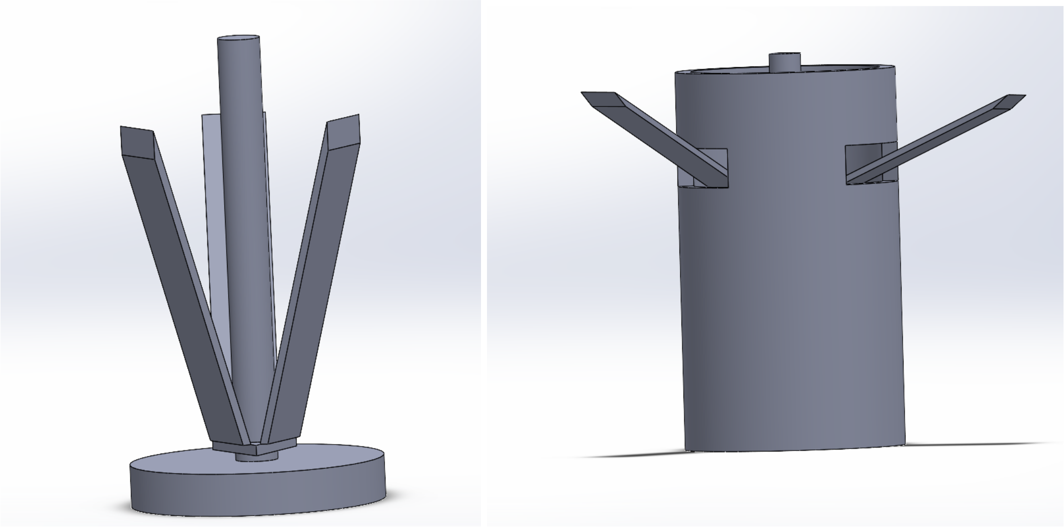
This design has several advantages, most notably its simplicity due to the design being inspired by previous ACS designs. It increases the area of the air brake while minimizing the size of the cut-outs in the airframe of the launch vehicle. Another advantage is the simplicity of flap control. The amount of drag created by the flaps can be reliably controlled since the flaps consistently extend as the main tab extends. In addition, this is an in-plane design and thus will not affect the launch vehicle's center of pressure as significantly as an out-of-plane design would.

One potential drawback of this design is that the allowable extension distance of the tabs is limited, making it harder to generate drag in the turbulent air created by the launch vehicle. Another drawback lies in the durability of the small flaps and ensuring they do not break off from the larger tab due to in-flight loads. Overall, this design proved to be a viable choice due to its simplicity and evolution of previous designs.

7.3.1.3 Ejection Flap Design

The third design examined utilizes the vertical space inside the airframe of the launch vehicle to store the flaps.

The design has three flaps stored at an angle inside the airframe, which are attached by a hinge to a central nut which can move up and down along a lead screw. The nut moves linearly along the bar when it is rotated by the servo. The bar pushes the flaps out through three slots in the airframe as it moves up, causing the flaps to be rotated about their respective hinges to a horizontal position. The system level CAD for the design is shown in Figure 37.



(a) Internal Mechanism (b) Deployed configuration

Figure 37: Mechanism Option 3 - Ejection Flap Design

The ejection flaps design comes with a number of benefits. Firstly, the flaps are large relative to the pizza slice design and would therefore produce more drag. Additionally, the deployment of the flaps is aided by the increased drag, thereby decreasing stress on the servo.

The complexity of the system is the main drawback to this design. The design has more hinge locations with less constrained movement than the other two leading designs, both implying additional failure modes and requiring tighter tolerances. The flaps could also easily get caught on or miss the openings in the airframe which would prevent them from deploying. Lastly, the deign is also larger than other designs, which would make integration into the launch vehicle more difficult.

7.3.1.4 Trade Study and Final Selection

The mechanisms were evaluated using a trade study with the following criteria: manufacturability, effective surface area, precision, mechanism structural integrity, airframe structural integrity, and complexity. Due to the nature of the mission being precise velocity reduction given large variability in predicted altitudes, the two criteria that were weighted the most heavily were effective surface area at 30% and precision at 20%. Effective surface area was determined based on the system level CAD of each mechanism, and precision was determined based on the amount of rotation of the motor in order to induce one additional Newton of increased drag in the response. The next most important factors in the trade study were structural integrity of the mechanism itself and of the airframe, with each rated at 15%. The airframe structural integrity rating was based on the amount of material remaining because each of these designs involve removing some portion of the material from the airframe in which the ACS is housed. Mechanism structural integrity was determined based on the amount of support on the extended tabs in each design in addition to the amount of stress placed on internal components due to force on the extended tabs. Finally, manufacturability and complexity were each given a weight of 10% due to the fact that the team is confident each of these designs can be manufactured given the tools and workshops available. The complexity score is additionally based on the required tolerance on each component as well as the effect of any potentially out of spec manufactured component. The trade study is shown in Table 59.

Table 59: Mechanism Trade Study

		Ejection Flap Design		**Umbrella Flap Design**		**Pizza Slice Design**	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Effective Surface Area	30%	5	0.13	5	0.13	2	0.05
Precision	20%	4	0.07	5	0.08	3	0.05
Mechanism Structural Integrity	15%	4	0.06	3	0.05	3	0.05
Airframe Structural Integrity	15%	4	0.06	2	0.03	4	0.06
Complexity	10%	2	0.02	4	0.04	4	0.04
Manufacturability	10%	3	0.03	4	0.03	5	0.04
Total WNV		**0.15**		**0.16**		**0.09**	

The trade study determined that the Umbrella Flap design was the best option as a result of its high effective surface area, high precision, and relatively low complexity. The main concern the team has with this design is the structural integrity of the airframe given the fact that the entire area of the flap must be cut out of the airframe. However, as explained in the design of the umbrella flap section, the risk from these large cutouts will be mitigated using an internal load bearing brace system that will reinforce the airframe, preventing buckling caused by the compression force of the motor before burnout. The team plans to conduct extensive finite element analysis in order to ensure that a minimum factor of safety of 1.5 is maintained in all sections of the ACS, including the airframe housing the ACS.

7.3.2 Material Selection

The tabs will be manufactured with some curvature using 3D printed resin with carbon fiber inlay for structural stability. The drag surfaces will sit flush with the outside of the launch vehicle until deployment. This was chosen as it allows for the linkages connecting the drag flap surfaces to be manufactured as one piece with the drag flaps. Manufacturing in one piece reduces stress concentration around the linkages. In addition, the 3D printing process allows for material property and shape customization, so that the drag flaps can be toleranced to the exact shape of the airframe cutouts. The load bearing fore bulkhead will be manufactured out of aluminum in order to provide a load path from the drogue parachute to the walls of the airframe. All other components will be purchased or 3D printed out of resin.

7.3.3 Motor Selection

The motor selected must be a continuous turn motor given that the finalized design of the mechanism requires continuous rotation of a lead screw through several turns in order to reach full tab extension. Additionally, because of the limited time that the ACS is in its active configuration (the time between burnout and apogee), speed of response is critical to motor selection. As such, only continuous motion servos were selected for evaluation in the motor trade study. The criteria the motors were evaluated on were: weight, speed at 7.4 V, torque at 7.4 V, operating current draw, and cost. The primary design drivers for motor selection were speed and torque at 7.4 V, as these directly impact the response time of the tab actuation mechanism. The stall torque and stall speed weights are 35% and 25% respectively. The stall torque was weighted higher because the system has to be able to resist high drag forces without stall. Stall current was weighted at 20%, as a high value could negatively impact the performance of the ACS system or other subsystems within the launch vehicle. Finally, the cost and weight of the motor were both weighted at 10%. The trade study is shown in Table 60.

Table 60: Motor Trade Study

		SG12 Series		D840WP 32-Bit		HSR-M9382TH	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Stall Torque at 7.4V (oz in)	35%	700	0.15	419	0.09	472	0.1
No Load Speed at 7.4V (sec/60 deg)	25%	0.32	0.05	0.11	0.14	0.14	0.13
Stall Current (mA)	20%	3000	0.12	9000	0.04	2700	0.12
Weight (oz)	10%	6.9	0.04	8.0	0.05	2.4	0.01
Cost ($)	10%	93.49	0.05	99.99	0.05	209.90	0.02
Total WNV		**0.41**		**0.37**		**0.39**	

The SG12 Series Servo Gearbox with continuous motion was chosen for the system. This motor will be able to produce adequate force to the linkage arms to support the control surfaces against the induced drag force at a high stall torque and reasonable stall current and weight. The one drawback to this motor selection is the speed at which the motor responds, which is more than double the other options. However, this speed scales with the torque on the motor, and it is possible to keep both torque and no load speed within reasonable limits because this motor is relatively oversized for the application.

7.4 Mechanical Test Plan

The mechanical system will be tested both in isolation from and integrated with the electrical and software components of the system. The motor will be used to actuate the tabs through their full range of motion both in static air and in flight conditions in a wind tunnel once the mechanism has been constructed. The mechanical system will have passed this test if and when the mechanism can fully extend and retract through its full range of motion and if the limit switches prevent the mechanism from over-extension or over-retraction.

The mechanism will be integrated with the PID control algorithm with both simulated and heritage flight data after it passes this test. The purpose of this test from a mechanical standpoint will be to ensure that the mechanism is able to respond to the signals received by the micro controller and that the PID control software is not requiring over- or under-extension of the mechanism.

Finally, the mechanism will be integrated with the sensor subsystem and tested in flight conditions in the vehicle demonstration and payload demonstration flight. The mechanical system will have passed this test when it is demonstrated to be able to actuate according to the signal passed by the micro controller in flight conditions.

7.5 Electrical Design

The Apogee Control System relies heavily on its electrical subsystem to function. The ACS mechanism is driven by a servo motor, which is controlled by a microcontroller, which itself makes decisions based on input from sensors. The purpose of the electrical design is to integrate all of these components together to ensure that the system as a whole can function. The team must choose sensors which can provide an accurate estimate of the current state of the vehicle at a fast sampling rate. Additionally, a servo motor must be chosen which can provide the torque necessary to actuate the mechanism, while drawing a minimal amount of power. A microcontroller is used to interface with each of these components, and it must have the ability to communicate with the chosen sensors and servo motor and the computing power to run the required control algorithm. Finally, each of these components must be powered by a battery. The batteries for the system must have the required voltage, while also having a high enough capacity to power the system for the duration of the flight, as well as any time spent on the pad before launch.

The team is also considering the creation of a Printed Circuit Board (PCB). This would allow the team to integrate all of the electrical components more efficiently and securely. This could place constraints on the physical design of the system, but would be effective at creating a stable, high-performance system.

7.5.1 Microcontroller Selection

Sensor data processing and control algorithm calculations will be done using a Raspberry Pi 4b microcontroller. It is a fully functional computer which is fitted with General Purpose Input/Output Pins (GPIO) pins that will be used to interface the motors and sensors with the control code written to run the ACS subsystem. The Raspberry Pi version 4b has been chosen because it is a relatively powerful embedded computer. An image of the selected microcontroller is given in Figure 38.

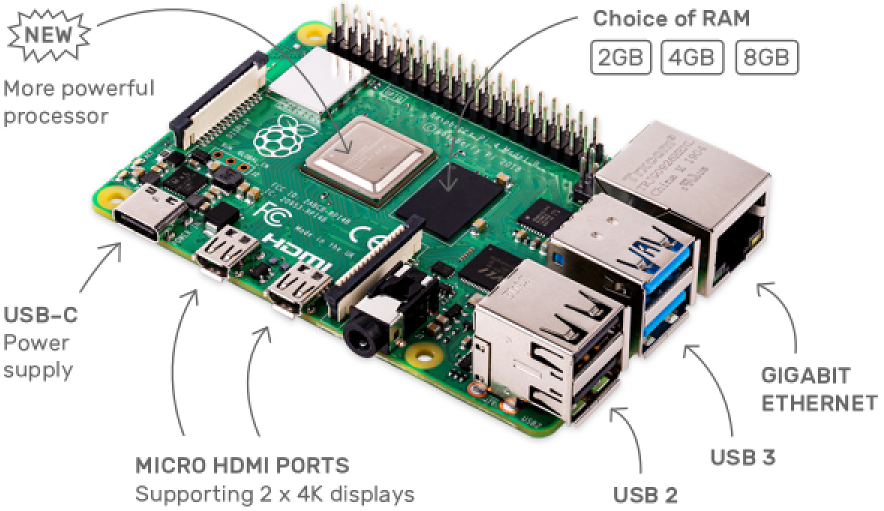


Figure 38: Selected microcontroller schematic with labeled input/output ports

The team can choose between 2 GB and 8 GB of RAM and it comes with 4 USB ports: two USB 2.0 and two USB 3.0 ports. These will enable high speed data transfer with low latency. It can also operate in a wide range of temperatures (0-50°C), making it suitable for the vehicle's ACS system. The Raspberry Pi 4b comes with a 1.5 GHz Quad-Core 64-bit system-on-chip (SoC) which will be able to manage the required data filtering and analysis tasks. It has a microSD card slot and 5 V USB-C connector which will make it easy to load programs onto the computer and store sensor data in an expandable microSD card. Its small form factor makes it very useful for this embedded application, and it is capable of running Python code. The Raspberry Pi 4b's compatibility with many different sensors combined with its speed, reliability, and ease of use make it the perfect choice for the brain of the ACS unit.

7.5.2 Altimeter Selection

The launch vehicle requires an altimeter to collect data on the altitude of the rocket, which is critical in determining whether the flaps need to be actuated. The four criteria used to evaluate the sensors were availability, sampling rate, accuracy, and cost. Only sensors which could be ordered and received in a reasonable amount of time were considered. Here, sampling rate is measured as the number of samples the sensor can provide per second (Hz). Accuracy is measured as the margin of error for sensor readings. For example, an accuracy of ±1m means that the measured altitude is highly likely to be within 1m of the true altitude. The team gave accuracy the highest weight of 50% followed by sampling rate with a weight of 40%, and finally cost with a weight of 10%. Accuracy and sampling rate were deemed to be the most important criteria because they are directly related to the data collection of the flight and provide critical information to the team. Cost was given a lower weight because this criteria is not directly related to the data collection process and is not critical to the functionality of the sensor. Compatibility was not used as one of the criteria because all of the sensors were compatible with Raspberry Pi and were deemed equally easy to set up and use. The sensors chosen for the trade study are shown in Table 61.

Table 61: Altimeter Trade Study

		BMP390		BMP388		BMP 280		MPL3115A2	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Accuracy (m)	50%	0.25	0.244	0.5	0.183	1.0	0.061	0.3	0.2317
Sampling Rate	40%	200	0.1127	200	0.1127	182	0.1025	128	0.0721
Cost ($)	10%	10.95	0.0299	9.95	0.0436	9.95	0.0121	12.70	0.0254
Total WNV		**0.3877**		**0.3415**		**0.1722**		**0.3303**	

The BMP 390 is the leading choice for an altimeter due to its high accuracy and sampling rate based on the results of the trade study.

7.5.3 IMU Selection

Inertial measurement units are made up of a collection of sensors which include at least an accelerometer and a gyroscope. These are called 6-axis IMUs because they have 6 degrees of freedom: 3 axes for the accelerometer and 3 axes for the gyroscope. Some IMUs (9-axis) also include a magnetometer (compass). Others have an embedded temperature sensor and even a barometric altimeter ('10-axis' IMUs). The main purpose of an IMU is to help determine the current orientation of the launch vehicle. This in turn allows the team to predict the launch vehicle's trajectory and apogee at any given moment with high accuracy. Moreover, the accelerometer and altimeter included in an IMU can serve as a redundancy to the standalone sensors.

The four IMUs researched were compared using five criteria in this trade study. The number of degrees of freedom was assigned the greatest weight because each additional degree of freedom significantly affects the accuracy of the IMU in terms of determining orientation. Adding more degrees of freedom will enable a more accurate computation of the overall state of the launch vehicle. Sampling rate was given 20% weight because a high sampling rate gives a larger sample size for data filtering, which makes the filtered orientation data more reliable. Measurement range is not as important since all of the sensors compared meet the requirements for measuring range. Power consumption is also given a low weight (10%) because all the sensors compared are energy efficient and have a low current draw. Their operating voltages also meet the requirements for interfacing with the microcontroller. All four sensors are relatively cheap so cost is given a low weight as well (10%). The team will be choosing two IMUs in order to obtain an independent estimate of the acceleration, altitude, and orientation of the system.

Table 62: IMU Trade Study

		BerryIMU v3		**ICM-20948**		**ICM-20649**		**LSM6DSO**	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Degrees of Freedom	45%	10	0.15	9	0.13	6	0.09	6	0.09
Sampling Rate (Hz)	20%	6700	0.0011	400000	0.07	400000	0.07	400000	0.07
Measurement Range	15%	16	0.03	16	0.03	30	0.06	16	0.03
Operating Voltage (V)	10%	1.4	0.03	3.29	0.01	3.29	0.01	3.29	0.01
Cost ($)	10%	3.95	0.035	16.95	0.012	16.95	0.012	19.95	0.007
Total WNV		**0.241**		**0.252**		**0.236**		**0.203**	

The trade study determined the best two IMUs for the system are the ICM-20948 and

BerryIMU v3. Both of these sensors have a high number of degrees of freedom, while also having decent sampling rates and measurement ranges.

7.5.4 Accelerometer Selection

This trade study is intended to find the most suitable accelerometer from a range of options. There are 3 base criteria in this study, which are scaling, sample rate, and cost. The first criterion, scaling, is a dynamic range of the accelerometer, typically measured in g's. It is the maximum amplitude that the accelerometer can measure before distorting the output signal. The second criterion is sampling rate, which is the rate at which samples are collected and stored. A higher sampling rate will allow the team to make more fine-grained adjustments to the extension of the mechanism, which will enable the mechanism to be controlled with more precision. Sampling rate and scaling are both rated at 40% since both directly impact the system performance. Cost is important due to its impact on the budget, but it is not as immediately relevant, so it is given a weight of 20%.

Table 63: Accelerometer Trade Study

		LIS3DH		ADXL377		ADXL345		BerryIMU-10DOF	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Sampling Rate (Hz)	40%	5000	0.13	500	0.01	3200	0.08	6700	0.17
Scaling (g)	40%	16	0.03	200	0.32	16	0.03	16	0.03
Cost ($)	20%	20.60	0.01	4.95	0.09	12.14	0.05	1.95	0.1
Total WNV		**0.17**		**0.42**		**0.30**		**0.16**	

The results of the trade study show that the ADXL377 is the best option. This is mainly due to the higher scaling, which is sufficient to handle any possible scenario during launch without hitting any kind of threshold. It is also reasonably cheap. The only downside of this sensor is a relatively low sampling rate, but this rate is still significantly higher than the predicted processing rate of the system.

7.5.5 Battery Selection

The team has chosen to use lithium polymer (LiPo) batteries for the power supply to the sensor system and motor, which have the advantage of being much more lightweight and higher capacity than comparable Nickel Metal Hydride batteries. Two batteries will be used because the motor requires a higher voltage than the sensor/microcontroller system. The first, which will be used to power the low voltage system, will have a voltage of 3.7 V, and the second, which will be used to power the motor, will have a voltage of 7.4 V.

Several criterion need to be considered when choosing a battery. The most important is the voltage of the battery. Another important consideration is the capacity of a battery, generally measured in milliAmp hours (mAh), which is a measure of how many mA of current a battery can supply for an hour. A larger capacity means that the system will be able to operate for a longer period of time. The final electrical property under consideration is the maximum current of the battery. This is another threshold category, as any battery which supplies a maximum current lower than the operating current of the system will be unable to adequately power the system. The mass, volume, and cost of each battery are also considered to ensure that the chosen battery is not too heavy, does not take up too much space, and is relatively cheap.

The logic circuit consists of the Raspberry Pi and all sensors. It will integrate with the Raspberry Pi through the Adafruit PowerBoost 500, which boosts a 3.7 V signal to a 5.2 V signal and provides a consistent power supply to the circuit. The chosen battery must supply power at 3.7 V and be capable of providing current for the Pi and all chosen sensors. The current draw of the major components in the logic system is summarized in Table 64.

Table 64: Logic Circuit Current Draw

Component	Current Draw (mA)
Raspberry Pi 4b	600
BMP390	0.1
MPL3115A2	2.0
ICM-20948	3.1
BerryIMU v3	2.0
ADXL377	0.3
Total	**605.5**

The vast majority of the current drawn by the system is done so by the Raspberry Pi, as shown in Table 64. The team will design around this current draw, but if it leads to a reduced system performance, the team will switch the Raspberry Pi 4b for a Raspberry Pi Zero, which draws an average of 100 mA during operation. The team considered several batteries to power this system of varying capacities and sizes. This includes a 2500 mA battery from Adafruit, a 2800 mA battery from Liter, and a 2000 mAh battery from Turnigy. All batteries chosen have a maximum current greater than the 605.5 mA required for the system. The other factors under consideration are the capacity, cost, volume, and mass. Capacity is the most important factor since it has the most direct impact on system performance. Size and mass are important due to their impact on mechanical design. Finally, cost is important due to budget constraints, but is the least important factor otherwise. Table 65 shows the results of the team's analysis of these factors.

Table 65: Logic Battery Trade Study

		Adafruit		Liter		Turnigy	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Capacity (mAh)	65%	2500	0.22	2800	0.25	2000	0.18
Mass (g)	15%	43	0.37	60	0.04	33	0.07
Volume (mm^3)	15%	19208	0.06	26112	0.04	16600	0.6
Cost ($)	5%	14.95	0.01	12.99	0.01	4.53	0.02
Total WNV		**0.342**		**0.336**		**0.331**	

All of the batteries had fairly similar results on the trade study. The Adafruit battery turned out to be the best mix of capacity and small size. It also provides enough capacity to power the system for four hours, which is well beyond the amount of time the system is expected to be on the launch pad.

The motor circuit consists solely of the servo motor powered by a 7.4 V battery. The SG12 Series motor has a stall current of 3000 mA, so all motors considered will need to provide at least that much current. Otherwise, all criteria in this trade study are the same as the criteria for the logic circuit. The team again considered three batteries for this circuit from different manufacturers and with different capacities. This includes a 2200 mAh battery from Ovonic, a 1000 mAh Sypom battery, and a 1300 mAh Admiral battery. Table 66 shows the results of this trade study.

Table 66: Motor Battery Trade Study

		Ovonic		Sypom		Admiral	
Criteria	**Weight**	**Value**	**WNV**	**Value**	**WNV**	**Value**	**WNV**
Capacity (mAh)	65%	2200	0.32	1000	0.14	1300	0.19
Mass (g)	15%	130	0.03	58	0.07	84	0.06
Volume (mm^3)	15%	55176	0.04	30600	0.07	40320	0.05
Cost ($)	5%	16.90	0.01	13.99	0.02	10.59	0.02
Total WNV		**0.399**		**0.298**		**0.320**	

The Ovonic battery was the best overall based on the data in Table 66. It had the highest capacity by far, while not being significantly heavier or larger than the other options. This battery has the capacity to operate the servo at stall current for roughly 45 minutes, which is more than enough time for the system to operate.

7.5.6 Battery Sensor Selection

This year the team added two additional components: a battery power sensor and a power relay. The power sensor determines whether the battery powering the ACS system has sufficient power to complete its task when the launch vehicle is waiting to begin the launch sequence. No trade study was completed for this sensor because there were only two applicable sensors and the options were nearly identical. The selected power sensor is the Adafruit INA260 High or Low Side Voltage, Current, Power Sensor. The other power sensor the team looked at was the NA219 High Side DC Current Sensor Breakout. The only difference between the two sensors was that the sensor selected has a higher maximum voltage of 36 V.

The purpose of the power relay is to turn different components of the design on or off so that the ACS system can conserve power. There is little variation in power relay properties between brands. Simply, power relays either work with the Raspberry Pi or they do not, so comparing the precision of models is irrelevant. The team found two potential power relays: the Adafruit Power Relay FeatherWing and the SunFounder 2 Channel DC 5 V Relay Module. The only major difference between the two models was that the SunFounder 2 Channel DC 5 V Relay Module was less expensive and was therefore selected.

7.5.7 Integration

The electrical system of the ACS forms a closed-loop control system. It consists of sensors to determine the state of the launch vehicle, a servo motor to exert control over the mechanism, and a microcontroller to tie the two together. The chosen sensors and microcontroller operate at a voltage of 5 V, while the motor requires a higher voltage of 7.4 V to operate. As a result, the electrical system will be divided into two main circuits.

The first circuit will consist of the Raspberry Pi and the sensors. Each item will receive power from the 3.7 V battery, with the voltage stepped up to 5 V using the Adafruit Powerboost. Connections between each sensor and the Raspberry Pi being established through the I2C protocol. The team will establish these connections by designing a Printed Circuit Board (PCB). The team has had success using a similar approach in the past. The PCB ensures that all electrical connections are firm and will not become disconnected during flight. Since connections will be made using copper traces instead of wires, there is no chance of a wire coming disconnected during flight. Additionally, this approach makes the system easier to repair if any components become damaged during flight.

The second circuit will consist of the servo motor and a 7.4 V battery. Additionally, a control wire will be fed from the Raspberry Pi to the motor to enable control of the motor through a Pulse-Width Modulation (PWM) signal. The two circuits will share a common ground to to ensure that this signal is incorporated correctly. Isolating the two circuits will help to ensure that the larger current draw from the motor will be isolated from the sensors and microcontroller, which will lead to more consistent performance overall.

7.5.8 Test Plan

The team plans to rigorously test each component of the hardware to ensure that the system is working as anticipated. These tests will include both component and system-level testing. Each electrical component will be tested to ensure proper functionality at the component level. The Raspberry Pi will be integral in the testing of the other components, since it is the main mechanism by which sensor data will be read and the servo motor will be controlled.

Each of the sensors will be tested by physically interacting with the sensor, measuring the activity, and comparing the actual and expected readings. The altimeter will be tested by placing it in a vacuum, since higher altitudes will correspond with lower atmospheric pressure. The accelerometer and IMU will be tested by physically perturbing the system to induce acceleration. For example, by quickly shaking the sensor along one axis of its measurement, a spike in acceleration will be detected in one direction, while the other readings remain relatively stable. Additionally, the capability of the IMU to detect orientation will be tested by placing the system in various orientations and measuring the sensor readings.

The servo motor will be tested both inside and outside of the assembly. The Raspberry Pi outside of the assembly will command the servo to move to a variety of positions and to rotate at a variety of rates, and the team will observe to ensure that these programmed behaviors match the reality. The team will program the servo inside of the system to move the mechanism through its full range of motion several times to ensure that the motion is consistent.

Batteries will be tested to ensure that their lifetimes and capacities are within an acceptable range. The team will start by simply measuring the voltage across the battery after charging. Next, the team will leave the system in a powered state for a long period of time, with the servo motor firing at safe intervals. This will allow the team to ensure that the batteries can fulfil the power needs of the system.

The 3.7 V portion of the electrical system will be tested during the subscale launch. The team will integrate each of the sensors with the Pi and record data during launch. This will ensure that all of the sensors are able to effectively integrate with the Pi and send reasonable data. Portions of the full system will be tested through simulation of launch conditions, and the full system will be tested during the vehicle demonstration flight before FRR.

7.6 Control Structure

The team will utilize a Raspberry Pi 4b to control the system, reading in sensor data and actuating the drag flaps. The sensors will provide data on the current altitude, acceleration, and orientation of the launch vehicle. This data and a physical model will be used in a filtering algorithm to minimize noise and determine the current state of the launch vehicle. The control algorithm will then use this data to predict the launch vehicle's apogee, and from this determine the required rotation of the motor to actuate the screw and the drag flaps. Figure 39 outlines the controls process. Data is read until burnout has been reached after initializing the sensors. The data and actuation will then proceed in a closed loop until apogee or overshoot have been detected, at which point the flaps will be fully retracted.

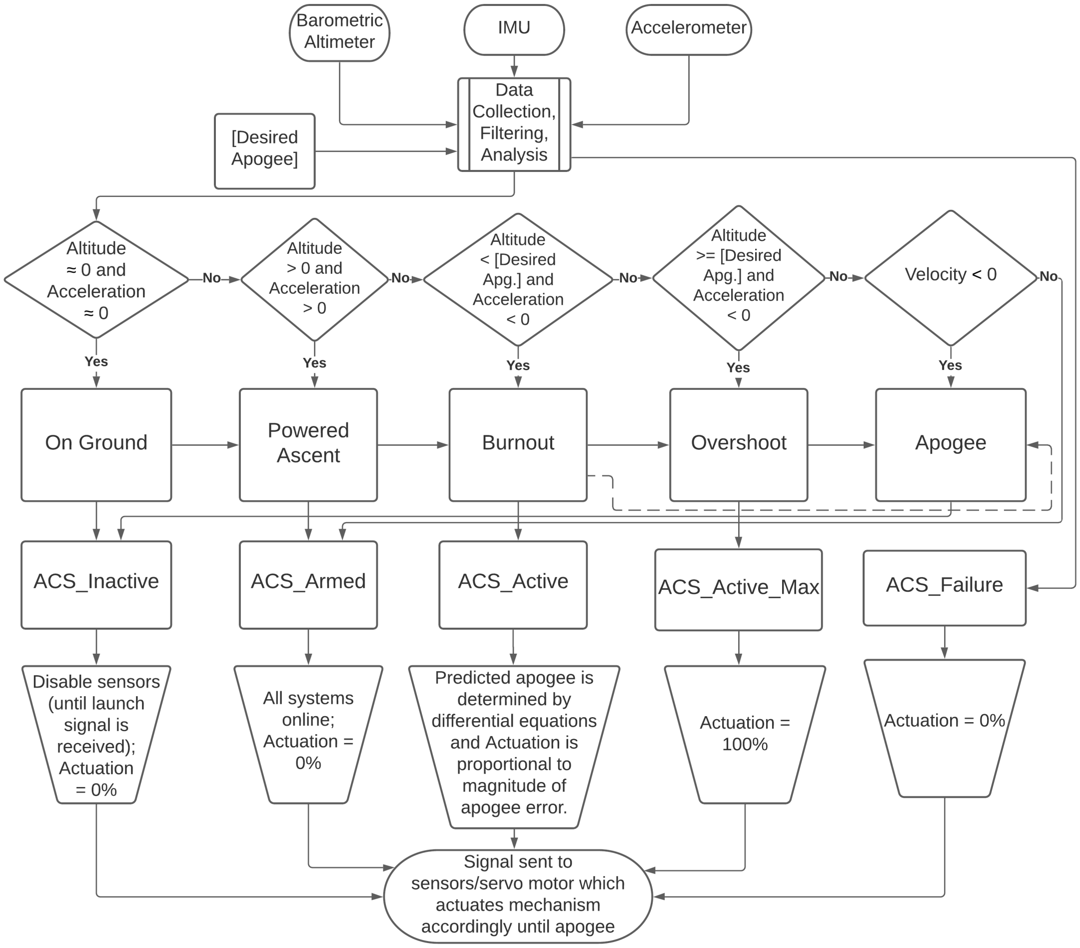


Figure 39: ACS Control Code Flow Chart

7.6.1 Data Filtering

Data filtering is the process of reducing noise in some signal. This involves processing noisy sensor data into an estimate of the current state of the launch vehicle for the ACS. The main purpose of data filters is to clean the data and suppress noise. Sensors, especially those with high sample rates, tend to give out data that can randomly fluctuate, so data filters are necessary to smooth the data, allowing the system to make more accurate predictions about the current state of the vehicle and its trajectory at any given time. A good data filter should smooth out erratic sensor data with as little time lag ('error lag') as possible. There are various ways of doing this. Two of the most common approaches are single-stream filters like the median filter, as well as more complicated fusion algorithms like the Kalman filter.

Single-stream filters are designed to improve the quality of a single stream of data. For example, this could be the output from the altimeter at any given time. Single-stream filters apply some mathematical operations to the input signal to transform it in a desired way. An example transformation would be one which aims to reduce noise from a source of data. Some common single-stream data filters include the averaging filter, low-pass filter, and median filter. The main idea of the median filter is to process the signal at each time step and replace each element in the input signal with the median of the previous n points, where n, which is referred to as the 'window', is an integer which can be tuned as necessary. For an input signal x_t and an output signal y_t, this filter is defined as follows:

$$y_{t+1} = \text{median}(x_{(t-n+1)}, x_{(t-n+2)}, ..., x_t) \tag{18}$$

The window moves one data point at a time and replaces each value in the output with the median of all the values in the window. A certain amount of lag is introduced during the filtering process depending on the size of the moving window. The smaller the window, the less the lag when applying the median filter. However, a window that is too small is more likely to be influenced by outliers (due to a smaller sample size). Figure 40 shows an example of the application of the median filter to accelerometer data from one of last year's flights. It shows how the median filter could be applied to altimeter and accelerometer data to produce a smooth output signal that can be analyzed by the control algorithm. Additionally, note that the amount of noise decreases as n increases. Realistically, a value of n would need to be less than 10 to avoid significant delays in information propagation.

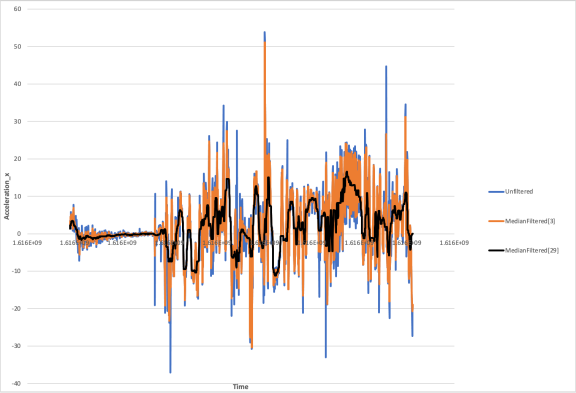


Figure 40: Median Filter of Accelerometer Data

Several algorithms exist which share the same intuition of sliding a window across the input signal and applying some transformation to the values in that window. An averaging filter works by taking the mean of the previous n data points instead of taking the median. This approach is more sensitive to outliers, but is also quicker to respond to change. A low-pass filter, by contrast, considers the signal in the frequency domain instead of the time domain. The filter can be designed in the frequency domain and then translated back into the time domain through the creation of a finite impulse response (FIR) filter. This works similarly to an averaging filter. An averaging filter can be thought of a weighted sum of previous inputs, where each input x_i gets a weight of $\frac{1}{n}$. Finite impulse response filters operate on the same sliding window approach, except the weight of each previous term may be different. A low-pass filter can eliminate the source of the noise without impacting the actual signal if the signal is impacted by some higher frequency noise. An averaging filter may unfortunately fail to effectively eliminate the noise if the distribution of the noise is not well-known.

Fusion algorithms take data from different sources in order to produce a more accurate estimate of the overall state of the system, in contrast with single-stream data filters. The Kalman filter is one of the most popular data filtering algorithms, and has seen applications in a wide variety of fields. The Kalman filter combines data obtained from sensors with a mathematical model of how the system will evolve over time. The errors between the sensors and the mathematical models are determined at each time step, and the Kalman filter accounts for both of the errors to determine the position of the system while minimizing the error. The greatest benefit of using the Kalman filter is the ability to take information from more than one source and arrive at a lower error than if the information was taken independently from each source. One major limitation of the Kalman filter is that it requires a linear model of how the system will evolve over time, which limits its ability to handle nonlinear phenomena like drag. Additionally, its increased complexity when compared with single-stream filtering algorithms means that it operates at a slower processing speed. The Kalman Filter overall remains a strong candidate as a possible choice for the ACS’ data filter because of its ability to minimize error and utilize both physical sensor and mathematical model information. The team will consider other data fusion algorithms in addition to the Kalman filter, but the Kalman filter acts as a sane default due to its relatively low complexity and memory footprint.

7.6.2 Actuation Control Algorithm

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

$$F_r = F_g + F_d \tag{19}$$

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. The drag force F_d is then split into two components: F_{dr}, the drag force acting on the launch vehicle, and F_{dt}, the drag force acting on the ACS mechanism. A new equation can be written for F_d using Eq. 20 and assuming that drag acts in the negative y direction:

$$F_d = F_{dr} + F_{dt} = -\frac{1}{2}\rho C_{dr} A_r \dot{y}^2 - \frac{1}{2}\rho C_{dt} A_t \dot{y}^2 \tag{20}$$

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:

$$m_r \ddot{y} = -mg - \frac{1}{2}\rho C_{dr} A_r \dot{y}^2 - \frac{1}{2}\rho C_{dt} A_t \dot{y}^2 \tag{21}$$

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. The drag profile may not be entirely linear with the opening angle because of the length of the drag flaps, as drag should increase sharply once they extend beyond the boundary layer. CFD and physical modeling will be done to obtain a relationship between the servo angle and the amount of drag induced. The motor rotation will be calculated proportional to this error with the apogee error and this relationship. This should be sufficient, along with the model predictive aspect to drive down the error in the allotted window.

7.6.3 Software Test Plan

Each component of the software will need to be rigorously tested to ensure proper system functionality during flight. This will ensure that the system is as accurate, reliable, and fault-tolerant as possible. Unit tests will form the basis of the test plan. A combination of simulation, ground testing, and test flights will be used to ensure system accuracy when it is not possible to unit test a given module.

The most basic form of testing for the system is the unit test. Unit tests are most useful for modules which have an expected, deterministic behavior. For example, the data filter should filter data in a consistent way, and the team will be able to provide expected output for a known input signal. Ensuring that the module behaves as expected for a suite of test cases will help to ensure the accuracy of the system during flight. Unit tests will be most useful for the data filter, forward projection, and control algorithm individually. These components are each based on mathematical formulas, which allows for predictable test cases to be generated.

One important method of testing the system as a whole will be the use of simulations. Here, the team will feed the system data from either previous flights or flight simulators and observe how the different components of the software pipeline respond. The output from the data filters and control algorithm will be captured and compared to the expected behavior. This type of test is critical for catching a wide array of failure modes before the system is used in a full-scale launch. It is also important for tweaking some parameters in the model, such as the gains of the data filter.

The sensors will be tested through a form of ground testing as specified in Section 7.5.8. This will involve reading input from individual sensors, physically perturbing the sensors, and observing the corresponding change in sensor readings. Additionally, the servo motor can be tested by having the Raspberry Pi send the servo through a series of positions at varying speeds. The servo can additionally be tested in conjunction with the rest of the control code through the use of simulations. The system will again be fed fake sensor data, filter the data, and produce a signal for how the servo should move. The servo will then actually perform the requisite motions. This ensures that the mechanism and the servo are properly calibrated with the software and that the model of the mechanism used in the software lines up with the physical mechanism.

The various launches throughout the year will provide the final test of how well the system performs in addition to these other methods. The subscale launch will give the team the ability to test the data collection code, and the collected data will help later in the year when developing algorithms for data filtering and controls. The full-scale launches will be even more important, providing the opportunity to fully demonstrate that the software is capable of reading in data from sensors, transforming it, computing a desired output, and controlling the servo as required.

7.7 Integration of System Components

Accessibility of various system components will be prioritized in integrating the mechanical and electrical subsystems of the Apogee Control System. The electronic components will be placed perpendicular to the motor bulkhead at the top of the mechanical system, and will be permanently affixed to the top bulkhead, and held in place to the motor bulkhead by a 3D printed standoff. When the fore bulkhead, which will be positioned close to the opening of the airframe, is removed, the electronic components will come with it. The electronic system thus can be isolated from the mechanical system and each can be tested separately. The micro controller and servo battery will be attached to the servo motor using an XT60 snap connector attached to a long wire, again to allow for easy removal of the electrical subsystem. The mechanical subsystem will be semi-permanently installed due to the nature of the flaps sitting flush with the airframe. Finally, the foremost aluminum bulkhead will serve as the attachment point for the recovery parachute.

7.8 ACS Preliminary Testing Plan

NDRT has developed a preliminary testing plan to properly verify the design, fabrication, and integration of the Apogee Control System. The systems team will continue developing each of the tests described in Figure 67 and provide full detailed test plans for CDR.

Table 67: Apogee Control System Preliminary Testing Plan

Test Name	Description	Success Criteria
Electronics Unit Tests	Connect each sensor to a computer to print real time data from the sensor and ensure each sensor can accurately read physical input data	Each sensor accurately records physical input data within sensor specifications
Full System Integration Test	Test performance of ACS system through full course of flight by providing ACS sample flight data from computer and ensure ACS data filter, control algorithm, and servo motor accurately respond to simulated flight data	The data filter and control algorithm produce the expected tab extensions
Battery Duration Test	Activate system with fully charged battery and leave in cold environment to simulate launch delay in extreme limit of launch temperature window.	System remains active for 3 hours, fulfilling battery duration requirement
Flap Mechanism Actuation Test	Activate system with commands to actuate drag flaps through full range of motion	Mechanical system operates through full expected range of motion

Table 67: Apogee Control System Preliminary Testing Plan (continued)

Test Name	Description	Success Criteria
Limit Switch Detection Test	Activate system with commands for constant actuation of drag flap mechanism to test system response to limit switches	System stops flap actuation upon contact with limit switches at extreme limits of travel
Flap Mechanism Torque Test	Test for sufficient motor torque by mounting weights corresponding to the maximum expected load on the ACS flaps, and attempting full flap actuation	The ACS fully deploys its flaps and incurs no damage to the mechanism
Subscale Flight Test	Integrate data collection module into vehicle to record all flight data necessary to perform the Full System Integration Test using real flight data	Necessary data is successfully collected during flight
Launch Vehicle Demonstration Flight Test	Integrate full mechanical system into full-scale vehicle for flight with pre-programmed drag surface movements to measure sensor perturbations due to actuation	Drag surfaces actuate after burnout and sensor suite records flight data
Payload Demonstration Flight Test	Integrate full system into launch vehicle with full control flow to test integrated mechanical and software systems	System records data, predicts apogee, and actuates control surfaces appropriately to bring predicted apogee to target apogee

8 Safety

8.1 Safety Officer Role

The Safety Officer for the Notre Dame Rocketry Team for this year's competition is Michael Bonaminio. The role of Safety Officer includes, but is not limited to, the following responsibilities:

- Ensure the team is actively updating safety procedures throughout the design, construction and test process.
- Enforce the use of appropriate PPE at all stages of design, construction, test, and launch.
- Require that active team members are properly certified on the necessary equipment and inform them of safety hazards and procedures.
- Maintain and distribute a safety handbook to all members of the team.
- Compile and update all necessary SDS sheets into one readily available document which is easily accessible in the workshop.
- Provide standard operating procedures for all tools, machines, and procedures.
- Apply a risk assessment matrix to classify risks based on severity and probability of occurrence to appropriately mitigate hazards.
- Restrict launch personnel to only members that have passed a launch test and have attended the pre-launch briefing.
- Compile and distribute launch checklists and procedures to all team members before launch.
- Create and follow a plan for the obtaining, using, and disposing of all hazardous materials.
- Create a repair action summary to establish protocols for repairing components that are damaged or destroyed.
- Ensure team compliance with all local, state, and federal laws and regulations.
- Ensure team compliance with all NAR/TRA rules and regulations.
- Ensure team compliance with all NASA Student Launch rules and regulations.

- Ensure team compliance with all University of Notre Dame rules and regulations.

These responsibilities result from the team's paramount goal of ensuring the safety of all individuals, both public and team members, at every stage of the project. The Safety Officer is assisted by a Safety Team who aid in the execution of the responsibilities and increase safety involvement in each squad. Safety Team members are either primary Safety Team members or Safety Team liaisons and are also a member of a design squad. This distinction allows for Safety Team members to focus on their strong suits; primary Safety Team members can work on general team safety, while Safety Team liaisons can analyze the risks and mitigations of specific components of the launch vehicle's airframe, recovery system, payload, and apogee control system.

8.2 Risk Assessment Method

All hazards are categorized by their level of risk based on the same numerical analysis of both their severity and probability of occurrence. This method is applied to personnel hazards, Failure Modes and Effects Analysis (FMEA) hazards, environmental hazards, and project risks hazards. The Safety Team thoroughly identifies, evaluates, and compiles all hazards in a document for the rest of the team to utilize in their efforts to improve their design.

The probability of occurrence of the hazard are scored on a scale of 1 to 5, with 5 being an extreme likelihood of the hazard to occur under present condition and 1 signifying the hazard is improbable to occur under present conditions. The full probability occurrence value criteria is in Table 68.

Table 68: Probability of Occurrence Value Criteria

Description	Value	Criteria
Improbability	1	Less than a 1% chance the event will occur
Rare	2	Between a 1 - 10% chance the event will occur
Sporadic	3	Between a 10 - 20% chance the event will occur
Likely	4	Between a 20 - 40% chance the event will occur
Frequent	5	Greater than a 40% chance the event will occur

The hazards' severity are scored on a 1 to 4 scale, with 4 being catastrophic to the mission or the personnel involved, and 1 having a negligible impact on the mission or the personnel involved. The full severity value criteria is in Table 69.

Table 69: Severity Value Criteria

Description	Value	Personnel	Vehicle Damage	Environmental Impact	Mission Success
Negligible	1	Minor Injury	Insignificant	Insignificant	Complete Mission Success
Minimal	2	Slight Injury	Slight	Reversible	Slight Mission Failure
Dangerous	3	Severe Injury	Severe	Somewhat Reversible	Major Mission Failure
Catastrophic	4	Critical Injury	Loss of Vehicle	Irreversible	Complete Mission Failure

A total risk score can be assigned to the hazard by multiplying the probability of occurrence and severity values together. The risk score falls within a range of 1 to 20, and an increased score indicates an increased risk. The complete breakdown of the risk levels can be found in Tables 70 and 71. The risk levels are then ordered in a manner that places the highest risks at the top and the lowest at the bottom once all of them are calculated. This is done in order to show the order the hazards should be prioritized in for the given category, however all risks are eventually addressed.

Table 70: Risk Assessment Table

Probability	**Severity**			
	Negligible (1)	Marginal (2)	Critical (3)	Catastrophic (4)
Improbable (1)	1	2	3	4
Unlikely (2)	2	4	6	8
Moderate (3)	3	6	9	12
Likely (4)	4	8	12	16
Unavoidable (5)	5	10	12	20

Table 71: Risk Levels

Level	Color	Range
Desired	Green	Less than 5
Acceptable	Yellow	Between 5 and 9
Unacceptable	Red	Greater than 10

A total of 12 divisions of hazards have been identified for the 2021-2022 year. The complete list of hazard sections and their abbreviated naming convention can be found in Table 72. Labels are used to help facilitate to discussion and finding of safety information. The structure of the label goes AAA.N, where "A" is any letter up to three, as seen in Table 72 and "N" is the row number in the table in each respective table. For example, the fourth recovery hazard would have the label "R.4".

Table 72: Hazard Table Nomenclature

Safety Table	Value
Construction Personnel Hazards	C
Launch Operation Personnel Hazards	L
Vehicle Flight Mechanics FMEA	VFM
Vehicle Structures FMEA	VS
Apogee Control System FMEA	ACS
Recovery FMEA	R
Launch Vehicle Identification System FMEA	LVIS
Launch Vehicle Identification System Integration FMEA	LI
Launch Equipment FMEA	LE
Environmental Hazards to Vehicle	EV
Vehicle Hazard to Environmen	VE
Project Risks	PR

8.3 Overall Risk Reduction

The Safety Team then works to identify ways to mitigate the risks once the risk levels are identified, which will lower the total risk score through lowering the probability, severity, or both. Mitigation implementation will be prioritized from the highest risk scores to the lowest risk scores until all foreseeable hazards have been reduced to the best of the team's ability. This hierarchy of mitigation implementation helps the Safety Officer better allocate the team's time and resources to the hazards that require the greatest attention. Mitigations can take multiple forms, such as design adjustments to reduce the probability and severity of failure, newly designed physical systems to ensure proper operating conditions, and rewrites on procedures. Every mitigation will be subject to verifications in order to ensure that the necessary actions will occur to foster a consistent, safer working environment in a timely manner. There are a variety of verification methods, such as approval from team members or leaders, limiting actions to certain team members, or requiring written documentation before further action.

The Notre Dame Rocketry Team will be able to reduce the probability and or severity of each potential hazard upon implementation of the mitigations and verifications. Tables 73 and 74 and outline the risk levels among all 117 identified potential hazards before mitigations and verifications go into effect.

Table 73: Pre-Mitigation Risk Assessment Distribution

Probability	**Severity**			
	Negligible (1)	Marginal (2)	Critical (3)	Catastrophic (4)
Improbable (1)	0.00%	0.00%	0.85%	1.71%
Unlikely (2)	0.00%	2.56%	8.55%	17.95%
Moderate (3)	0.00%	8.55%	26.50%	22.22%
Likely (4)	0.00%	2.56%	2.56%	3.42%
Unavoidable (5)	0.00%	1.71%	0.00%	0.85%

Table 74: Pre-Mitigation Risk Levels

Level	**Quantity**	**Percentage**
Desired	6	5.13%
Acceptable	75	64.10%
Unacceptable	36	30.77%

The safety team predicts that the potential hazards will drop dramatically in their risk level once mitigations and verifications go into effect. Tables 75 and 76 outline the risk levels among all 117 identified potential hazards after mitigations and verifications go into effect. The risks levels for all 117 potential hazards are in a very acceptable range with the inclusion of mitigations. The dramatic shift in risks levels demonstrates the effectiveness and realism of mitigation and verification implementation.

Table 75: Post-Mitigation Risk Assessment Distribution

Probability	**Severity**			
	Negligible (1)	Marginal (2)	Critical (3)	Catastrophic (4)
Improbable (1)	4.27%	16.24%	18.80%	31.62%
Unlikely (2)	2.56%	16.24%	5.98%	1.71%
Moderate (3)	0.85%	0.00%	0.00%	0.00%
Likely (4)	0.00%	0.00%	0.00%	0.00%
Unavoidable (5)	1.71%	0.00%	0.00%	0.00%

Table 76: Post-Mitigation Risk Levels

Level	**Quantity**	**Percentage**
Desired	106	90.60%
Acceptable	11	9.40%
Unacceptable	0	0.00%

8.4 Personnel Hazard Analysis

Table 77: Construction Personnel Hazards

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
C.1	Inhalation of airborne particulates, such as carbon fiber, fiberglass, and wood dust	Performing work that creates harmful airborne particles, such as sanding or cutting	Short and/or long term respiratory health issues	4	4	8	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear respirators when working with airborne particles. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn. 4. The NDRT Safety Data Sheet will be updated and made available to all team members, and it will outline all material properties.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. The updated NDRT Safety Data Sheet Document is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 6. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	4	4

C.2	Inhalation of toxic fumes	Performing work that creates harmful toxic fumes, such as sanding, heating, gluing, or spray painting	Short and/or long term respiratory health issues	4	4	16	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear respirators when working with toxic fumes. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn. 4. The NDRT Safety Data Sheet will be updated and made available to all team members, and it will outline all material properties.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. The updated NDRT Safety Data Sheet Document is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 6. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	4	4

C.3	Contact with the rotating component or cutting blade of a tool or machine	1. Improper use of any rotary tool, such as a portable drill, drill press, or a dremel 2. Improper use of any type of cutting tool, such as a band saw, scroll saw, hand saw, exacto knife, or wire cutter and strippers	1. Severe injury to, or loss of, extremities 2. Severe skin abrasions or cuts to the contact region	3	4	12	1. All team members must complete the necessary safety training prior to construction eligibility 2. Standard Operating Procedures will be written, and they will outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures for the dremel, portable drill, drill press, lathe, techno router, and other rotating component or cutting blade machinery will be completed prior to construction 4. The NDRT Safety Handbook has been updated is readily available to all members as a physical version in the workshop, as well as a digital version shared with all members 5. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	4	4

C.4	Entanglement of baggy clothes or long hair in machinery	Performing work on rotating or fast-moving machinery	1. Severe injury to, or loss of, extremities 2. Severe skin abrasions or cuts to the contact region 3. Potential death	3	4	12	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear long pants, short sleeves, and tie long hair back when operating on rotating or fast-moving machinery. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The NDRT Safety Handbook has been updated is readily available to all members as a physical version in the workshop, as well as a digital version shared with all members 5. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	4	4

C.5	Contact with the abrasive surface of any type of tool or machine	Improper use of tools or machines that include abrasive surfaces, such as a belt sander, circular sander, portable sander, or sandpaper	1. Severe cuts or abrasions to the bodily contact region 2. Burns on the skin, leading to short term health issues and/or long term scarring	3	4	12	1. All team members must complete the necessary safety training prior to construction eligibility. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures for the belt sander, disc sander, sandpaper, and other abrasive-surfaced machinery will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	4	4

C.6	Electric shock	1. Improper operation on exposed wiring 2. Buildup of static electricity	Electrocution, leading to short term burns or potentially long term injuries or death	3	4	🟥 12	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all tools must be disconnected to a power source when not in use. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	4	🟩 4

C.7	Skin contact with strong adhesive materials	Improper application of adhesive materials, such as epoxy	1. Potentially severe allergic reaction 2. Severe skin irritation and/or permanent skin damage to the contact region	3	3	9	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear chemical-resistant gloves when operating on strong adhesive materials. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn. 4. The NDRT Safety Data Sheet will be updated and made available to all team members, and it will outline all material properties.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures for epoxying will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. The updated NDRT Safety Data Sheet Document is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 6. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	2	3	6

C.8	Materials become unsecured during construction	1. Improper utilization of motion-restriction tools 2. Excessive force is applied to materials	1. Potential cuts, abrasions, or blunt bodily damage to nearby personnel 2. Damage to vehicle materials results in project delays	3	3	9	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all tools must be disconnected to a power source when not in use. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedure for clamps will be completed prior to construction 4. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	3	3

C.9	Prolonged exposure to loud machinery or construction tools	Operating on or in the presence of power tools or heavy machinery which generate unsafe levels of sound	Temporary or long-term health issues, especially hearing loss	3	3	9	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all members use wear hearing protection when in the presence of loud machinery. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	3	3

C.10	Fire	1. Sparks from metal cutting 2. Overheating parts 3. Electronics short-circuit 4. Lithium-Polymer battery explosion 5. Leaving heat-inducing equipment, such as a soldering iron, in inappropriate locations 6. Leaving vulnerable fire-hazard materials and tools unattended	1. Burns, resulting in short term health issues or death, or long term scarring on skin and extremities 2. Smoke inhalation, resulting in short and long term health issues or death due to smoke suffocation	2	4	8	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must not wear loose clothing when operating near flammable materials and all team members must clean up their workspace after operating with flammable materials. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE and clean-up steps required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE and fire-prevention materials available, their locations in the workshop, and how they should be worn or used. 4. The NDRT Safety Data Sheet will be updated and made available to all team members, and it will outline all material properties. All team members must consult the SDS before operating with any flammable materials.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. The NDRT Safety Handbook includes the location and operation of the workshop's up to code fire extinguisher and fire blanket in the event of a fire 6. The updated NDRT Safety Data Sheet Document is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 7. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	3	3

C.11	Blunt damage	Improper handling of heavy tools or project materials	1. Potential bodily damage, especially to extremities 2. Potential damage to tools or stock materials	4	2	8	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, all team members must wear closed-toed shoes and perform construction with at least one other member in the event they need help handling heavy machinery and/or project materials 2. Standard Operating Procedures will be written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	2	2	4

C.12	Tripping or falling	1. Trip hazards exist on the floor, such as loose cords, backpacks, liquid spills, or project materials 2. Carrying large equipment or materials hinders one's ability to observe potential obstacles	1. Potential injury 2. Tripping or falling into nearby work, resulting in further injuries 3. Potential damage to nearby materials and/or vehicle	4	2	8	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, all team members must clean up the entire workspace completing the task. 2. NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 4. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	2	2

C.13	Contact with a hot surface	Performing work on any tool or machine that expels heat during use, such as soldering irons	Burns on skin and extremities, leading to short term health issues and/or long term scarring	2	3	6	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear heat-resistant gloves when operating near hot surfaces. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE and operation required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn. 4. The NDRT Safety Data Sheet will be updated and made available to all team members, and it will outline all material properties.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The NDRT Safety Handbook has been updated is readily available to all members as a physical version in the workshop, as well as a digital version shared with all members 5. The NDRT Safety Data Sheet Document has been updated is readily available to all members as a physical version in the workshop, as well as a digital version shared with all members 6. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	3	3

C.14	Pinch-points	1. Electronics clamp down at unintended times 2. Improper handling of heavy machinery or tools 3. Improper handling of heavy equipment 4. Operation on components with small clearance for extremities	Severe injury to or loss of extremities	2	3	6	1. All team members must complete the necessary safety training prior to construction eligibility. In particular, all team members must wear cut-resistant gloves when operating in pinch points. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	2	2

Table 78: Launch Operation Personnel Hazards

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
L.1	Motor explosion near launch area	1. Motor imperfections 2. Improper installation of motor into vehicle body	Severe injury to personnel or death	3	4	12	1. The motor will be carefully transported to the launch site and inspected prior to installation. 2. The motor will be purchased from a reputable vendor and installed using proper techniques.	1. Launch procedures will be written, and they will outline the necessary steps for all launch vehicle component integration. 2. Multiple Recovery system tests will be performed in order to ensure the systems act accurately, reliably, and in accordance to all NASA Requirements. 3. Vehicle drift will be restricted to less than 2,500 ft (NASA Recovery Requirement 3.10). 4. The maximum allowable kinetic energy of the vehicle is understood to be 75 ft-lbf at landing (NASA Recovery Requirement 3.3). 5. All team members will stand at a safe distance away from the launch vehicle. The Range Safety Officer has the final say of the safe distance, albeit it's at least 300 ft away, as required by NAR.	1	4	4

L.2	Uncontrollable launch direction	1. Launch rail leans over during launch sequence 2. Actual vehicle stability differs greatly from calculated stability 3. Vehicle stability is unsuitable for launch	Potentially high velocity impact with nearby personnel or civilians, leading to severe injury or death	3	4	12	1. All team members will stand at a safe distance away from the launch vehicle. The Range Safety Officer has the final say of the safe distance, albeit it's at least 300 ft away, as required by NAR. 2. Launch Procedures will be written, and they will outline the necessary steps for installing the launch equipment while following all NAR standards. 3. NDRT will abide by all instructions given by our Team Mentor Dave Brunsting and Range Safety Officer when installing the vehicle on the launch pad/rail. 4. Stability calculations will be performed, and they must be approved by the Project Manager and the Safety Officer.	1. The Range Safety Officer will ensure the distance away from the launch vehicle is safe, and the launch will not occur until everyone is at a safe distance. 2. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations. 3. Launch procedures for launch rail setup and vehicle installation will be written prior to FRR. 4. Stability calculations will be performed prior to launch.	1	4	4

L.3	Uncontrolled vehicle descent	1. The vehicle lands on personnel upon proper descent under a parachute 2. Failure of vehicle's recovery systems	1. High velocity impact with personnel, leading to severe injury or death 2. Low velocity impact with personnel, leading to injuries such as bruises or cuts 3. Damage to nearby buildings or natural structures via impact	3	4	12	1. Launch procedures will be written, and they will outline the necessary steps for all launch vehicle component integration. 2. Multiple Recovery system tests will be performed in order to ensure the systems act accurately, reliably, and in accordance to all NASA Requirements. 3. Vehicle drift will be restricted to less than 2,500 ft (NASA Recovery Requirement 3.10). 4. The maximum allowable kinetic energy of the vehicle is understood to be 75 ft-lbf at landing (NASA Recovery Requirement 3.3). 5. All team members will stand at a safe distance away from the launch vehicle. The Range Safety Officer has the final say of the safe distance, albeit it's at least 300 ft away, as required by NAR.	1. Launch Procedures will be written prior to FRR. 2. All testing procedures will be written prior to FRR. 3. A more detailed look at recovery system hazards and mitigations can be found in the recovery Failure Modes and Effects Analysis tables. 4. The Range Safety Officer will ensure the distance away from the launch vehicle is safe, and the launch will not occur until everyone is at a safe distance. 5. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations. 6. Main parachute and streamer drift calculations will be performed before CDR, and they must be approved by the Project Manager and the Safety Officer.	2	3	6

L.4	Unncontrolled LVIS descent	1. Unintended separation of LVIS from launch vehicle during launch 2. Failure of LVIS recovery systems	1. Personnel injury via impact 2. Damage to nearby buildings or natural structures via impact	3	3	9	1. Launch procedures will be written, and they will outline the necessary steps for all launch vehicle component integration. 2. Multiple Recovery system tests will be performed in order to ensure the systems act accurately, reliably, and in accordance to all NASA Requirements. 3. LVIS drift will be restricted to less than 2,500 ft (NASA Recovery Requirement 3.10). 4. The maximum allowable kinetic energy of the LVIS is understood to be 75 ft-lbf at landing (NASA Recovery Requirement 3.3). 5. All team members will stand at a safe distance away from the launch vehicle. The Range Safety Officer has the final say of the safe distance, albeit it's at least 300 ft away, as required by NAR.	1. Launch Procedures will be written prior to FRR. 2. All testing procedures will be written prior to FRR. 3. A more detailed look at recovery system hazards and mitigations can be found in the recovery Failure Modes and Effects Analysis tables. 4. The Range Safety Officer will ensure the distance away from the launch vehicle is safe, and the launch will not occur until everyone is at a safe distance. 5. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations. 6. Main parachute and streamer drift calculations will be performed before CDR, and they must be approved by the Project Manager and the Safety Officer.	2	2	4

L.5	Uncontrolled nosecone descent	1. Unintended separation of nosecone from launch vehicle during launch 2. Failure of nosecone's recovery system	1. Personnel injury via impact 2. Damage to nearby buildings or natural structures via impact	3	3	9	1. Launch procedures will be written, and they will outline the necessary steps for all launch vehicle component integration. 2. Multiple Recovery system tests will be performed in order to ensure the systems act accurately, reliably, and in accordance to all NASA Requirements. 3. Nosecone drift will be restricted to less than 2,500 ft (NASA Recovery Requirement 3.10). 4. The maximum allowable kinetic energy of the nosecone is understood to be 75 ft-lbf at landing (NASA Recovery Requirement 3.3). 5. All team members will stand at a safe distance away from the launch vehicle. The Range Safety Officer has the final say of the safe distance, albeit it's at least 300 ft away, as required by NAR.	1. Launch Procedures will be written prior to FRR. 2. All testing procedures will be written prior to FRR. 3. A more detailed look at recovery system hazards and mitigations can be found in the recovery Failure Modes and Effects Analysis tables. 4. The Range Safety Officer will ensure the distance away from the launch vehicle is safe, and the launch will not occur until everyone is at a safe distance. 5. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations. 6. Main parachute and streamer drift calculations will be performed before CDR, and they must be approved by the Project Manager and the Safety Officer.	2	2	4

L.6	Ignited motor heat	1. Motor retains high temperatures even after landing 2. Personnel recover the motor immediately after landing 3. Personnel are positioned too close to the launchpad during motor burnout	1. Short term skin burns, and potentially long term scarring 2. High temperatures increase the motor's likelihood of explosion	3	3	9	1. Team members will wait a considerable amount of time after landing before touching the launch vehicle. 2. Team members will not approach the launch vehicle until the Range Safety Officer grants permission. 3. All team members will stand at a safe distance away from the launch vehicle. The Range Safety Officer has the final say of the safe distance, albeit it's at least 300 ft away, as required by NAR.	1. Launch Procedures will be written prior to FRR, and they will outline the necessary procedure for recovery the launch vehicle after touchdown. 2. The Range Safety Officer will ensure the distance away from the launch vehicle is safe, and the launch will not occur until everyone is at a safe distance.	1	2	2

L.7	Battery leakage or explosion	1. Battery experiences intense vibrations and high temperatures during launch 2. Battery is damaged during its transportation to launch field 3. Battery was purchased with pre-existing defects	1. Chemical burns from the battery acid 2. Potential battery explosion, resulting in personnel injuries 3. Chemical leakage from battery is harmful to nearby personnel and the environment	3	3	9	1. All team members must complete the necessary safety training prior to launch. In particular, training outlines that all team members are required to wear rubber gloves if handling a damaged lithium-polymer battery. 2. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline how PPE should be worn. 3. Launch Procedures will be written, and they will outline the PPE required and the procedure for dealing with battery leakage and explosion. 4. Launch Procedures will be written, and they will outline the PPE required and the procedure for storing and transporting batteries. 5. Launch Procedures will be written, and they will outline the PPE required and the procedure for checking battery quality.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer. 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer. 3. Launch Procedures will be written prior to FRR. 4. The updated NDRT Safety Handbook is readily available to all members, and a digital version is shared with all members.	2	2	4

L.8	Operation of sharp or rotating tools for assembling the launch vehicle's interior systems	1. Launch vehicle assembly may require sharp tools, such as pliers and scissors 2. Launch vehicle assembly may require rotating tools, such as drills	1. Severe injury to extremities 2. Severe skin abrasions or cuts to the contact region	3	3	9	1. All team members must complete the necessary safety training prior to launch. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline how PPE should be worn. 4. Launch Procedures will be written, and they will outline all PPE available at the launch site.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer. 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer. 3. Standard Operating Procedures will be completed prior to construction. 4. Launch Procedures will be written prior to FRR. 5. The updated NDRT Safety Handbook is readily available to all members, and a digital version is shared with all members. 6. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes.	2	2	4

L.9	Pinch-points	1. Vehicle assembly includes procedures with small clearances only for hands 2. Electronics clamp down at unexpected times, especially ACS	Injury to hands, such as cuts or bruises	4	2	8	1. All team members must complete the necessary safety training prior to launch. In particular, all team members must wear cut-resistant gloves when operating in pinch points. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline how PPE should be worn. 4. Launch Procedures will be written, and they will outline all PPE available at the launch site.	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer. 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer. 3. Standard Operating Procedures will be completed prior to construction. 4. Launch Procedures will be written prior to FRR. 5. The NDRT Safety Handbook has been updated is readily available to all members as a digital version shared with all members. 6. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes.	2	1	2

L.10	Intense frigid weather	Inclement weather conditions	Prolonged exposure can result in hypothermia and/or Frostbite	2	3	6	1. Team leads will inform all team members attending of the launch day conditions. 2. All members attending will be required to wear proper clothes, especially multiple layers, for intense frigid weather.	1. It will be the responsibility of the Safety Officer to provide weather information to all members attending the launch at the day of the launch. 2. It will be the responsibility of the Safety Officer and Project Manager to provide all potential weather hazards to all members attending the launch in the email prior to launch. 3. The Safety Officer will bring extra gloves, hats, and blankets to the launch site in the event someone forgets to bring their own.	2	2	4
L.11	Car accident to and/or from the launch site	1. Bad traffic due to other drivers 2. Poor road conditions due to weather	Severe injury or death	1	4	4	Only members with a proper driver license will be allowed to drive to any team events, such as launches and off-campus Educational Outreach Events.	1. The Project Manager will ensure all drivers posses updated drivers licenses before departure from the workshop. 2. The Project Manager and Safety Officer will announce road conditions and necessary actions to all drivers on the day of the event if road conditions are off-nominal.	1	3	3

L.12	Intense Sunlight Exposure	Personnel are directly exposed to the sun for an extended period of time without the necessary sun protection equipment	1. Prolonged exposure can result in sunburn, with increased likelihood of long term health risks, such as skin cancer 2. Dizziness and/or heatstroke	2	2	4	1. Team leads will inform all team members attending of the launch day conditions. 2. All members attending will be required to wear proper clothes, especially sunscreen for long term sun exposure. 3. Team leads will inform all team members of the necessary personal items to bring to launch, such as water.	1. It will be the responsibility of the Safety Officer to provide weather information to all members attending the launch at the day of the launch. 2. it will be the responsibility of the Safety Officer and Project Manager to provide all potential weather hazards to all members attending the launch in the email prior to launch. 3. The Safety Officer will bring sunscreen to the launch site in the event someone forgets to bring their own.	2	1	2
L.13	Launch vehicle dropped	1. Careless handling of launch vehicle by personnel 2. Launch vehicle falls off tables while at staging area due to being improperly secured and/or high winds	Injury to extremities, such as bruising, cuts or broken bones	2	2	4	1. Launch Procedures will be written, and they will outline that at least four team members are required to transport the fully constructed launch vehicle to the launch rail and an additional team member is required to ensure their path to the launch rail is clear. 2. Launch Procedures will be written, and they will outline the necessary steps for stabilizing the launch vehicle on the tables.	1. Launch Procedures will be written prior to FRR.	1	2	2

8.5 Failure Modes and Effects Analysis

Table 79: Vehicle Flight Mechanics Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
VFM.1	Fin Flutter	1. Fin imperfections due to manufacturing failures 2. Fins are improperly attached to the launch vehicle	1. Launch vehicle has unexpected flight trajectory 2. Potential damage to launch vehicle and/or components 3. Potential Injury to nearby personnel, civilians, and/or structures	3	3	9	1. Construction procedures will be written, and they will outline the necessary steps for fin construction and instillation 2. Computer simulations and calculations will be performed in order to ensure the stability margin is at least 2 at the point of rail exit (NASA Vehicles Requirement 2.14) 3. The material of the fins will be chosen with strength, weight, and system stability in mind 4. Wind tunnel testing will be performed to evaluate the forces and flow of the wind on the vehicle, especially the fins 5. Fin can drop test will be performed to evaluate the strength of the fins during a ground impact	1. Construction procedures will be written prior to construction 2. Calculations and simulations for the fins and stability margin will be reported by CDR, and they must first be approved by both the Safety Officer and the Systems Officer 3. Team members ordering the fins and adhesives must consult the team's trusted vendor list and past motor data before making any motor purchase 4. Wind tunnel testing will be performed prior to FRR 5. Launch procedures will be written by FRR and accessible to all members, and they will outline the necessary steps for fin quality inspection on the day of the launch 6. Fin can drop test will be performed prior to FRR	2	2	4

VFM.2	Launch vehicle is unstable during flight	1. Design fails to place the center of pressure below the center of mass 2. Improper installation of the fins and/or motor results in failure to place the center of pressure below the center of mass	1. Launch vehicle turns against the wind, resulting in unintended flight trajectory 2. Potential failure to reach target apogee 3. Potential damage to launch vehicle and/or components	3	3	9	1. Construction procedures will be written, and they will outline the necessary steps for fin construction and instillation 2. Computer simulations and calculations will be performed in order to evaluate the location of the center of pressure and center of mass 3. Computer simulations and calculations will be performed in order to ensure the stability margin is at least 2 at the point of rail exit (NASA Vehicles Requirement 2.14) 4. The center of mass will be calculated at the launch field in order to ensure the calculated value is accurate 5. The material of the fins will be chosen with strength, weight, and system stability in mind 6. Wind tunnel testing will be performed to evaluate the forces and flow of the wind on the vehicle, especially the fins 7. The motor will be purchased from a reputable vendor and installed using proper techniques	1. Construction procedures will be written prior to construction 2. Calculations and simulations for the fins, motor, and stability margin will be reported by CDR, and they must first be approved by both the Safety Officer and the Systems Officer 3. Center of mass calculations will be reported by CDR 4. Launch procedures will be written and accessible to all team members, and they will outline the necessary steps for determining the actual center of mass location of the launch vehicle 5. Team members ordering the motor and fins must consult the team's trusted vendor list and past motor data before making any motor purchase 6. Wind tunnel testing will be performed prior to FRR 7. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, which includes motor installation, and he will do so in accordance to all NAR/TRA rules and regulations	2	2	4

VFM.3	Launch vehicle is overstable during flight	1. Design places the center of pressure too far below the center of mass 2. Improper installation of the fins and/or motor places the center of pressure too far below the center of mass	1. Launch vehicle turns into the wind, resulting in unintended flight trajectory 2. Potential failure to reach target apogee 3. Potential damage to launch vehicle and/or components	3	3	9	1. Construction procedures will be written, and they will outline the necessary steps for fin construction and instillation 2. Computer simulations and calculations will be performed in order to evaluate the location of the center of pressure and center of mass 3. Computer simulations and calculations will be performed in order to ensure the stability margin is at least 2 at the point of rail exit (NASA Vehicles Requirement 2.14) 4. The center of mass will be calculated at the launch field in order to ensure the calculated value is accurate 5. The material of the fins will be chosen with strength, weight, and system stability in mind 6. Wind tunnel testing will be performed to evaluate the forces and flow of the wind on the vehicle, especially the fins 7. The motor will be purchased from a reputable vendor and installed using proper techniques	1. Construction procedures will be written prior to construction 2. Calculations and simulations for the fins, motor, and stability margin will be reported by CDR, and they must first be approved by both the Safety Officer and the Systems Officer 3. Center of mass calculations will be reported by CDR 4. Launch procedures will be written and accessible to all team members, and they will outline the necessary steps for determining the actual center of mass location of the launch vehicle 5. Team members ordering the motor and fins must consult the team's trusted vendor list and past motor data before making any motor purchase 6. Wind tunnel testing will be performed prior to FRR 7. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, which includes motor installation, and he will do so in accordance to all NAR/TRA rules and regulations	1	2	2

VFM.4	Launch vehicle initially travels in an unintended line of motion	1. Failure to secure the motor at the proper angle 2. Failure to properly install the rail buttons at the proper angle	1. Launch vehicle continues to follow an unintended flight trajectory 2. Potential failure to reach target apogee 3. Potential damage to launch vehicle and/or components	3	3	9	1. The motor will be carefully transported to the launch site and inspected prior to installation 2. Launch procedures will be written, and they will outline the necessary steps for motor instillation 3. Construction procedures will be written, and they will outline the necessary steps for rail button, fin, and motor mount construction and instillation 4. Launch Procedures will be written, and they will outline the necessary steps for installing the launch equipment while following all NAR standards 5. NDRT will abide by all instructions given by our Team Mentor Dave Brunsting and Range Safety Officer when installing the vehicle on the launch pad/rail 6. Computer simulations and calculations will be performed in order to ensure the stability margin is at least 2 at the point of rail exit (NASA Vehicles Requirement 2.14)	1. Team members ordering the motor must consult the team's trusted vendor list and past motor data before making any motor purchase 2. Launch procedures will be written prior to FRR 3. Construction procedures will be written prior to FRR 4. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, which includes motor installation, and he will do so in accordance to all NAR/TRA rules and regulations 5. Calculations and simulations for the fins, motor, and stability margin will be reported by CDR, and they must first be approved by both the Safety Officer and the Systems Officer	2	2	4

VFM.5	Failure of launch vehicle to clear launch rails	1. Launch rail deformations 2. Selected motor inadequate in clearing launch rail 3. Pre-existing motor imperfections 4. Rail buttons deformations and/or break during clearance	1. Mission failure due to failed launch 2. Potential damage to launch vehicle	3	3	9	1. Calculations and simulations will be performed prior to motor selection to ensure an exit velocity of at least 52 feet per second (NASA Vehicles Requirement 2.17) 2. The motor will be purchased from a reputable vendor and installed using proper techniques 3. The systems squad will allocate and enforce weight limits to each system 4. Proper installation of launch rail and launch vehicle on launch rail will be enforced with launch procedures 5. Rail buttons will be purchased from reputable vendors and installed using proper techniques	1. Calculations and simulations will be reported by CDR, and they must first be approved by both the Safety Officer and the Systems Officer 2. Team members ordering the motor and rail buttons must consult the team's trusted vendor list and past motor data before making any motor purchase 3. All preliminary information of weight allocation can be found in Section 3.5.1 4. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, which includes motor installation and inspection, and he will do so in accordance to all NAR/TRA rules and regulations 5. Launch procedures will be written by FRR and accessible to all members, and they will outline the necessary steps for launch rail setup, inspection, and launch vehicle installation on the launch rail 6. Launch procedures will be written by FRR and accessible to all members, and they will outline the necessary steps for determining the center of mass of the launch vehicle for stability reasons 7. Construction procedures will be written prior to construction	1	3	3

VFM.6	Excessive and/or unbalanced drag	1. Imperfections with exterior of launch vehicle 2. Excessive exterior coatings and/or attachments 3. Actual drag exerted on the launch vehicle is greater than calculated	1. Launch vehicle follows an unintended flight trajectory 2. Potential failure to reach target apogee 3. Potential damage to launch vehicle and/or components	3	2	6	1. Construction procedures will be written, and they will help ensure proper methods are used to mitigate imperfections 2. Launch procedures will be written, and they will outline the necessary steps for identifying imperfections 3. Wind tunnel testing will be performed, and it will help highlight possible drag issues with our design 4. Paint layers to the exterior of our launch vehicle will be as minimal as possible to reduce any potential drag induced by it 5. All drag calculations and simulations will be performed and approved by our team graduate student and team University professor	1. Construction procedures will be written prior to FRR 2. Launch procedures will be written prior to FRR 3. Wind tunnel testing will occur prior to FRR 4. Our team graduate student and University professor has greater experience with drag calculations and simulations	1	2	2
VFM.7	Failure to ignite motor	1. Malfunction of E-match 2. Pre-existing motor imperfections	Mission failure due to no launch, resulting in project delays and/or competition ineligibility	3	2	6	1. The motor will be carefully transported to the launch site and inspected prior to installation 2. The motor will be purchased from a reputable vendor and installed using proper techniques 3. Backup motors will be brought to every launch in the event of a defective motor	1. Team members ordering the motor must consult the team's trusted vendor list and past motor data before making any motor purchase 2. Launch procedures will be written by FRR and accessible to all members, and they will outline the necessary steps for motor inspection and handling 3. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, which includes motor installation, and he will do so in accordance to all NAR/TRA rules and regulations 4. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for installing the launch equipment while following all NAR standards	1	1	1

VFM.8	Insufficient launch rail exit velocity (Failure to meet NASA Vehicles Requirement 2.17)	1.Selected motor inadequate in generating sufficient launch rail exit velocity 2. Pre-existing motor imperfections 3. Excessive launch vehicle mass 4. External forces on launch vehicle are greater than calculated	1. Launch vehicle has unexpected flight trajectory 2. Potential damage to launch vehicle and/or components 3. Potential Injury to nearby personnel, civilians, and/or structures	2	3	6	1. Calculations and simulations will be performed prior to motor selection to ensure an exit velocity of at least 52 feet per second (NASA Vehicles Requirement 2.17) 2. The motor will be purchased from a reputable vendor and installed using proper techniques 3. The systems squad will allocate and enforce weight limits to each system	1. Calculations and simulations will be reported by CDR, and they must first be approved by both the Safety Officer and the Systems Officer 2. Team members ordering the motor must consult the team's trusted vendor list and past motor data before making any motor purchase 3. All preliminary information of weight allocation can be found in Section 3.5.1 4. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, which includes motor installation and inspection, and he will do so in accordance to all NAR/TRA rules and regulations 5. Launch procedures will be written by FRR and accessible to all members, and they will outline the necessary steps for launch rail setup and launch vehicle installation on the launch rail	1	3	3

Table 80: Vehicle Structures Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
VS.1	Centering Ring Failure	1. Improper attachment of centering rings 2. Centering ring material and/or construction imperfections	1. Motor becomes improperly aligned, resulting in an unintended flight trajectory 2. Launch vehicle fails to reach the target apogee 3. Potential severe injury to nearby personnel	3	4	12	1. Centering rings will be chosen based on research and calculations 2. Centering ring materials will be purchased from reputable vendors 3. Construction procedures will be written and made accessible to all members, and they will outline the necessary steps for centering ring construction and integration	1. Team members ordering the centering ring material must consult the team's trusted vendor list 2. Construction procedures will be written prior to FRR	1	4	4
VS.2	Coupler Failure	1. Improperly sized couplers 2. Improper fastening of couplers to launch vehicle body tube	1. Unexpected launch vehicle body tube separation 2. Potential damage to launch vehicle and/or components	3	4	12	1. Couplers will be chosen based on research and calculations 2. Couplers will be purchased from reputable vendors 3. Launch procedures will be written and made accessible to all members, and they will outline the necessary steps for coupler integration	1. Team members ordering the couplers must consult the team's trusted vendor list 2. Launch procedures will be written prior to FRR	1	4	4

VS.3	Bulkhead Structural Failure	1. Improper bulkhead construction 2. Adhesives fail to secure the bulkhead to the body tube 3. Bulkhead materials and/or design inadequate at withstanding the forces exerted on the system	1.Potential damage to interior launch vehicle components 2. Unintended body tube separation	3	3	9	1. The material and design of the bulkheads and U-bolts will be chosen with strength and weight in mind 2. Bulkhead material and U-bolts will be purchased from reputable vendors 3. Construction procedures will be written and accessible to all members, and they will outline the necessary steps for constructing and integrating the bulkheads and U-bolts 4. Bulkhead strength test will be performed, and it will evaluate the amount of weight the U-bolt and bulkhead can withstand to simulate the launch loads and parachute forces	1. Team members ordering the bulkhead material and U-bolts must consult the team's trusted vendor list 2. Construction procedures will be written prior to FRR 3. Bulkhead strength test will be performed prior to FRR	1	3	3
VS.5	Fin failure	1. Fins are improperly secured to the launch vehicle fin can 2. Fin imperfections due to materials and/or construction method	1. Launch vehicle travels in an unpredictable trajectory 2. Potential damage to launch vehicle and/or components	3	3	9	1. The material of the fins will be chosen with strength and weight in mind 2. Wind tunnel testing will be performed to evaluate the forces of the wind on the fins 3. Fin can drop test will be performed to evaluate the ability of the fin can to withstand touchdown forces 4. Simulations and calculations will be performed prior to launch to evaluate the strength of the fins 5. Launch Procedures will be written and made accessible to all members, and they will outline the necessary steps for evaluating the fins on the day of the launch 6. Proper installation of the fins will be ensured through the use of construction procedures	1. All information of the fins can be found in Section 3.3.4 2. Wind tunnel testing will be performed prior to FRR 3. Fin can drop test will be performed prior to FRR 4. All fin calculations will be performed before CDR 5. Launch procedures will be written prior to FRR 6. Construction procedures will be written prior to construction	1	2	2

VS.4	Motor Retainer Failure	1. Motor retainer imperfections 2. Motor retainer improperly secured to the motor	1. Motor shifts, resulting in unpredictable flight trajectory 2. Motor detaches from launch vehicle 3. Potential damage to launch vehicle and/or components 4. Potential injury to nearby personnel and/or structures	2	4	8	1. The motor retainer will be chosen with strength and weight in mind 2. Vehicle shake test will be performed to evaluate the ability of the motor retainer to stay on the launch vehicle during launch vibrations 3. Launch procedures will be written and made accessible to all members, and they will outline the necessary steps for motor retainer integration	1. All information of the motor retainer can be found in Section 3.4.2 2. Vehicle shake test will be performed prior to FRR 3. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, which includes motor installation, and he will do so in accordance to all NAR/TRA rules and regulations	1	4	4
VS.6	Motor explosion	1.Improper motor casing instillation 2. Motor imperfections	1. Severe damage to launch vehicle and/or components 2. Severe injury and/or death to nearby personnel	2	4	8	1. The motor will be carefully transported to the launch site and inspected prior to installation 2. The motor will be purchased from a reputable vendor and installed using proper techniques	1. Team members ordering the motor must consult the team's trusted vendor list and past motor data before making any motor purchase 2. Launch procedures will be written by FRR and accessible to all members, and they will outline the necessary steps for motor inspection and handling 3. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, which includes motor installation, and he will do so in accordance to all NAR/TRA rules and regulations	1	4	4

VS.7	Structural failure upon landing	1.Launch vehicle body constructed with inadequate materials 2. Launch vehicle lands at a greater than anticipated descent velocity	1. Potential damage and/or complete destruction of launch vehicle body 2. Potential damage to nearby personnel, civilians, and/or structures	3	3	6	1. The material of the body tubes will be chosen with strength, weight, and data transmission in mind 2. Nosecone drop test will be performed to evaluate the ability of the nosecone to withstand touchdown forces 3. Fin can drop test will be performed to evaluate the ability of the fin can to withstand touchdown forces 4. Vehicle shake test will be performed in order to evaluate the ability of the system to withstand flight conditions 5. CAD models and drawings will be created prior to construction to accurately fabricate the vehicle structure 6. Proper construction of the launch vehicle structure will be ensured through the use of launch procedures and construction procedures	1. The material of the vehicle structure can be found in Section 3.3.1, 3.3.2, and 3.3.3 2. Nosecone drop test will be performed prior to FRR 3. Fin can drop test will be performed prior to FRR 4. Vehicle shake test will be performed prior to FRR 5. Preliminary CAD models and/or drawings for the vehicle design can be found in Section 3.2 6. Construction procedures will be written prior to construction 7. Launch procedures will be written prior to FRR	1	2	2
VS.8	Launch vehicle dropped	1. Careless handling of launch vehicle by personnel 2. Launch vehicle falls off tables while at staging area due to being improperly secured and/or high winds	1. Potential damage to launch vehicle, especially external extremities such as the fins and nosecone 2. Potential damage to launch vehicle internal components, especially recovery and payload electronics	3	2	6	1. Launch Procedures will be written, and they will outline that at least four team members are required to transport the fully constructed launch vehicle to the launch rail and an additional team member is required to ensure their path to the launch rail is clear 2. Launch Procedures will be written and made accessible to all members, and they will outline the necessary steps for stabilizing the launch vehicle on the tables	Launch Procedures will be written prior to FRR	1	1	1

VS.9	Failure to to transmit tracking position of independent sections of the vehicle at all times (NASA Recovery Requirement 3.12)	1. Transmitter radio frequency shielded by outside components 2. Additional tracking devices in other components interfere with each other's ability to transmit tracking positions	Failure to track all launch vehicle independent sections accurately during the flight	3	2	6	1. The material of the body tubes will be chosen with strength, weight, and data transmission in mind 2. Long-distance testing will be performed in order to ensure the system's data can be transmitted long distances 3. Vehicle shake test will be performed in order to evaluate the ability of the system to withstand flight conditions 4. Transmitting frequencies of all electronic devices will be chosen to avoid potential interference 5. System interference testing will be performed, and it will ensure all components don't interfere with data transmission	1. The material of the payload body tube can be found in Section 3.3.1 2. Launch Procedures will be written prior to FRR, and they will outline the necessary steps for all vehicle component integration 3. Long-distance testing will be performed prior to FRR 4. Vehicle shake test will be performed prior to FRR 5. System interference testing will be performed prior to FRR 6. All transmitter frequencies will be reported to NASA prior to launch in order to compare the team's frequencies with other nearby teams' frequencies	1	2	2

Table 81: Apogee Control System Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
ACS.1	Power system failure	1. Improper construction and/or integration procedures yield damaged electronics 2. Intense vibrations and/or heat during launch result in damaged electronics 3. Batteries are insufficiently charged due to team negligence and/or frigid weather	1. Launch vehicle potentially overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to ACS failing to function properly, failing NASA Vehicles Requirement 2.1 2. Launch vehicle fails to reach the target apogee of 4,800 ft	4	3	12	1. All electronic components will be properly checked prior to every test, departure for launch site, and before integration at every launch. 2. ACS battery duration tests will be performed under multiple situations in order to evaluate the quality of the system's batteries. 3. All batteries brought to the launch site will be required to be fully charged prior to launch.	1. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ensuring all batteries are fully charged before departure from the workshop 2. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ACS electronics integration 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for battery charging and transportation 4. Launch procedures will be written and accessible to all members, and they will include a detailed packing list for all ACS components, including charged batteries 5. ACS battery duration tests will be performed prior to FRR	2	2	4

ACS.2	Mechanism for securing the Apogee Control System to the launch vehicle is damaged before apogee is reached	1. Improper installation of ACS sensors 2. ACS sensor programming ineffective at reading sensor data during launch 3. Loss of power to electrical systems 4. Sensors incorrectly calibrated	1. ACS fails to properly deploy, resulting in the launch vehicle failing to reach the target apogee of 4,800 ft 2. Potential shift of the ACS inside the launch vehicle, resulting in internal component damage and/or unintended mass distribution 3. Premature deployment of ACS from fin can	3	4	🟥 12	1. ACS will be tested with simulated flight data in order to evaluate the system's accuracy 2. ACS battery duration tests will be performed under multiple situations in order to evaluate the quality of the system's batteries 3. Redundancy will be implemented into the system 4. ACS sensors will be purchased from reputable vendors and installed using proper methods	1. ACS will be tested using simulated flight data prior to FRR 2. ACS battery duration tests will be performed prior to FRR 3. ACS redundancy tests will be performed prior to FRR 4. ACS sensor trade study can be found at Section 7.5	2	2	🟩 4

ACS.3	Incorrect and/or unavailable sensor data	1. Improper installation of ACS sensors 2. ACS sensor programming ineffective at reading sensor data during launch 3. Loss of power to electrical systems 4. Sensors incorrectly calibrated	Launch vehicle fails to reach the target apogee of 4,800 ft	4	3	12	1. ACS will be tested with simulated flight data in order to evaluate the system's accuracy 2. ACS battery duration tests will be performed under multiple situations in order to evaluate the quality of the system's batteries 3. Redundancy will be implemented into the system 4. ACS sensors will be purchased from reputable vendors and installed using proper methods	1. ACS will be tested using simulated flight data prior to FRR 2. ACS battery duration tests will be performed prior to FRR 3. ACS redundancy tests will be performed prior to FRR 4. ACS sensor trade study can be found at Section 7.5	2	2	4

ACS.4	Apogee Control System electronics become unsecured during launch	1. Intense vibrations and/or heat during flight 2. Improper construction and/or installation of ACS electronics 3. Extension and/or retraction of ACS flaps induce unexpected forces on the inside of the body tube	1. ACS electronics become unsecured, resulting in internal component damage and/or unintended mass distribution 2. Launch vehicle potentially undershoots or overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to damaged electronics, failing NASA Vehicles Requirement 2.1 3. Launch vehicle fails to reach the target apogee of 4,800 ft due to damaged electronics	3	4	12	1. ACS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions 2. Wind tunnel testing will be performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps mechanism 3. Proper installation of the ACS into the launch vehicle will be ensured through the use of launch procedures	1. ACS shake test will be performed prior to FRR 2. ACS wind tunnel testing will be performed prior to FRR 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ACS integration	1	4	4

ACS.5	Micro-controller sends improper command signals	1. Improper programming of ACS electronics systems 2. Flight sensor data computations yield unexpected errors	1. Launch vehicle potentially undershoots or overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to improper command signals, failing NASA Vehicles Requirement 2.1 2. Launch vehicle fails to reach the target apogee of 4,800 ft due to improper command signals	3	3	9	1. ACS control algorithm will be tested with simulated flight data in order to evaluate the system's ability to filter data 2. ACS flap deployment mechanism will be tested using simulated flight data in order to ensure the microcontroller is sending the correct data to the mechanism 2. ACS battery duration tests will be performed under multiple situations in order to evaluate the quality of the system's batteries 3. Redundancy will be implemented into the system 4. ACS microcontroller will be purchased from reputable vendors and installed using proper methods	1. ACS control algorithm will be tested using simulated flight data prior to FRR 2. ACS flap deployment mechanism will be tested using simulated flight data prior to FRR 3. ACS battery duration tests will be performed prior to FRR 4. ACS redundancy tests will be performed prior to FRR 5. ACS sensors trade studies can be found at Sections 7.5 6. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ACS electronics integration	2	2	4

ACS.6	Flap extension and/or retraction mechanism failure	1. Flap unable to extend and/or retract during flight due to extreme outside forces hindering movement 2. Improper construction and/or installation methods of the ACS 3. Mechanism's materials insufficient for withstanding flight loads 4. Intense vibrations and/or heat during launch damage ACS mechanisms 5. Flaps lock inward or outward in a motion singularity	1. Flaps cannot properly deploy or retract, resulting in the launch vehicle failing to reach the target apogee of 4,800 ft 2. Launch vehicle potentially overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to ACS flap mechanism unable to deploy outwards, failing NNASA Vehicles Requirement 2.1 3. Launch vehicle potentially undershoots the acceptable apogee range of 4,000 ft to 6,000 ft due to ACS flap mechanism unable to retract inwards, failing NASA Vehicles Requirement 2.1	3	3	9	1. Flap mechanism material and design will be carefully selected to withstand the forces exerted on the system during flight while also reducing the vehicle's drag by a considerable degree 2. CAD models and drawings will be created prior to construction to accurately fabricate the flap deployment mechanism 3. The University of Notre Dame Engineering Innovation Hub Manager will approve of all construction methods prior to part machining 4. ACS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions 5. ACS wind tunnel testing will be performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps mechanism 6. ACS flap mechanism torque test will be performed in order to evaluate the system's ability to withstand the highest expected load with a safety factor of 1.25 7. Proper installation of the ACS into the launch vehicle will be ensured through the use of launch procedures	1. Calculations for flap extensions will be reported by CDR, and they must first be approved by both the Safety Officer and the Systems Officer 2. Preliminary CAD models for the ACS design can be found in Section 7.3 3. ACS shake test will be performed prior to FRR 4. ACS wind tunnel testing will be performed prior to FRR 5. ACS flap mechanism torque test will be performed prior to FRR 6. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ACS electronics integration	2	2	4

ACS.7	Micro controller damaged and/or unresponsive during flight	1. Battery pack fails to consistently output a voltage within the microcontroller's necessary range 2. Improper construction and/or installation of the battery pack	1. Launch vehicle potentially undershoots or overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to electrical system shutdown and/or loss of flap extension control, failing NASA Vehicles Requirement 2.1 2. Launch vehicle fails to reach the target apogee of 4,800 ft due to electrical system shutdown and/or loss of flap extension control	3	3	9	1 . All electronic components will be properly checked prior to every test, departure for launch site, and before integration at every launch 2. ACS battery duration tests will be performed under multiple situations in order to evaluate the quality of the system's batteries 3. All batteries brought to the launch site will be required to be fully charged prior to launch 4. ACS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions	1. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ensuring all batteries are fully charged before departure from the workshop 2. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ACS electronics integration 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for battery charging and transportation 4. Launch procedures will be written and accessible to all members, and they will include a detailed packing list for all ACS components, including charged batteries 5. ACS battery duration tests will be performed prior to FRR 6. ACS shake test will be performed prior to FRR	1	3	3

ACS.8	Apogee Control System has a slow response time, resulting in belated adjustments during flight	1. Current data filters unable to process flight data at an adequate speed 2. Flight data exceeds the memory capacity of the microcontroller	1. Launch vehicle potentially overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to belated adjustments, failing NASA Vehicles Requirement 2.1 2. Launch vehicle likely fails to reach the target apogee of 4,800 ft due to belated adjustments	3	3	9	1. ACS data filtration system will be chosen based on the criteria of speed and memory 2. ACS will be tested with simulated flight data in order to evaluate the system's accuracy and speed	1. ACS data filtration system will be chosen by CDR 2. ACS will be tested using simulated flight data prior to FRR	2	2	4

ACS.9	Apogee Control System flaps are damaged during deployment and/or retraction	1. Flap materials unable to withstand intense launch vibrations and/or winds 2. Interior launch vehicle walls buckle 3. Ineffective construction and/or installation of ACS flaps	1. Launch vehicle potentially overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to ACS flaps unable to function, failing NASA Vehicles Requirement 2.1 2. Launch vehicle fails to reach the target apogee of 4,800 ft due to ACS flaps unable to function 3. ACS flaps disconnect from vehicle, resulting in potential damage to nearby personnel, structures, or environment	2	3	6	1. Flap material and design will be carefully selected to withstand the forces exerted on the system during flight while also reducing the vehicle's drag by a considerable degree 2. The University of Notre Dame Engineering Innovation Hub Manager will approve of all construction methods prior to part machining 3. ACS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions 4. ACS wind tunnel testing will be performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps 5. ACS drop test will be performed in order to evaluate the ability to of the system to withstand launch touchdown 6. Proper installation of the ACS into the launch vehicle will be ensured through the use of launch procedures	1. Calculations for flap extensions will be performed by CDR, and they must first be approved by both the Safety Officer and the Systems Officer 2. ACS preliminary flap material justification can be found in Section 7.3.2 3. ACS shake test will be performed prior to FRR 4. ACS wind tunnel testing will be performed prior to FRR 5. ACS drop test will be performed prior to FRR 6. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ACS electronics integration	1	2	2

Table 82: Recovery Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
R.1	Power system failure	1. Improper construction procedures yield damaged electronics 2. Intense vibrations and/or heat during launch result in damaged electronics 3. Batteries are Insufficiently charged due to team negligence	1. Failure of recovery to deploy parachutes, resulting in launch vehicle landing with unacceptably high kinetic energy (Failure to comply with NASA Recovery Requirement 3.3) 2. Potential high velocity vehicle impact with civilians, leading to severe injuries or death 3. Potential damage to nearby buildings or natural structures via impact 4. Catastrophic damage to vehicle and components	4	4	16	1. All electronic components will be properly checked prior to every test, departure for launch site, and before integration at every launch 2. Recovery battery duration tests will be performed under multiple situations in order to evaluate the quality of the system's batteries 3. All batteries brought to the launch site are required to be fully charged prior to launch	1. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ensuring all batteries are fully charged before departure from the workshop 2. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for recovery electronics integration 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for battery charging and transportation 4. Launch procedures will be written and accessible to all members, and they will include a detailed packing list for all recovery components, including charged batteries 5. Recovery battery duration tests will be performed prior to FRR	2	3	6

R.2	Vehicle fails to separate once reaching apogee	1.Malfunction with altimeters communicating data 2. Black powder charges incorrectly integrated	1. Parachute(s) do not deploy 2. Vehicles falls with kinetic energy larger than required (Failure to meet NASA Recovery Requirement 3.3) 3. Free fall vehicle can cause damage to surrounding structures and/or people 4. Severe damage to vehicle	3	4	12	1. Redundancy will be implemented in black powder charges 2. Separate recovery systems with individual avionics and black powder charges will be integrated into body tube 3. Altimeters will be properly shielded from interference 4. Altimeters will be tested with simulated flight data in order to evaluate the system's accuracy 5. Black powder and altimeters will be supplied from reputable sources and installed using proper methods	1. Black powder charge redundancy tests will be performed prior to FRR 2. Black powder separation tests will be performed prior to FRR 3. Altimeters will be tested using simulated flight data prior to FRR 4. System interference testing will be performed prior to FRR 5. Recovery battery duration tests will be performed prior to FRR 6. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for recovery electronics integration 7. NDRT Mentor Dave Brunsting, who is NAR/TRA Level 3 Certified, will be the only individual permitted to install any energetics, and he will abide by all NAR/TRA procedures and regulations	1	4	4

R.3	Premature body tube and/or nosecone separation	1. Body tubes not properly pinned together 2.Shear Pins fail to hold vehicle body tubes together 3. Altimeters supply false reading, causing premature black powder ignition	1. Potential loss of interior components 2. Potential high velocity impact with civilians, leading to severe injuries or death 3. Potential damage to nearby buildings or natural structures via impact 4.Potential high velocity impact, resulting in potential damage to launch vehicle and/or components 5. Vehicle potentially fails to reach desired apogee	3	4	12	1. Shear pins will be carefully selected to withstand the forces exerted on the system during flight 2. Shear pins will be purchased from reputable vendors and installed using proper methods 3. Altimeters will be purchased from reputable vendors and installed using proper methods 4. Altimeters will be tested with simulated flight data in order to evaluate the system's accuracy	1. Safety factor calculations for shear pins will be reported by CDR, and all safety factor calculations must first be approved by both the Safety Officer and Systems Officer 2. Recovery battery duration tests will be performed prior to FRR 3. Altimeters will be tested using simulated flight data prior to FRR 4. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for shear pin and body tube integration 5. NDRT Mentor Dave Brunsting, who is NAR/TRA Level 3 Certified, will be the only individual permitted to install any energetics, and he will abide by all NAR/TRA procedures and regulations	1	4	4

R.4	Vehicle components fully deatch during launch	1. Shock cords and/or recovery system ineffective at resisting high loads 2. Black powder detonation pressure damages shock cord strength and/or recovery system 3. Incorrect integration of shock cords, or complete absence of shock cords integration	1. Launch vehicle components lands with unacceptably high kinetic energy (Failure to comply with NASA Recovery Requirement 3.3) 2. Potential high velocity impact with civilians, leading to severe injuries or death 3. Potential damage to nearby buildings or natural structures via impact 4. Damage to vehicle components	3	4	12	1. Shock cords will be purchased from reputable vendors and installed using proper methods 2. Shock cords will be carefully selected to withstand the forces exerted on the system during flight 3. Recovery system structural materials be chosen based on their ability to withstand the forces exerted on the system during flight 4. Recovery system ground separation test will be performed in order to evaluate the structural integrity of the system during black powder ignition	1. Safety factor calculations for shock cords will be reported by CDR, and all safety factor calculations must first be approved by both the Safety Officer and Systems Officer 2. Safety factor calculations for recovery structural components will be reported by CDR, and all safety factor calculations must first be approved by both the Safety Officer and Systems Officer 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for shock cord integration 4. Recovery system ground separation test will be performed prior to FRR 5. NDRT Mentor Dave Brunsting, who is NAR/TRA Level 3 Certified, will be the only individual permitted to install any energetics, and he will abide by all NAR/TRA procedures and regulations	1	4	4

R.5	Main parachute fails to reduce descent velocity to acceptable levels after deployment	1. Main parachute too small to reduce the vehicle descent velocity 2. Recovery systems deploy main parachute at an incorrect time 3. Entanglement of shock chords causes incorrect deployment of main parachute 4. Main parachute damaged during deployment by black powder charges 5. Ineffective installation of main parachute	1. Launch vehicle lands with unacceptably high kinetic energy (Failure to comply with NASA Recovery Requirement 3.3) 2. Potential high velocity impact with civilians, leading to severe injuries 3. Potential damage to nearby buildings or natural structures via impact 4. Damage to vehicle and/or components	3	4	12	1. Main parachute will be carefully selected to withstand the forces exerted on the system during flight while also adequately reducing the descent velocity of the launch vehicle 2. Black powder, altimeters, and the main parachute will all be purchased from reputable vendors and installed using proper methods 3. Main parachute deployment testing will be performed in order to evaluate the parachute's ability to fully deploy over a short period of time 4. Altimeters will be tested with simulated flight data in order to evaluate the system's accuracy 5. Main parachute will be properly protected from black powder charges	1. Preliminary main parachute information can be found in Section 4.3.1 2. All calculations and simulations for the main parachute will be approved by both the Safety Officer and the Systems Officer 3. Main parachute deployment testing will be performed prior to FRR 4. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for parachute folding and integration 5. NDRT Mentor Dave Brunsting, who is NAR/TRA Level 3 Certified, will be the only individual permitted to install any energetics, and he will abide by all NAR/TRA procedures and regulations	2	4	8

R.6	Drogue parachute / streamer fails to reduce descent velocity to acceptable levels after apogee	1. Drogue parachute / streamer not sized correctly to reduce the vehicle descent velocity 2. Recovery systems deploy drogue parachute at an incorrect time 3. Shock cords become tangled prohibiting full deployment of drogue parachute 4. Drogue parachute / streamer damaged during deployment by black powder charges 5. Ineffective installation of drogue parachute	1. Launch vehicle lands with unacceptably high kinetic energy (Failure to comply with NASA Recovery Requirement 3.3) 2. Potential high velocity impact with civilians, leading to severe injuries 3. Potential damage to nearby buildings or natural structures via impact 4. Damage to vehicle and/or components	3	4	12	1. Drogue parachute/streamer will be carefully selected to withstand the forces exerted on the system during flight while also adequately reducing the descent velocity of the launch vehicle 2. Black powder, altimeters, and the drogue parachute/streamer will all be purchased from reputable vendors and installed using proper methods 3. Drogue parachute/streamer deployment testing will be performed in order to evaluate the system's ability to fully deploy over a short period of time 4. Altimeters will be tested with simulated flight data in order to evaluate the system's accuracy 5. Drogue parachute/ streamer will be properly protected from black powder charges	1. Preliminary Drogue parachute/ streamer information can be found in Section 4.3.1 2. All calculations and simulations for the drogue parachute/streamer will be approved by both the Safety Officer and the Systems Officer 3. Drogue parachute/ streamer deployment testing will be performed prior to FRR 4. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for parachute folding and integration 5. NDRT Mentor Dave Brunsting, who is NAR/TRA Level 3 Certified, will be the only individual permitted to install any energetics, and he will abide by all NAR/TRA procedures and regulations	2	4	8

R.7	Premature Apogee Control System detachment from fin can	1. Improper construction and/or installation of ACS and/or recovery systems 2.Shear Pins fail to hold vehicle tubes together 3. Altimeters supply false reading, causing premature black powder ignition	1. Potential high velocity vehicle and/or component impact with civilians, leading to severe injuries or death 2. Damage to vehicle and/or components 3. Launch vehicle potentially overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to loss of ACS, failing NASA Vehicles Requirement 2.1 4. Launch vehicle fails to reach the target apogee of 4,800 ft due to loss of ACS (NASA Vehicles Requirement 2.3)	3	4	12	1. Shear pins will be carefully selected to withstand the forces exerted on the system during flight 2. Shear pins will be purchased from reputable vendors and installed using proper methods 3. Altimeters will be purchased from reputable vendors and installed using proper methods 4. Altimeters will be tested with simulated flight data in order to evaluate the system's accuracy 5. ACS will be properly installed into the launch vehicle	1. Safety factor calculations for shear pins will be reported by CDR, and all safety factor calculations must first be approved by both the Safety Officer and Systems Officer 2. Recovery battery duration tests will be performed prior to FRR 3. Altimeters will be tested using simulated flight data prior to FRR 4. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for shear pin integration 5. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ACS integration 6. NDRT Mentor Dave Brunsting, who is NAR/TRA Level 3 Certified, will be the only individual permitted to install any energetics, and he will abide by all NAR/TRA procedures and regulations	1	4	4

R.8	Vehicle lands outside the allowable recovery radius of 2,500 ft (Failure to comply with NASA Recovery Requirement 3.10)	1. Main or drogue streamer parachutes deploy early (before 680 ft AGL; 4,800 ft AGL respectively) 2. Main or drogue parachutes are too large	1. LVIS mission failure due to a vehicle landing zone outside the 2,500 by 2,500 ft grid 2. Low velocity vehicle impact with civilians, leading to injuries such as bruises or cuts 3. Damage to nearby buildings or natural structures via impact	3	3	9	1. Calculations will be performed during CDR to determine the maximum expected drift radius 2. Redundancy will be implemented in black powder charges 3. Altimeters will be purchased from reputable vendors 4. Altimeters will be tested with simulated flight data in order to evaluate the system's accuracy 5. Altimeters will be properly shielded from interference 6. Black powder and altimeters will be supplied from reputable sources and installed using proper methods	1. All parachute calculations and simulations will have to be verified and approved by both the Safety Officer and Systems Officer 2. Black powder charge redundancy tests will be performed prior to FRR 3. Black powder separation tests will be performed prior to FRR 4. Altimeters will be tested using simulated flight data prior to FRR 5. System interference testing will be performed prior to FRR 6. Recovery battery duration tests will be performed prior to FRR 7. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for recovery electronics integration 8. NDRT Mentor Dave Brunsting, who is NAR/TRA Level 3 Certified, will be the only individual permitted to install any energetics, and he will abide by all NAR/TRA procedures and regulations	1	2	2

R.9	Recovery System fails to seperate ACS from fin can	1. Inaccurate altimeter data results in failure of e-match to ignite black powder charges 2. Black powder charges set incorrectly 3. Improper installation of recovery system and/or ACS	1. Launch vehicle component lands with unacceptably high kinetic energy (Failure to comply with NASA Recovery Requirement 3.3) 2. Potential high velocity vehicle impact with civilians, leading to severe injuries or death 3. Potential damage to nearby buildings or natural structures via impact 4. Damage to vehicle and/or components	2	4	8	1. Redundancy will be implemented in black powder charges 2. Altimeters will be properly shielded from interference 3. Altimeters will be tested with simulated flight data in order to evaluate the system's accuracy 4. Black powder and altimeters will be supplied from reputable sources and installed using proper methods 5. Launch procedures will ensure the proper installation of the recovery systems and ACS are known to all team members	1. Black powder charge redundancy tests will be performed prior to FRR 2. Black powder separation tests will be performed prior to FRR 3. Altimeters will be tested using simulated flight data prior to FRR 4. System interference testing will be performed prior to FRR 5. Recovery battery duration tests will be performed prior to FRR 6. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for recovery electronics integration 7. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ACS integration 8. NDRT Mentor Dave Brunsting, who is NAR/TRA Level 3 Certified, will be the only individual permitted to install any energetics, and he will abide by all NAR/TRA procedures and regulations	1	4	4

R.10	Parachute fully detaches from vehicle during launch	1. Shock chord's connection to vehicle fails to resist high loads 2. Shock chord ineffective at resisting high loads 3. Black powder detonation pressure damages shock cord or connection strength 4. Incorrect integration of shock chord and/or main parachute, or complete absence of shock chord integration	1. Launch vehicle lands with unacceptably high kinetic energy (Failure to comply with NASA Recovery Requirement 3.3) 2. Potential high velocity vehicle impact with civilians, leading to severe injuries or death 3. Potential damage to nearby buildings or natural structures via impact 4. Damage to vehicle and/or components	2	4	8	1. Shock cords and quick links will be purchased from reputable vendors and installed using proper methods 2. Shock cords will be carefully selected to withstand the forces exerted on the system during flight 3. Recovery system structural materials be chosen based on their ability to withstand the forces exerted on the system during flight 4. Recovery system ground separation test will be performed in order to evaluate the structural integrity of the system during black powder ignition	1. Safety factor calculations for shock cords will be reported by CDR, and all safety factor calculations must first be approved by both the Safety Officer and Systems Officer 2. Safety factor calculations for recovery structural components will be reported by CDR, and all safety factor calculations must be approved by both the Safety Officer and Systems Officer 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for shock cord integration 4. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for parachute folding and integration 5. Recovery system ground separation test will be performed prior to FRR	1	4	4

Table 83: Launch Vehicle Identification System Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
LVIS.1	Software Error	1. Values and/or constants used in LVIS algorithms significantly alter the outcome of calculations 2. Noisy data	Returned landing location is significantly displaced from actual landing location, resulting in inaccurate grid coordinate	5	4	20	1. LVIS will be tested with subscale flight data in order to evaluate the system's accuracy with the actual landing location 2. LVIS will be tested in a variety of conditions to determine the proper elements necessary for accurate flight trajectory simulation	1. LVIS will be tested using subscale flight data prior to FRR 2. LVIS situational testing will be performed prior to FRR	2	3	6
LVIS.2	Nothing is detected by LVIS	1. LVIS batteries are uncharged and/or unconnected 2. LVIS software fails to identify launch vehicle motion 3. LVIS is damaged during and/or before flight, resulting in inability to properly function	No grid coordinate is returned, resulting in complete payload mission failure	3	4	12	1. Detailed launch procedure outlining the integration of LVIS components will be created and rigorously followed to ensure the proper installation of all LVIS components 2. LVIS sensors will be supplied from reputable sources and installed using proper methods 3. LVIS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions 4. Redundancy will be implemented in LVIS in case one set of sensors is unable to detect any data 5. LVIS will be tested in a variety of conditions to determine the proper elements necessary for accurate flight trajectory simulation	1. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for LVIS integration 2. LVIS shake will be performed prior to FRR 3. LVIS will be tested using simulated flight data prior to FRR 4. LVIS redundancy tests will be performed prior to FRR 5. LVIS situational testing will be performed prior to FRR	1	4	4

LVIS.3	Redundant System Conflict	1. Inadequate LVIS sensors chosen 2. Sensor imperfections 3. Improper installation of LVIS sensors	Multiple systems return drastically different locations, resulting in inaccurate data and grid coordinate	3	4	12	1. LVIS sensors will be supplied from reputable sources and installed using proper methods 2. LVIS redundancy tests with Identical sets of LVIS sensors will be performed with subscale flight data in order to evaluate each system's accuracy and precision with the actual subscale landing position 3. A minimum of three identical sensor systems will be implemented in LVIS so there can always be a majority decision 4. LVIS will be tested in a variety of conditions to determine the proper elements necessary for accurate flight trajectory simulation	1. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for LVIS integration 2. LVIS redundancy tests will be performed prior to FRR 3. LVIS situational testing will be performed prior to FRR	2	3	6
LVIS.4	Data Overload	1. Inadequate LVIS sensors chosen 2. Sensor imperfections 3. Simulation data does not accurately include all necessary forces	1. Flight path is disproportional on different axes based on inaccurate data, resulting in inaccurate grid coordinate 2. Flight path is proportional but scaled improperly due to disconnect in simulation algorithm, resulting in inaccurate grid coordinate	2	4	8	1. LVIS sensors will be supplied from reputable sources and installed using proper methods 2. Maximum grid dimensions (250 ft by 250 ft) will reduce necessary precision in calculations 3. LVIS will be tested with subscale flight data in order to evaluate the system's accuracy with the actual landing location 4. Redundancy will be implemented in LVIS 5. LVIS will be tested in a variety of conditions to determine the proper elements necessary for accurate flight trajectory simulation	1. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for LVIS integration 2. LVIS will be tested using subscale flight data prior to FRR 3. LVIS redundancy tests will be performed prior to FRR 4. LVIS situational testing will be performed prior to FRR	1	4	4

LVIS.5	Antenna Obstruction	LVIS unable to transmit the necessary signal due to landing configuration, distance from computer, and/or structural damage	No grid coordinate is returned, resulting in complete payload mission failure	2	4	8	1. The material of the payload body tube will allow data transmission 2. Long-distance testing will be performed in order to ensure the system's data can be transmitted long distances 3. Payload drop test will be performed in order to ensure that launch touchdown doesn't damage any LVIS components 4. LVIS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions	1. The material of the payload body tube can be found in Section 3.3.1 2. LVIS long-distance testing will be performed prior to FRR 3. LVIS drop test will be performed prior to FRR 4 LVIS shake test will be performed prior to FRR	1	4	4
LVIS.6	Launch vehicle lands nearby and/or between grid borders	1. Launch vehicle, as determined by the grid layout and LVIS systems, lands between and/or nearby grid boarders 2. The location of the payload body tube is to be reported if complications occur	Slight inaccuracies in LVIS software may result in the incorrect grid coordinate being reported	2	3	6	1. Use of maximum grid dimensions (250 ft by 250 ft) will reduce the chances of grid intersection 2. LVIS will be tested with subscale flight data in order to evaluate the system's accuracy with the actual landing location 3. Redundancy will be implemented in LVIS 4. LVIS will be tested in a variety of conditions, especially near grid borders, to determine the proper elements necessary for accurate flight trajectory simulation	1. LVIS will be tested using subscale flight data prior to FRR 2. LVIS redundancy tests will be performed prior to FRR 3. LVIS situational testing will be performed prior to FRR	1	3	3

Table 84: Launch Vehicle Identification System Integration Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
LI.1	LVIS attachment to launch vehicle compromises data collection and/or transmission	1. Data from sensors is manipulated by mechanical structures, such as damping 2.Additional devices in nearby electronics interfere with LVIS's ability to transmit and/or receive data 3.Improper installation of LVIS into launch vehicle	Obstructed LVIS data is inaccurate and/or missing, resulting inaccurate grid location and payload mission failure	4	4	16	1. LVIS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions 2.Long-distance testing will be performed in order to ensure the system's data can be transmitted long distances 3.Launch vehicle system components will be designed to mitigate risk of transmission interference 4.LVIS integration tests will be performed in order to evaluate how the payload's integration affects data collection and/or transmission 5.The material of the payload body tube will allow data transmission	1. LVIS shake test will be performed prior to FRR 2.Long-distance testing will be performed prior to FRR 3.LVIS integration testing will be performed prior to FRR 4.The material of the payload body tube can be found in Section 3.3.1 5.System interference testing will be performed prior to FRR 6.Launch procedures will be written and accessible to all members, and they will outline the necessary steps for LVIS integration	2	3	6
LI.2	Excessive vibrations and/or accelerations during flight	1. Actual forces exerted on LVIS is greater than calculated 2.LVIS design and/or materials insufficient for maintaining its structural integrity 3.Improper installation of LVIS into launch vehicle	Damaged LVIS reports inaccurate data or is unable to report data entirely, resulting in partial or complete payload mission failure	3	4	12	1. LVIS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions 2.LVIS materials and design will be carefully selected to withstand the forces exerted on the system during flight	1. LVIS shake test will be performed prior to FRR 2.LVIS preliminary material selection and CAD models can be found in Section 6.3 3.Launch procedures will be written and accessible to all members, and they will outline the necessary steps for LVIS integration	2	3	6

LI.3	LVIS power failure	1. Failure to charge batteries prior to launch 2.Failure to check battery voltages prior to launch 3.Frigid weather conditions shorten battery life 4.Improper installation of LVIS into launch vehicle 5.Intense vibrations and/or heat during launch result in dislodged power systems	LVIS will operate incorrectly, or it will not be able to operate entirely, resulting in payload mission failure	2	4	8	1. All electronic components will be properly checked prior to every test, departure for launch site, and before integration at every launch 2.LVIS battery duration tests will be performed under multiple situations in order to evaluate the quality of the system's batteries 3.All batteries brought to the launch site are required to be fully charged prior to launch 4.LVIS shake test will be performed in order to evaluate the ability of the system to withstand flight conditions	1. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for ensuring all batteries are fully charged before departure from the workshop 2.Launch procedures will be written and accessible to all members, and they will outline the necessary steps for LVIS electronics integration 3.Launch procedures will be written and accessible to all members, and they will outline the necessary steps for battery charging and transportation 4.Launch procedures will be written and accessible to all members, and they will include a detailed packing list for all LVIS components, including charged batteries 5.LVIS battery duration tests will be performed prior to FRR 6.LVIS shake test will be performed prior to FRR	1	4	4

Table 85: Launch Equipment Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
LE.1	Launch ignition wires are primed during installation into motor	1. Failure to turn off the launch controller after the previous vehicle launch 2. Faulty launch controller	Motor ignites prematurely, resulting in severe damage and/or death to the launch vehicle and/or nearby personnel.	3	4	12	1. Only NDRT-purchased launch controllers will be utilized at launches to ensure quality 2. All launch equipment — including launch controller, wires and motor — will be thoroughly inspected prior to motor installation	1. The Range Safety Officer will ensure that the launch equipment is properly set up prior to launch vehicle installation, as instructed by Section 9 of NAR's High Powered Rocketry Safety Code 2. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for aligning both the launch rail and launch pad 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for installing the launch vehicle on the launch rail 4. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for operating launch equipment 5. Launch procedures will be written and accessible to all members, and they will highlight the importance of approval from our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification), Range Safety Officer, and Launch Control Officer to proceed with launch	1	4	4

LE.2	Launch rail is positioned at an angle less than five degrees or greater than ten degrees, violating NASA General Requirement 1.12	1. Failure to properly set up the launch equipment 2. Failure to properly position the launch vehicle on the launch pad	1. Launch vehicle travels in an unintended trajectory, resulting in potential harm to nearby personnel, civilians, and/or structures 2. Potential failure to reach target apogee due to undershooting 3. Vehicle potentially lands outside the allowable recovery radius of 2,500 ft (Failure to comply with NASA Recovery Requirement 3.10)	3	3	9	1. Launch equipment will constructed while following all NAR standards 2. NDRT will abide by all instructions given by our Team Mentor Dave Brunsting and Range Safety Officer when installing the vehicle on the launch pad/rail 3. The launch rail will be positioned at an angle between five degrees and ten degrees from the vertical axis at the time of launch	1. The Range Safety Officer will ensure that the launch equipment is properly set up prior to launch vehicle installation, as instructed by Section 9 of NAR's High Powered Rocketry Safety Code 2. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for aligning both the launch rail and launch pad 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for installing the launch vehicle on the launch rail 4. Launch procedures will be written and accessible to all members, and they will highlight the importance of approval from our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification), Range Safety Officer, and Launch Control Officer to proceed with launch 5. A protractor will be used to ensure the launch rail angle is between five degrees and ten degrees	1	3	3

LE.3	Unstable launch rail	1.Improper installation of vehicle on the launch rail base 2. Launch rail is not properly locked while in the vertical position	1. Launch vehicle travels in an unintended trajectory, resulting in potential harm to nearby personnel, civilians, and/or structures 2. Potential failure to reach target apogee due to undershooting 3. Vehicle potentially lands outside the allowable recovery radius of 2,500 ft (Failure to comply with NASA Recovery Requirement 3.10)	3	3	9	1. Launch equipment will constructed while following all NAR standards 2. NDRT will abide by all instructions given by our Team Mentor Dave Brunsting and Range Safety Officer when installing the vehicle on the launch pad/rail	1. The Range Safety Officer will ensure that the launch equipment is properly set up prior to launch vehicle installation, as instructed by Section 9 of NAR's High Powered Rocketry Safety Code 2. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for aligning both the launch rail and launch pad 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for installing the launch vehicle on the launch rail 4. Launch procedures will be written and accessible to all members, and they will highlight the importance of approval from our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification), Range Safety Officer, and Launch Control Officer to proceed with launch	1	3	3

LE.4	Failure of launch controller to ignite the motor	1. Improper installation of the wired connection between the launch controller and the motor 2. Faulty wires and/or controller	Motor does not ignite, resulting in no launch	3	2	6	1. Only NDRT-purchased launch controllers will be utilized at launches to ensure quality 2. All launch equipment — including launch controller, wires and motor — will be thoroughly inspected prior to motor installation	1. The Range Safety Officer will ensure that the launch equipment is properly set up prior to launch vehicle installation, as instructed by Section 9 of NAR's High Powered Rocketry Safety Code 2. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for aligning both the launch rail and launch pad 3. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for installing the launch vehicle on the launch rail 4. Launch procedures will be written and accessible to all members, and they will outline the necessary steps for operating launch equipment 5. Launch procedures will be written and accessible to all members, and they will highlight the importance of approval from our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification), Range Safety Officer, and Launch Control Officer to proceed with launch	1	2	2

8.6 Environmental Risks

Table 86: Environmental Risks to Vehicle

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
EV.1	Damage to electrical components of the launch vehicle, such as electrical circuits and batteries	Weather conditions, such as humidity, rain, or snow cause an electrical discharge	1. Potential failure of recovery systems to properly operate, or recovery systems fail to operate entirely 2. Potential failure of LVIS to properly operate, or LVIS fails to operate entirely 3. Potential failure of ACS to properly operate, or ACS fails to operate entirely	3	4	12	1. All electrical components will be stored in re-sealable electrostatic discharge (ESD) shielding bags when not in active use. 2. Altimeters for recovery, payload, and apogee control system will be shielded in Faraday cages. 3. Electrical components will be securely fastened to structural components or brackets in the launch vehicle.	1. A launch checklist for safe handling and integration of recovery avionics will be created prior to the vehicle demonstration flight 2. A launch checklist for safe handling and integration of ACS avionics will be created prior to the vehicle demonstration flight 3. A launch checklist for safe handling and integration of LVIS avionics will be created prior to the vehicle demonstration flight	1	4	4

EV.2	Weather cocking during launch flight	Wind speeds greater than 20 mph occur at the launch site	Launch vehicle travels in an unintended flight path	3	4	12	1. The static stability margin will be a minimum of 2 calipers NASA Vehicles Requirement 2.14 2. Launch will be postponed if wind speeds exceed 20 miles per hour.	1. Preliminary calculations for the stability margin of the launch vehicle can be found in 3.6.3 and have been verified and approved by the Safety Officer, Systems Lead, and Vehicles Lead. 2. A launch checklist for evaluating launch conditions, especially wind speed, will be created prior to the vehicle demonstration flight.	1	4	4
EV.3	Inadequate ground visibility of launch vehicle during its flight	Low cloud cover on launch day	1. Failure of team to track the entire flight path, leading to potential loss of vehicle or injury to nearby personnel 2. Launching the launch vehicle into clouds violates the NAR High Power Rocket Safety Code Rule 9	3	4	12	1. Launch will not occur when cloud cover hides the vehicle from eyesight during any segment of the flight or descent.	1. A launch checklist for evaluating launch conditions, especially cloud cover, will be created prior to the vehicle demonstration flight. 2. The Range Safety Officer will always have full authority as to when launches may proceed.	1	3	3

EV.1	Launch vehicle lands in trees or other elevated structures	1. Trees or other elevated structures exist in the proximity of the launch area 2. Vehicle's recovery landing area exceeds expected radius	1. Loss or damage of vehicle and/or payload 2. Vehicle's actual recovery area potentially violated NASA Recovery Requirement 3.10	3	4	12	1. The drogue streamer and main parachute sizings will be based on calculations and flight simulations. 2. Launches will occur in an open field away from any trees.	1. Calculations in Section 5.3.3 show the maximum possible simulated drift of the vehicle is 2389.94 ft, which is within the acceptable range of 2,500 ft (NASA Recovery Requirement 3.10). 2. A launch checklist for evaluating launch conditions, especially launch area terrain, will be created prior to the vehicle demonstration flight.	1	3	3
EV.5	Disrupted wireless signal	Weather, environmental obstacles, or other teams' operations hinder our team's ability to establish a strong signal	Disrupted wireless communication between launch vehicle systems	3	4	12	1. Vehicle flight will not occur when fog or landscape prohibits the transmitters from operating properly during the entire flight and post-flight LVIS operation. 2. All transmission frequencies will be reported prior to flight. 3. Transmitters will be tested prior to launch according to avionics test plans developed by the Systems Team. 4. All electrical components will be stored in re-sealable electrostatic discharge (ESD) shielding bags when not in active use.	1. All transmitter frequencies will be reported to NASA prior to competition launch and compared to other devices at the launch site. 2. A test plan containing proper procedures and success criteria for testing data transmission between LVIS and a team device will be created prior to CDR by the Systems Team. 3. A test plan containing proper procedures and success criteria for testing GPS transmitters will be created prior to CDR by the Systems Team. 4. A launch checklist for evaluating launch conditions, especially cloud and fog cover members will be created prior to the vehicle demonstration flight. 5. The Range Safety Officer will always have full authority as to when launches may proceed.	1	4	4

EV.6	Uneven launch pad	Uneven or soft ground below the launch pad due to poor launch pad location and/or recent weather conditions	1. Expected launch angle not accurate, potentially missing our target and/or minimum required apogee (NASA Vehicles Requirement 2.1 & NASA Vehicles Requirement 2.3) 2. Forces acting on the sides of rocket can be greater than calculated, resulting in unintended flight performance	3	3	9	1. The launch pad will be positioned at a 0° ± 1° angle with respect to the ground during all vehicle flights using a digital level.	1. A launch checklist for setting up launch equipment, specifically the launch pad and rail, will be created prior to the vehicle demonstration flight.	1	1	1

EV.7	Animal Interference	Existence of local animal populations near the launch site	1. Animals can potentially damage launch vehicle and/or components before, during, and/or after launch 2. Potentially severe injury or death to nearby animals due to proximity to launch vehicle before, during, and/or after launch	3	3	9	1. Launches will occur in an open field away from any animal habitats. 2. The launch field will be visually surveyed immediately prior to flight to ensure no animals are in the proximal area.	1. A launch checklist for evaluating launch conditions, including checking for wildlife, will be created prior to the vehicle demonstration flight.	2	1	2
EV.8	Motor propulsion materials get wet	1. Weather conditions, such as snow, rain, or humidity increase the likelihood of dampening or soaking the motor propulsion materials 2. Motor makes contact with swampy ground, snow, or rain	1. Complete or partial failure to ignite motor, resulting in unintended launch conditions. 2. If another motor is unavailable, the launch cannot occur	3	3	9	1. Motors will be stored by the team mentor in a protective case prior to integration in the 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 3 Certification) is the only individual allowed to store and handle motors and will obey NAR/TRA guidelines and procedures.	1	3	3

EV.9	Bonding materials such as epoxy and other adhesives weaken	High temperature and humidity, including direct contact with water	1. Components can shift during flight affecting stability. 2. Components can become detached from the vehicle and enter free fall.	2	4	8	1. Adhesive materials will be researched prior to purchase from reputable brands, as determined by the NDRT Project Manager. 2. Bonding materials will be stored correctly according to material-specific Safety Data Sheets. 3. Assemblies with components attached via bonding material will be properly stored and transported according to material-specific Safety Data Sheets.	1. Standard Operating Procedures will be written by FRR, and they will outline the correct procedure for epoxying. 2. NDRT Safety Data Sheet Document Sections 4.8, 4.9, 4.15, and 4.16 contain the SDS documents for multiple bonding materials in the NDRT Workshop, and is readily available for all members. 3. Routine workshop checks will occur, during which storage of bonding materials will be checked and corrected as necessary.	1	3	3
EV.10	Ultraviolet light exposure	Electronics are exposed to direct sunlight for long periods of time	Ultraviolet light exposure can result in damaged electronics or sensors, causing unintended performances	2	4	8	1. All electrical components will be stored in re-sealable electrostatic discharge (ESD) shielding bags when not in active use. 2. All electronics will be protected from direct sunlight once integrated into launch vehicle.	1. A launch checklist for assembling and initiating the recovery electrical system on launch day will be created prior to the vehicle demonstration flight. 2. A launch checklist for assembling and initiating the ACS electrical system on launch day will be created prior to the vehicle demonstration flight. 3. A launch checklist for assembling and initiating the LVIS electrical system on launch day will be created prior to the vehicle demonstration flight. 4. A launch checklist for integrating electronics in the vehicle will be created prior to the vehicle demonstration flight.	1	4	4

EV.11	Unintended battery charge loss	Cold temperatures, especially below the freezing point (32°F, or 0°C)	Vehicle component electronics are unable to operate without power	2	4	8	1. Batteries will be stored in a dedicated protective container prior to assembly on launch day. 2. Batteries will be fully charged prior to transportation to launch site. 3. Batteries will not be charged at temperatures below freezing 32°F/0°C. 4. Multiple batteries will be packed for launch day in the event a battery loses charge between departure and vehicle flight. 5. The launch vehicle will be assembled in an order that allows electronics to be the last integrated component, immediately prior to vehicle setup on launch rail. 6. Launch will not occur if the Range Safety Officer, Team Mentor, or Safety Officer deem the temperature to be too cold.	1. A launch checklist for evaluating launch conditions, especially wind speed, will be created prior to the vehicle demonstration flight. 2. A launch checklist for charging batteries prior to departure from the workshop will be created prior to the vehicle demonstration flight. 3. A packing checklist for all vehicle components, including extra charged batteries, will be created prior to the vehicle demonstration flight. 4. A launch checklist for testing batteries with a multimeter prior to launch will be created prior to the vehicle demonstration flight. 5. A launch checklist for installing and arming LVIS electronics into the vehicle will be created prior to the vehicle demonstration flight.	1	2	2
EV.12	Launch vehicle and/or components are dropped during assembly and/or launch operations	High wind speeds occur at the launch site	Potential damage to the vehicle, launch equipment, and/or launch vehicle components, such as the recovery systems, ACS, and LVIS	3	2	6	1. The static stability margin will be a minimum of 2 calipers (NASA Vehicles Requirement 2.14). 2. Launch will be postponed if wind speeds exceed 20 miles per hour.	1. Calculations for the stability margin of the launch vehicle can be found in Section 5.2.2 and have been verified and approved by the Safety Officer, Systems Lead, and Vehicles Lead. 2. A launch checklist for evaluating launch conditions, especially wind speed, will be created prior to the vehicle demonstration flight.	2	2	4

EV.13	Excessive vehicle drift during parachuted descent	Wind speeds greater than 20 mph occur at the launch site	1. Vehicle lands outside the allowable drift radius, violating NASA Recovery Requirement 3.10 2. Low velocity vehicle impact with unsuspecting civilians, leading to injuries such as bruises or cuts 3. Damage to nearby buildings or natural structures via impact	3	2	6	1. The parachute will be designed primarily to properly reduce descent velocity, but also restrict drift radius. 2. Launch will be postponed if wind speeds exceed 20 miles per hour.	1. Calculations and simulations for the drogue streamer and main parachute can be found in Section 5.3 and have been verified by the Safety Officer and Systems Officer. 2. Expected drift calculations can be found in Section 5.3.3 and have been verified and approved by the Safety Officer and Systems Officer. 3. A launch checklist for evaluating launch conditions, especially wind speed, will be created prior to the vehicle demonstration flight.	1	2	2

EV.14	Physical damage to vehicle due to severe weather conditions	Hail or lightning	1. Body of the vehicle can become compromised, affecting flight dynamics 2. Overall vehicle weakened, causing higher risk of individual component failure 3. If the motor is struck by lightning, possible motor explosion, resulting in catastrophic damage to all nearby launch vehicle components	2	3	6	1. Safe launch conditions will be guaranteed before exposing vehicle to environment. 2. Components will be assembled properly on launch day according to checklists. 3. Components of the vehicle will be reliable, durable, and able to withstand minor physical forces.	1. A launch checklist for evaluating launch conditions, especially wind speed and weather, will be created prior to the vehicle demonstration flight. 2. The Range Safety Officer will always have full authority as to when launches may proceed.	1	1	1

EV.15	Alteration to vehicle structure and/or component geometry due to swelling	Weather conditions, such as high humidity and/or temperature changes	1. Components do not fit together, resulting in difficulty or inability to assemble the launch vehicle 2. If already assembled, components are unable to separate, resulting in unintended performance of components during launch	2	3	6	1. Components will be transported in a safe manner before assembly, integration, and launch. 2. Tools brought to the launch site will be used to make minor adjustments, upon approval of the Safety Officer and Project Manager, so that parts fit properly together.	1. A packing list for all necessary tools and equipment required at the launch site, will be created prior to the vehicle demonstration flight. 2. A launch checklist for assembling the vehicle on launch day will be created prior to the vehicle demonstration flight. 3. A launch checklist for storing components prior to integration in the vehicle will be created prior to the vehicle demonstration flight.	1	2	2

Table 87: Vehicle Risks to Environment

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
VE.1	Solder, Wire, or Plastic Waste	1. Use of solder to secure wire connections in electrical components 2. Use of wires for connecting electrical components 3. Use of plastic for prototyping and subscale construction 3. Improper disposal of solder, wires, and/or plastic	1. Solder, wires, and/or plastics disposed of in a landfill may never fully decompose (plastics may take over 1,000 years to decompose) 2. Potential damage to wildlife which may ingest or be injured by solder, wires, and/or plastics 3. Contamination of nearby agricultural land	4	3	12	1. Solder, wires, and plastics will be disposed of according to local recycling guidelines, when possible 2. Solder, wires, and plastics will be disposed of properly according to local landfill guidelines, when recycling is not possible 3. All members completing construction using solder, wires, and plastics will minimize waste 4. Alternative wire connection mechanisms, such as lever wire connectors, will be favored over solder, when possible 5. Standard Operating Procedures will be written, and they will outline the necessary steps for soldering	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer. This includes the understanding of recycling all applicable objects. 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. The updated NDRT Safety Data Sheet Document is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 6. A recycling bin is always present in the team workshop, and emptied regularly by University of Notre Dame maintenance staff	2	1	2

VE.2	High velocity impact of any launch vehicle component (NASA Recovery Requirement 3.3)	1. High wind speeds, resulting in unintended flight trajectories 2. Failure of recovery systems to properly reduce launch vehicle descent velocity	1. High velocity impact to nearby personnel or wildlife, resulting in severe injury or death 2. High velocity impact with nearby structures, resulting in severe damage 3. High velocity impact with nearby land and/or habitats, resulting in agricultural damage and/or wildlife homelessness	3	4	12	1. The motor will be installed correctly and carefully by an individual with at least NAR/TRA Level 2 certification 2. The recovery systems are designed to prioritize reliability and redundancy for each separation, in accordance with NASA Recovery Requirement 3.14 3. Recovery-related tests will be performed in order to ensure the accuracy, precision, and strength of the system. 4. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR	1. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations. 2. The chosen motor will be procured from a trusted vendor and will be approved by the Vehicles Lead, Systems Lead, and Project Manager 3. All recovery information can be found in Section 4. Notably, recovery deployment can be found in Section 4.2 4. Testing Procedures will be written prior to FRR 5. Launch Procedures will be written prior to FRR, and they will outline the necessary procedure for recovery system integration 6. The Range Safety Officer will ensure the distance away from the lanch vehicle is safe, and the launch will not occur untill everyone is at a safe distance.	1	3	3

VE.3	Airborne fiberglass particulates, such as styrene (C8H8) gas	Use of sanding for any fiberglass material	1. Airborne particles reduce local air quality 2. Contamination of nearby agricultural land 3. Exposure to styrene poses a health risk to team members	3	4	12	1. Design squads will keep in mind that the amount of airborne particles produced by the launch vehicle must be minimized, such that there are negligible effects on personnel or environment 2. Standard Operating and Construction Procedures will be written, and they will outline the necessary steps for sanding components 3. All potential airborne particulates produced will be completed in a space with appropriate ventilation and air filtration 4. Important material properties for all materials are listed in the NDRT Safety Data Sheet Document	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer. 3. Construction procedures will be written prior to construction, and they will be made readily accessible to all team members 4. Standard operating procedures will be written prior to construction, and they will be made readily accessible to all team members 5. NDRT Safety Data Sheet Document Section 3.10 contains the Fiberglass G10 SDS, and is readily available for all members as a physical copy in the workshop as well as a digital copy in the team Google Drive	1	3	3

VE.4	Excessive Carbon Dioxide (CO2) emission	Motor burnout and black powder ignition will both produce carbon dioxide (CO2) emissions	Increased levels of carbon in the atmosphere, resulting in intensified climate change related issues	5	2	10	1. Design squads will keep in mind that the amount of carbon dioxide produced by the launch vehicle must be minimized, such that there are negligible effects on personnel or environment 2. Safety documentation for all materials will be kept available for team members 3. The motor and black powder will be chosen with environmental impact and performance both in mind, and it will be installed with proper techniques	1. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations. 2. NDRT Safety Data Sheet Document Section 3.4 contains safety data sheeets for Black Powder 3. NDRT Safety Data Sheet Document will contain the Aerotech L2200G-18 Motor Propellant information, and the SDS will be readily available for all members as a physical copy in the workshop as well as a digital copy in the team Google Drive 4. The NDRT Safety Data Sheet Document is readily available for all members as a physical copy in the workshop as well as a digital copy in the team Google Drive	5	1	5

VE.5	Launch Vehicle Components fully separate from vehicle during flight	1. Failure to properly secure launch vehicle components, or complete failure to secure launch vehicle components 2. Failure of launch vehicle components to maintain properly secured amidst the intense vibrations and heat of launch	1. Wildlife could ingest small components, resulting in terrible reactions 2. Contact with sharp and/or abrasive surfaces of launch components may inflict damage to wildlife 3. Impact velocity of launch vehicle components can inflict damage to nearby wildlife, crops, and/or buildings	3	3	9	1. Components in the vehicle are designed to be secured using reliable fasteners, adhesives,and/or shear pins 2. Vehicle-related tests will be performed in order to ensure the accuracy, precision, and strength of the system. 3. Recovery-related tests will be performed in order to ensure the accuracy, precision, and strength of the system. 4. Integration testing will be performed in order to test how all components engage with each other when put together	1. Calculations and simulations for vehicle structural components and recovery structural components (Section 5) have been verified and approved by both the Safety Officer and Systems Lead 2. A test plan containing proper procedures and success criteria for testing recovery and vehicle structural integrity will be created prior to CDR by the Systems and Safety Teams 3. Detailed CAD models and drawings will be used to accurately fabricated, assembling, and integrate the launch vehicle and all internal systems	1	2	2

VE.6	Vehicle and/or LVIS debris	1. Launch vehicle explodes due to motor explosion 2. Extreme miscalculation of black powder charges results in excessive, unintended forces on system	1. Tiny debris can be practically impossible to fully clean up, resulting in littering and contamination of land 2. Tiny component debris could potentially be ingected by wildlife, resulting in injury or death 3. Tiny components may be sharp or abrasive, and contact with wildlife can result in injury	2	4	8	1. The motor will be installed correctly and carefully by an individual with at least NAR/TRA Level 2 certification 2. The recovery systems are designed to prioritize reliability and redundancy for each separation, in accordance with NASA Recovery Requirement 3.14 3. Recovery-related tests will be performed in order to ensure the accuracy, precision, and strength of the system. 4. Vehicle-related tests will be performed in order to ensure the strength of the system. 5. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR	1. Launch procedures will be written by FRR and accessible to all members, and they will outline that our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations. Procedures for motor instillation will also be included 2. The chosen motor will be procured from a trusted vendor and will be approved by the Vehicles Lead, Systems Lead, and Project Manager 3. All recovery information can be found in Section 4. Notably, recovery deployment can be found in Section 4.2 4. Testing Procedures will be written prior to FRR 5. Launch Procedures will be written prior to FRR, and they will outline the necessary procedure for recovery system integration and vehicle integration on the launch rail 6. The Range Safety Officer will ensure the distance away from the launch vehicle is safe, and the launch will not occur until everyone is at a safe distance.	1	4	4
VE.7	Battery acid discharge	1. Battery ruptured by sharp object and/or impact 2. Intense vibrations and temperatures during launch may impact the structural strength of the battery	1. Contamination of nearby soil and/or groundwater 2. Contamination of nearby agricultural land	2	4	8	1. Batteries will be stored in a fireproof battery bag when not in active use or charging 2. All batteries will be thoroughly inspected before being properly integrated into a system and vehicle assembly 3. Safety documentation for batteries will be made available for team members 4. Battery duration tests will be performed in order to test how certain situations affect the performance and integrity of all system batteries	1. NDRT Safety Data Sheet Document Section 3.13 contains the Lithium Polymer Battery SDS 2. The NDRT Safety Data Sheet Document is readily available for all members in electronic format 3. Battery duration tests will be written and performed prior to FRR 4. Launch Procedures for battery storing, transportation, testing, and integration at the launch field will be written prior to FRR and made accessible to all team members	1	4	4

VE.8	Fire	1. Motor burnout generates flames 2. Electrics short circuit 3. Dry grass, due to local droughts and/or dry humidity	1. Severe burns to nearby personnel or wildlife or possible death 2. Destruction of nearby natural habitats and/or agricultural land 3. Carbon Dioxide is generated from fires, resulting in increased Greenhouse gas emissions	2	4	8	1. All team members must complete the necessary safety training prior to launch engagement. In particular, the training outlines that all team members must not wear loose clothing when operating near flammable materials and all team members must clean up their workspace after operating with flammable materials. These measures will help to ensure fires do not spread. 2. Standard Operating Procedures will be written, and they will outline the necessary PPE and clean-up steps required for such tasks. 3. The NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE and fire-prevention materials available, their locations in the workshop, and how they should be worn or used. 4. Launch procedures will be written, and they will outline the necessary steps if a fire does emerge 5. The NDRT Safety Data Sheet will be updated and made available to all team members, and it will outline all material properties. All team members must consult the SDS before operating with any flammable materials. 6. The motor will be installed correctly and carefully by an individual with at least NAR/TRA Level 2 certification 7. All electronics will be inspected prior to departure to the launch site, and again immediately prior to integration into vehicle 8. All electronics will remain OFF until necessary 9. The launch pad will be positioned in an area free of debris or flammable objects	1. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer. While launches are not in the workshop, the same rules apply 2. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 3. Standard Operating Procedures will be completed prior to construction 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 5. The NDRT Safety Handbook includes the location and operation of the workshop's up to code fire extinguisher and fire blanket in the event of a fire 6. The updated NDRT Safety Data Sheet Document is readily available to all members as a physical version in the workshop, and a digital version is shared with all members 7. Launch Procedures will be written prior to FRR 8. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR 9. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations.	1	4	4

VE.9	Hydrogen Chloride (HCl gas) emission	Use of Ammonium perchlorate (NH4ClO4) motors, resulting in release of hydrogen chloride	Hydrogen chloride (HCl gas) and water (H2O) react to form hydrochloric acid (HCl aqueous), resulting in contaminated waters and/or habitats	3	2	6	1. Design squads will keep in mind that the amount of Hydrogen Chloride (HCl) produced by the launch vehicle must be minimized, such that there are negligible effects on personnel or environment. This is important when it comes to black powder and motors. 2. Important material properties for all materials are listed in the NDRT Safety Data Sheet Document	1. Launch procedures will be written by FRR and accessible to all members, and they will outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be able to handle all energetics, and he will do so in accordance to all NAR/TRA rules and regulations. 2. NDRT Safety Data Sheet Document will contains the Aerotech L2200G-18 Motor Propellant information, and the SDS will be readily available for all members as a physical copy in the workshop as well as a digital copy in the team Google Drive 3. The Range Safety Officer will always have full authority as to when launches may proceed	3	1	3
VE.10	Loss of Body Tube(s) and/or Vehicle Components Upon landing	1. Vehicle lands outside the allowable drift radius, violating NASA Recovery Requirement 3.10 2. Launch vehicle body tubes and/or components land in difficult recovery locations, such as high grass, cornfields, and/or water	1. Leftover vehicle components can be harmful to nearby wildlife, agriculture, and/or habitats 2. Components may never fully decompose	2	3	6	1. GPS will be installed to all launch vehicle subsystems, per NASA Recovery Requirement 3.12 2. Long-distance testing will be performed, and it will ensure all electronics can send signals at far distances 3. Calculations will be performed during CDR to determine the maximum expected drift radius	1. Long-distance testing will be performed prior to FRR 2. All parachute calculations and simulations will have to be verified and approved by both the Safety Officer and Systems Officer	1	3	3

VE.11	Loud, excessive noise	Excessive sounds resulting from the launch vehicle's motor burnout or during team launch operations	Potential otic damage to nearby wildlife, personnel, civilians, and/or structures	1	4	4	1. Noise produced will be temporary and will not exceed EPA regulations, as stipulated by the Noise Control Act of 1972 (42 U.S.C §4901 et. seq.) 2. The Safety Handbook outlines the necessary PPE required for ear protection and its location in the workshop and at launch field 3. Launch Procedures for launch vehicle integration on launch rail will be written 4. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR	1. Launch Procedures will be written prior to FRR 2. The Range Safety Officer will designate safe areas to view the launch in accordance with NAR guidelines 3. The Range Safety Officer will always have full authority as to when launches may proceed 4. The Tripoli Rocketry Association and the RSO will affirm that it maintains the correct noise permits to launch at the site prior to launch day 5. The Safety Handbook will be updated and made accessible to all team members as a physical copy in the workshop as well as a digital copy in the team Google Drive	1	2	2

VE.12	Paint chips off of the exterior of the launch vehicle during transportation and/or flight	1. Use of paint to decorate the exterior of the launch vehicle 2. Intense vibrations and heat during launch 3. Launch vehicle impact velocity	1. Paint left un-recovered may take a while to fully decompose 2. Potential damage to wildlife who may ingest paint 3. Contamination of nearby agricultural land if chipped off during flight	2	2	4	1. The amount of paint emissions from black powder charges will be minimized, such that there are negligible effects on personnel or environment 2. Components that require sanding will be noted in step-by-step fabrication procedures 3. Safety documentation for motors will be made available for team members 4. Painting will be completed professionally in a licensed paint shop with appropriate coatings and employees 5. Launch Procedures will be written, and they will outline the necessary steps for vehicle transportation and integration 6. Fin can and nosecone impact tests will be performed, and they will help gauge to amount of paint that will fall of the launch vehicle during launch and impact	1. All professional paint shops must have proper licenses and certifications 2. NDRT Safety Data Sheet Document Section 3.1 contains the Acrylic Enamel Paint SDS, and is readily available for all members 3. The NDRT Safety Data Sheet Document is readily available for all members as a physical copy in the workshop as well as a digital copy in the team Google Drive 4. Fan can and nosecone impact testing procedures will be written prior to FRR 5. Launch Procedures will be written prior to FRR	1	1	1

8.7 Project Risks Analysis

Table 88: Project Risks

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
PR.1	Team member leaves team	1. Injury or illness 2. Member contracts COVID-19 and has to go into quarantine or isolation 3. Member prioritizes other commitments 4. Member is asked to leave due to inappropriate actions	Project delays	5	2	10	1. Multiple team members will be assigned to the same task to ensure task completion 2. All team members will be made aware of the task's details to ensure task completion 3. A NDRT Google Drive will be created and shared with all team members as a unified reference of all team information in the event a reallocation of tasks is necessary	1. All team leaders will be made aware of the importance of assigning the same task to multiple team members 2. A NDRT Google Drive has already been created and shared with all team members, and it contains well documented information on the team's entire progress on the project	5	1	5

PR.2	Workshop safety violations	1. Insufficient PPE is available or worn 2. Insufficient training	1. Injury to personnel 2. Potential revocation of workshop space privileges 3. Potential damage to launch vehicle, resulting in project delays	3	3	9	1. It will be the duty of the Safety Officer to ensure that all necessary PPE will be available at all times in the workshop 2. All team members must complete the necessary safety training prior to construction eligibility. 3. Standard Operating Procedures will be written, and they will outline the necessary PPE and operation steps required for such tasks 4. NDRT Safety Handbook will be updated and made accessible to all team members, and it will outline all PPE available, its location in the workshop, and how it should be worn 5. NDRT Safety Data Sheet will be updated and made available to all team members, and it will outline all material properties	1. The Safety Officer will take inventory of workshop's PPE bi-weekly once construction has started 2. Additional PPE will be ordered by January 5h to ensure all PPE will arrive at the University of Notre Dame before the start of the Spring Semester (February 3rd) 3. All team members must pass the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and show proof of completion to the Safety Officer 4. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer 5. Standard Operating Procedures will be completed prior to construction 6. The NDRT Safety Handbook has been updated is readily available to all members as a physical version in the workshop, as well as a digital version shared with all members 7. The NDRT Safety Data Sheet Document has been updated is readily available to all members as a physical version in the workshop, as well as a digital version shared with all members 8. A near miss reporting form has been created and made readily available to all members as a means of identifying workshop safety malpractice in order to learn from our mistakes	1	3	3

PR.3	Shipping and/or manufacturing delays from vendors	1. The parts' anticipated arrival date conflicts with team deadlines 2. The shipped part is incorrect or does not meet the team's quality standards	1. Project delays 2. Potential inability to compete in competition due to incomplete vehicle	3	3	9	1. Custom parts will be ordered well in advance to ensure they will arrive in time 2. Additional components and materials will be purchased than necessary 3. NDRT has compiled a list of trusted vendor based on previous purchases	1. All custom parts should be ordered before January 5th to ensure arrival before the start of Spring Semester (February 3rd) 2. Additional material will always be purchased in case a component breaks and/or more material is simply required 3. Squads must consult the list of trusted vendors before purchasing any parts or materials 4. All purchases from vendors not on the list of trusted vendors must be approved by the Project Manager and the Systems Officer	2	2	4
PR.4	Failure to meet all necessary Requirements	1. Team prioritization of NDRT generated requirements over NASA's requirements 2. Inefficient time management 3. Miscommunication among team members 4. Misunderstanding of expected requirements	Team is ineligible to participate in competition	2	4	8	1. NASA requirements are to be understood by all team members prior to the start of the design process 2. The Systems squad will help ensure all teams are meeting all NASA requirements 3. Strong communication between all squads, team members, and team leaders	1. All NASA requirements will be met in accordance to SLI Handbook 2. The team uses Gantt charts to track the progress of all subsystems to ensure everyone is on track	1	4	4

PR.5	Complete destruction or loss of full-scale or subscale vehicle	1. Uncontrolled descent 2. Energetics operate in unintended manners	1. If occurred during launch, failure to design a reusable launch vehicle, as outlined in NASA Vehicles Requirement 2.4. 2. Team must construct an entirely new vehicle, resulting in project delays and increasing the costs of the project 3. Depending on when the hazard occurs, the team may be ineligible to compete in the competition due to time requirements for constructing a new vehicle	2	4	8	1. Extensive testing of all subsystems will occur prior to launch 2. Detailed CAD models and drawings will be created prior to construction to accurately manufacture all subsystems 3. Construction Procedures will be written, and they will help eliminate all construction-related imperfections 4. A NDRT Google Drive will be created and shared with all team members as a unified reference of all team information in the event a reallocation of tasks is necessary	1. All Testing Procedures and tests will be written and performed prior to FRR 2. The construction operation plan will be written before construction 3. Construction Procedures will be written prior to construction 4. A NDRT Google Drive has already been created and shared with all team members, and it contains well documented information on the team's entire progress on the project	1	4	4

PR.6	Failure to conduct subscale flight by January 3rd, 2022 and/or vehicle demonstration flight by March 7th, 2022 (NASA Vehicles Requirement 2.18 and NASA Vehicles Requirement 2.19, respectively)	1. Poor weather conditions on intended launch days 2. Incomplete construction of vehicle 3. Failure to schedule a launch date that is suitable for both the team and our mentor, Dave Brunsting 4. RSO deems team's launch vehicle unsuitable for launch on launch days	Team is ineligible to participate in competition	2	4	8	1. Multiple launch dates and locations have been chosen to provide the team with multiple opportunities to conduct the subscale launch 2. A Technology Readiness Level schedule will be implemented to ensure that all systems are going to finish by their deadlines 3. The team is planning on launching subscale on the first available date 4. A backup team mentor will asked to take over the team mentor's responsibilities if no other day for Dave Brunsting is available	1. The tentative date for subscale launch is November 6th, with the backup date as November 13th 2. The tentative date for demonstration launch is February 5th, with the backup date as February 12th 3. The team uses Gantt charts to track the Technology Readiness Level schedule of all subsystems to ensure progress is on track 4. The team will begin subscale construction at least two weeks before the tentative launch date 5. Jerry Vida has been chosen to be our backup team mentor, and he is at least Level 2 NAR Certified	1	3	3
PR.7	Insufficient materials and parts to fully complete construction	1. Parts to complete the project are not ordered 2. Insufficient funds to purchase all necessary parts and materials	1. Project delays 2.Potential inability to compete in competition due to incomplete vehicle	2	4	8	1. Design squads will purchase materials and parts as soon as they know the amount necessary in order to ensure availability 2. Design squads will make a list of all parts and materials necessary for construction 3. All CAD drawings will include the part's materials 4. Construction Procedures will be written, and they will include all necessary parts and materials for the construction of each component	1. All design squad materials should be purchased before January 15th so they will arrive at the University before the start of the Spring Semester (February 3rd) 2. Construction Procedures will be written prior to construction 3. The construction operation plan will be written before construction, and it will outline the parts and materials required for the construction of each component	1	4	4

PR.8	Transportation to Launch Field Complications	1. Transportation method of launch vehicle breaks down or is unable to start 2. Car accident 3. Excessive traffic	1. Damage to launch vehicle leaves it unlaunchable 2. Arriving late to the launch site, or missing the launch entirely	2	4	8	1. Chosen transportation is known to be reliable 2. Extra time is built into transportation schedule to account for unexpected complications	1. Transportation methods must have no pre-existing mechanical failures 2. Launch procedures will be written prior to FRR, and they will outline the extra time built into the transportation schedule	1	3	3
PR.9	Launch Vehicle Installation Complications	LVIS, recovery, ACS, or vehicles squads discover issues with their components while conducting launch procedures while at the launch site	1. Potential ineligibility to launch due to unsafe conditions or failure to meet NASA Vehicles Requirement 2.6 2. If resolved, Team potentially forgets to recheck crucial launch procedure steps upon resuming the checklist, resulting in unintended conditions during launch	2	4	8	1. Launch procedures will be written, and they will outline all troubleshooting steps necessary for resolving launch complications 2. Proper transportation of launch vehicle and components to the launch site to reduce complications 3. Launch Procedures will be re-written to increase the clarity of the steps 4. Launch vehicle and components will be evaluated before departure from the workshop	Launch Procedures will be written prior to FRR	1	4	4

PR.10	Contracting an illness, especially COVID-19	Respiratory transmission of an extremely contagious virus	1. If one contracts COVID-19, potential long-term health effects or death 2. Increased likelihood of spreading the virus to other team members 3. Increased likelihood of spreading the virus to general population	2	4	8	1. All team members must complete the necessary safety training 2. All team members must comply with all University of Notre Dame COVID-19 policies 3. Team members attending construction, launch, or any other in-person team activities cannot show up if they are experiencing COVID-19-like symptoms and/or were in contact with someone who tested positive 4. Masks are required to be worn at all in-person indoor Educational Outreach events	1. All team members must sign the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must be presented to the Safety Officer. This Safety Agreement includes COVID-19 related rules and regulations 2. The Safety Officer will ensure team compliance with all University, local, state, and national COVID-19 rules and regulations 3. The NDRT Safety Handbook has been updated is readily available to all members as a physical version in the workshop, as well as a digital version shared with all members, and it includes all team-related information on COVID-19 policy compliance	1	4	4
PR.10	Insufficient funds and/or overspending	1. Allocation of funds to design squads and/or subsystems is insufficient 2. Parts are not efficiently sourced 3. Spending on unnecessary components 4. Travel prices rise drastically	1. Team takes on debt 2. Funds allocated for subsystems diminish, resulting in reduced quality of vehicle subsystems 3. Funds allocated for travel diminish, resulting in less available personnel to assist with launches	2	3	6	1. Team fund allocation and spending process has been based on previous years' spending and design 2. All parts have been researched to find the best combination of quality and price 3. Further actions will been taken to increase corporate sponsorships 4. The team card will have a spending limit of $2,500, and this limit can be replenished upon request to department administrators 5. All team purchases will be limited to team leaders to ensure the least amount of people are using team funds at any moment 6. All purchases must be reported to ensure all funds are accounted for	1. Team fund allocation and spending process has never led to team debt 2. Each purchased part was considered from at least three different vendors 3. Complete list of fund allocation can be found in Section 9.3	2	2	4

PR.11	Approved altitude exceeded during launch	1. Launch site does not have proper waiver for the team's altitude requirement 2. Team's altitude estimations are drastically lower than the actual altitude value	Potential legal action due to violation of FAA rules	2	3	6	The team will never use any launch site without the necessary FAA waiver	The team will confirm with the launch site at least one week prior to the launch date the team has attained the proper waiver for the altitude of 4,800 ft	1	3	3
PR.12	Improper testing equipment or procedures	1. Equipment does not perform to standards 2. Inability to use University resources for complex testing 3. Inadequate verification of testing results and procedure	Incorrect or missing data could lead to faulty analyses, resulting in inaccurate design decisions	3	2	6	1. All tests will be confirmed with calculations and simulations 2. NDRT's graduate student, Joe Gonzalez, and/or University Professor, Hirotaka Sakaue, can be asked to confirm proper testing methods were used 3. The team will reach out to the desired testing facilities early in the year to ensure lab time availability and eligibility 4. Testing Procedures will be written to ensure proper testing methods are used	1. The team will reach out to all applicable test facilities upon knowing they want to possibly be used this year 2. Testing Procedures will be written prior to performing each test	1	2	2
PR.13	Team mentor, Dave Brunsting, is unable to attend the scheduled launch date	1. Unforeseen illness or injury 2. Scheduling issues and/or miscommunication	1. No one else on the team is officially allowed to handle Level 2 NAR Certified components, resulting in an ineligibility to launch 2. Project delays	1	3	3	1. NDRT will conform with our Team Mentor the week before, the day before, and the day of the launch to confirm his availability 2. Backup launch dates will be chosen with both the team's availability and the Team Mentor's availability in mind	1. Launch Procedures will be written prior to CDR, and they will outline the necessary steps for the backup team mentor	1	2	2

8.8 Workshop Safety

The Notre Dame Rocketry Team has already taken preemptive measures to ensure workshop safety during the 2021-2022 year. First, all team members are required to sign the Team Workshop Safety Agreement. Notably, this agreement is required for all team members, not just members who want to participate in construction or other workshop-related activities. The full Team Workshop Safety Agreement can be found in Appendix A. It is the duty of the Safety Officer to keep track of all members who have filled out the Team Workshop Safety Agreement. 58 team members have signed the Team Workshop Safety Agreement as of October 30th.

All team members who want to participate in construction activities must complete the Engineering Innovation Hub (EIH) Certification process. This process is done online, and it can be accessed by this link. Each team member must complete the Workshop Safety and Tool Quiz to be certified for construction. Further certifications will be necessary for certain workshop equipment, such as the band saw or drill press. It is the duty of the Safety Officer to keep track of all certified NDRT members. 22 team members have completed the basic EIH certification as of October 30th .

The Safety Squad will work also alongside the Systems Squad to create Standard Operating Procedures (SOPs) for construction, testing, and launch operations. Additionally, the Safety Squad will work to create SOPs for workshop tools and equipment. These documents will serve as resources for the necessary steps towards personnel safety and ideal results. Once written, the SOPs will be readily available to all team members as a physical copy in the workshop as well as a digital version in the team's shared drive and website. The construction, workshop equipment, and testing SOPs will be written prior to construction and testing so they will be completed at the beginning of CDR. The launch SOPs will be written before January 3rd. As well, SOPs will be updated when need be.

The Safety Squad has already updated all relevant safety documents. The team Safety Handbook includes all necessary information on team safety in aspects of the project. In particular, the handbook outlines how to put on PPE, when respective PPE should be worn, and where all PPE is located in the workshop. Additionally, the Safety Handbook outlines all necessary information on the safe handling of workshop tools and equipment. The team Safety Data Sheet (SDS) compiles all chemicals used by the team into a single resource. As well, the SDS outlines all necessary PPE for the respective chemicals, handling procedures, and important first aid information. The Safety Handbook and Safety Data Sheet are already readily available to all team members as a physical copy in the workshop as well as a digital version in the team's shared drive and website.

9 Project Plan

9.1 Requirements Verification

A combination of NASA requirements and NDRT team derived requirements have guided design, operation, and planning to accomplish mission success. Sections 9.1.1 and and 9.1.2 contain all requirements applicable in the 2021-22 mission cycle.

9.1.1 NASA Requirements

NDRT has abided by all NASA given requirements in order to guide the design of the launch vehicle and all subsystems. Tables 89 through 94 detail the full set of NASA provided requirements.

Table 89: NASA General Requirements

Req. 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 who plan to attend Launch Week activities by the Critical Design Review (CDR). Team members will include:
1.4.1	Students actively engaged in the project throughout the entire year.
1.4.2	One mentor (see requirement 1.13).
1.4.3	No more than two adult educators.

Table 89: NASA General Requirements (continued)

Req. ID	Description
1.5	The team will engage a minimum of 250 participants in direct educational, hands-on science, technology, engineering, and mathematics (STEM) activities. These activities can be conducted in-person or virtually. To satisfy this requirement, all events must occur between project acceptance and the FRR due date. A template of the STEM Engagement Activity Report can be found on pages 40-43.
1.6	The team will establish and maintain a social media presence to inform the public about team activities.
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. Late submissions of milestone documents will be accepted up to 72 hours after the submission deadline. Late submissions will incur an overall penalty. No milestone documents will be accepted beyond the 72-hour window. Teams that fail to submit milestone documents will be eliminated from the project.
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 attending Launch Week will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted at the NASA Launch Complex. At launch, 8-foot 1010 rails and 12-foot 1515 rails will be provided. The launch rails will be canted 5 to 10 degrees away from the crowd on Launch Day. The exact cant will depend on Launch Day wind conditions.

Table 89: NASA General Requirements (continued)

Req. ID	Description
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 90: NASA Launch Vehicle Requirements

Req. ID	Description
2.1	The vehicle will deliver the payload to an apogee altitude between 4,000 and 6,000 feet above ground level (AGL). Teams flying below 4,000 feet or above 6,000 feet on their competition launch will receive zero altitude points towards their overall project score and will not be eligible for the Altitude Award.
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, at a minimum, two commercially available barometric altimeters that are specifically designed for initiation of rocketry recovery events (see Requirement 3.4). An altimeter will be marked as the official scoring altitude used in determining the Altitude Award winner. The Altitude Award winner will be given to the team with the smallest difference between the measured apogee and their official target altitude for their competition launch.

Table 90: NASA Launch Vehicle Requirements (continued)

Req. ID	Description
2.4	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.
2.5	The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.
2.5.1	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 Federal Aviation Administration 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, although the capability to withstand longer delays is highly encouraged.
2.8	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider.
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 ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).
2.10.1	Final motor choices will be declared by the Critical Design Review (CDR) milestone.

Table 90: NASA Launch Vehicle Requirements (continued)

Req. ID	Description
2.10.2	Any motor change after CDR must be approved by the NASA Range Safety Officer (RSO). Changes for the sole purpose of altitude adjustment will not be approved. A penalty against the team's overall score will be incurred when a motor change is made after the CDR milestone, regardless of the reason.
2.11	The launch vehicle will be limited to a single stage.
2.12	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).
2.13	Pressure vessels on the vehicle will be approved by the RSO and will meet the following criteria:
2.13.1	The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews.
2.13.2	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. This will include the number of pressure cycles put on the tank, the dates of pressurization/depressurization, and the name of the person or entity administering each pressure event.
2.14	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.
2.15	The launch vehicle will have a minimum thrust to weight ratio of 5:1.
2.16	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.
2.17	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.

Table 90: NASA Launch Vehicle Requirements (continued)

Req. ID	Description
2.18	All teams will successfully launch and recover a subscale model of their rocket prior to CDR. The sub- scale flight may be conducted at any time between proposal award and the CDR submission deadline. Subscale flight data will be reported at the CDR milestone. Subscales are required to use a minimum motor impulse class of E (Mid Power motor).
2.18.1	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.
2.18.2	The subscale model will carry an altimeter capable of recording the model's apogee altitude.
2.18.3	The subscale rocket shall be a newly constructed rocket, designed and built specifically for this year's project.
2.18.3	Proof of a successful flight shall be supplied in the CDR report. Altimeter flight profile graph(s) OR a quality video showing successful launch and recovery events as deemed by the NASA management panel are acceptable methods of proof.
2.18.5	The subscale rocket shall not exceed 75% of the dimensions (length and diameter) of your designed full-scale rocket. For example, if your full-scale rocket is a 4" diameter 100" length rocket your subscale shall not exceed 3" diameter and 75" in length.
2.19	All teams will complete demonstration flights as outlined below.
2.19.1	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 shall be the same rocket to be flown for their competition launch. The purpose of the Vehicle Demonstration Flight is to validate the launch vehicle's stability, structural integrity, recovery systems, and the team's ability to prepare the launch vehicle for flight. A successful flight is defined as a launch in which all hardware is functioning properly (i.e. drogue chute at apogee, main chute at the intended lower altitude, functioning tracking devices, etc.). The following criteria shall be met during the full-scale demonstration flight:
2.19.1.1	The vehicle and recovery system will have functioned as designed.
2.19.1.2	The full-scale rocket shall be a newly constructed rocket, designed and built specifically for this year's project.

Table 90: NASA Launch Vehicle Requirements (continued)

Req. ID	Description
2.19.1.3	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. The following requirements still apply:
2.19.1.3.1	If the payload is not flown, mass simulators will be used to simulate the payload mass.
2.19.1.3.2	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.
2.19.1.4	If the payload changes the external surfaces of the rocket (such as camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight.
2.19.1.5	Teams shall fly the competition launch motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance if the home launch field cannot support the full impulse of the competition launch motor or in other extenuating circumstances.
2.19.1.6	The vehicle shall be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the maximum amount of ballast that will be flown during the competition launch flight. Additional ballast may not be added without a re-flight of the full-scale launch vehicle.
2.19.1.7	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 Range Safety Officer (RSO).
2.19.1.8	Proof of a successful flight shall be supplied in the FRR report. Altimeter flight profile data output with accompanying altitude and velocity versus time plots is required to meet this requirement.
2.19.1.9	Vehicle Demonstration flights shall be completed by the FRR submission deadline. No exceptions will be made. If the Student Launch office determines that a Vehicle Demonstration Re-flight is necessary, then an extension may be granted. THIS EXTENSION IS ONLY VALID FOR RE-FLIGHTS, NOT FIRST TIME FLIGHTS. Teams completing a required re-flight shall submit an FRR Addendum by the FRR Addendum deadline. General and Proposal Requirements

Table 90: NASA Launch Vehicle Requirements (continued)

Req. ID	Description
2.19.2	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. The rocket flown shall be the same rocket to be flown as their competition launch. The purpose of the Payload Demonstration Flight is to prove the launch vehicle's ability to safely retain the constructed payload during flight and to show that all aspects of the payload perform as designed. A successful flight is defined as a launch in which the rocket experiences stable ascent and the payload is fully retained until it is deployed (if applicable) as designed. The following criteria shall be met during the Payload Demonstration Flight:
2.19.2.1	The payload shall be fully retained until the intended point of deployment (if applicable), all retention mechanisms shall function as designed, and the retention mechanism shall not sustain damage requiring repair.
2.19.2.2	The payload flown shall be the final, active version.
2.19.2.3	If the above criteria are met during the original Vehicle Demonstration Flight, occurring prior to the FRR deadline and the information is included in the FRR package, the additional flight and FRR Addendum are not required.
2.19.2.4	Payload Demonstration Flights shall be completed by the FRR Addendum deadline. NO EXTENSIONS WILL BE GRANTED.
2.20	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.
2.20.1	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 a final competition launch.
2.20.2	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 a final competition launch.
2.20.3	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. Permission will not be granted if the RSO or the Review Panel have any safety concerns.

Table 90: NASA Launch Vehicle Requirements (continued)

Req. ID	Description
2.21	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.
2.22	All Lithium Polymer 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.
2.23	Vehicle Prohibitions
2.23.1	The launch vehicle will not utilize forward firing motors.
2.23.2	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)
2.23.3	The launch vehicle will not utilize hybrid motors.
2.23.4	The launch vehicle will not utilize a cluster of motors.
2.23.5	The launch vehicle will not utilize friction fitting for motors.
2.23.6	The launch vehicle will not exceed Mach 1 at any point during flight.
2.23.7	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad (i.e. a rocket with an unballasted weight of 40 lbs. on the pad may contain a maximum of 4 lbs. of ballast).
2.23.8	Transmissions from onboard transmitters, which are active at any point prior to landing, will not exceed 250 mW of power (per transmitter).
2.23.9	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.
2.23.10	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 91: NASA Recovery Requirements

Req. 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. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue stage descent is reasonable, as deemed by the RSO.
3.1.1	The main parachute shall be deployed no lower than 500 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. The term “altimeters” includes both simple altimeters and more sophisticated flight computers.
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.
3.11	Descent time of the launch vehicle will be limited to 90 seconds (apogee to touch down).

Table 91: NASA Recovery Requirements (continued)

Req. ID	Description
3.12	An electronic GPS 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 GPS tracking device.
3.12.3	The electronic GPS tracking device(s) will be fully functional during the official competition launch.
3.13	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).
	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 92: NASA Payload Requirements

Req. ID	Description
4.1	College/University Division – Teams shall design a payload capable of autonomously locating the launch vehicle upon landing by identifying the launch vehicle's grid position on an aerial image of the launch site without the use of a global positioning system (GPS). The method(s)/design(s) utilized to complete the payload mission will be at the teams' discretion and will be permitted so long as the designs are deemed safe, obey FAA and legal requirements, and adhere to the intent of the challenge. An additional experiment (limit of 1) is allowed, and may be flown, but will not contribute to scoring. If the team chooses to fly an additional experiment, they will provide the appropriate documentation in all design reports so the experiment may be reviewed for flight safety.
4.2	Launch Vehicle Landing Zone Mission Requirements
4.2.1	The dimensions of the gridded launch field shall not extend beyond 2,500 feet in any direction; i.e., the dimensions of your gridded launch field shall not exceed 5,000 feet by 5,000 feet.
4.2.1.1	Your launch vehicle and any jettisoned components must land within the external borders of the launch field.
4.2.2	A legible gridded image with a scale shall be provided to the NASA management panel for approval at the CDR milestone.
4.2.2.1	The dimensions of each grid box shall not exceed 250 feet by 250 feet.
4.2.2.2	The entire launch field, not to exceed 5,000 feet by 5,000 feet, shall be gridded.
4.2.2.3	Each grid box shall be square in shape.
4.2.2.4	Each grid box shall be equal in size, it is permissible for grid boxes occurring on the perimeter of your launch field to fall outside the dimensions of the launch field. Do not alter the shape of a grid box to fit the dimension or shape of your launch field.
4.2.2.5	Each grid box shall be numbered
4.2.2.6	The identified launch vehicle's grid box, upon landing, will be transmitted to your team's ground station.
4.2.3	GPS shall not be used to aid in any part of the payload mission.
4.2.3.1	GPS coordinates of the launch vehicles landing location shall be known and used solely for the purpose of verification of payload functionality and mission success.

Table 92: NASA Payload Requirements (continued)

Req. ID	Description
4.2.3.2	GPS verification data shall be included in your team's PLAR.
4.2.4	The gridded image shall be of high quality, as deemed by the NASA management team, that comes from an aerial photograph or satellite image of your launch day launch field.
4.2.4.1	The location of your launch pad shall be depicted on your image and confirmed by either the NASA management panel for those flying in Huntsville or your local club's RSO. (GPS coordinates are allowed for determining your launch pad location).
4.2.5	No external hardware or software is permitted outside the team's prep area or the launch vehicle itself prior to launch.
4.3	General Payload Requirements
4.3.1	Black Powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Energetics will not be permitted for any surface operations.
4.3.2	Teams shall abide by all FAA and NAR rules and regulations.
4.3.3	Any experiment element that is jettisoned during the recovery phase will receive real-time RSO permission prior to initiating the jettison event, unless exempted from the requirement at the CDR milestone by NASA.
4.3.4	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.
4.3.5	Teams flying UASs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112-95 Section 336; see https://www.faa.gov/uas/faqs).
4.3.6	Any UAS weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.

Table 93: NASA Safety Requirements

Req. 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.

Table 93: NASA Safety Requirements (continued)

Req. ID	Description
5.2	Each team shall 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
5.3.1.4	Subscale launch test(s)
5.3.1.6	Full-scale launch test(s)
5.3.1.7	Competition Launch
5.3.1.8	Recovery activities
5.3.1.9	STEM Engagement Activities
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.
5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and 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 94: NASA Final Flight Requirements

Req. ID	Description
6.1	NASA Launch Complex

Table 94: NASA Final Flight Requirements (continued)

Req. ID	Description
6.1.1	Teams shall complete and pass the Launch Readiness Review conducted during Launch Week.
6.1.2	The team mentor shall be present and oversee launch vehicle preparation and launch activities.
6.1.3	The scoring altimeter shall be presented to the NASA scoring official upon recovery.
6.1.4	Teams may launch only once. Any launch attempt resulting in the launch vehicle 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 shall 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 shall be granted by NASA prior to the launch.
6.2.2	Teams shall submit their launch vehicle and payload to the launch site Range Safety Officer (RSO) prior to flying the rocket. The RSO will inspect the launch vehicle 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 vehicle and payload may be flown.
6.2.3	The team mentor must be present and oversee launch vehicle 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 be three separate individuals who 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.

Table 94: NASA Final Flight Requirements (continued)

Req. ID	Description
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.
6.2.8	Teams may launch only once. Any launch attempt resulting in the launch vehicle 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.

9.1.2 NDRT Derived Requirements

NDRT has developed team derived requirements which supplement the given NASA requirements in order to further guide the subsystems in their design and testing. These requirements address design guidelines such as battery duration, structural limits, and functional necessities. Importantly, these requirements seek to aid and guide the subsystems, not restrict the design possibilities. Tables 95 through 98 detail the full set of NDRT derived requirements.

Table 95: NDRT Launch Vehicle Requirements

Req. ID	Description	Justification
LV.1	The launch vehicle shall be capable of exceeding the NDRT target apogee in all NASA defined launch conditions.	The launch vehicle must be capable of reaching beyond the target apogee for the ACS to modify the flight path and achieve the expected target apogee.
LV.2	All launch vehicle airframe components shall be designed to withstand the maximum loads of launch and landing with a factor of safety of 1.5. The calculated loads will be updated for CDR.	All airframe components must maintain function by withstanding the maximum expected load by a factor of safety of 1.5 to reduce the risk of structural failures in flight and ensure durability for subsequent flights.

Table 95: NDRT Launch Vehicle Requirements (continued)

Req. ID	Description	Justification
LV.3	All shock cord connection points shall be capable of withstanding the expected loads of separation events with a factor of safety of 1.5. The calculated loads will be updated for CDR.	All shock cord components must maintain function by withstanding the maximum expected load by a factor of safety of 1.5 to reduce the risk of mechanical failures in flight.
LV.4	All launch vehicle airframe components shall be designed to withstand the cyclic loading of repeated launches without wearing due to fatigue.	All airframe components must retain structural integrity throughout multiple test launches and the competition launch.
LV.5	All launch vehicle sections which contain a GPS or communication device shall be constructed from RF-transparent material.	GPS and other communication devices located inside the launch vehicle must be able to transmit through the launch vehicle body to communicate with the ground station.
LV.6	All epoxy joints which are located near the motor shall be constructed with epoxy rated to the maximum expected motor temperature.	Epoxy joints located near the motor must withstand the maximum temperature of the outer motor casing to reduce the risk of epoxy failures in flight.

Table 96: NDRT Recovery Requirements

Req. ID	Description	Justification
R.1	All structural recovery system components shall be designed to withstand the expected loads from separation events with a factor of safety of 1.5.	Recovery system components must tolerate greater loads than expected during separation events in order to ensure system reliability during flight and reusability after landing (NASA Req. 2.4).

Table 96: NDRT Recovery Requirements (continued)

Req. ID	Description	Justification
R.2	All recovery shock cords and parachutes shall be thermally protected from black powder ejection charges.	Recovery shock cords and parachutes are flight critical components which must remain intact for safe vehicle descent. Shock cords and parachutes will be stowed adjacent to ejection wells before separation so are susceptible to thermal damage by active black powder charges without adequate protection.
R.3	All electronics components shall be rated to operate between 0F and 100F	Electronic components must be functional in all feasible launch environments. Acceptable launch day temperatures are approximated to be within the range 0F - 100F.
R.4	Flight batteries shall be sized for 3 hours of operation in all expected flight conditions.	Sizing batteries for 3 hours of operation provides a safety factor of 1.5 from the 2 hour standby requirement given by NASA requirement 2.7. This capability should be upheld in all possible flight conditions, since batteries lose capacity in extreme cold.
R.5	All epoxy joints which are located near black powder charge wells shall be constructed with high-temperature epoxy rated to the maximum expected temperature of black powder charge firing.	Each black powder charge will produce a local high-temperature environment. High-temperature rated epoxy is necessary, therefore, to ensure epoxy joints near separation events remain intact throughout the vehicle's flight and for all subsequent flights.

Table 96: NDRT Recovery Requirements (continued)

Req. ID	Description	Justification
R.6	All separation event modules shall have redundant and dissimilar altimeters	Separation events are required to release parachutes for reducing vehicle descent energy to a kinetic energy value below 75 ft-lb at landing (NASA Req. 3.3). Redundant and dissimilar altimeters are necessary to ensure each separation event module is a fail safe system, increasing confidence in a successful separation event.

Table 97: NDRT Payload Requirements

Req. ID	Description	Justification
LVIS.1	Critical LVIS electronic components shall have at minimum one redundancy.	Built-in redundancy both in electronic hardware and control flow creates a more reliable system that can retain full functionality with component failures.
LVIS.2	All structural LVIS components shall be designed to withstand the maximum loads of launch and landing with a factor of safety of 1.5. The calculated loads will be updated for CDR.	All structural LVIS components must maintain function by withstanding the maximum expected load by a factor of saftey of 1.5 to reduce the risk of components coming loose during flight
LVIS.3	LVIS shall be capable of successful launch and mission completion in temperatures between 0 and 100 degrees F.	Electronic components must be functional in all feasible launch environments. Acceptable launch day temperatures are approximated to be within the range 0F - 100F.

Table 97: NDRT Payload Requirements (continued)

Req. ID	Description	Justification
LVIS.4	LVIS flight batteries shall be sized for 3 hours of operation in all expected flight conditions.	Sizing batteries for 3 hours of operation provides a safety factor of 1.5 from the 2 hour standby requirement given by NASA requirement 2.7. This capability should be upheld in all possible flight conditions, since batteries lose capacity in extreme cold.
LVIS.5	The ground station power supply shall be capable of powering the system for a minimum of three hours.	The ground station should be capable of remaining operational for as long as the payload, with a maximum delay time of up to two hours, giving a safety factor of 1.5.
LVIS.6	Lvis shall have sensors capable of recording the launch vehicle acceleration due to main parachute deployment.	In order for the LVIS to accurately determine the final location of the launch vehicle, it must be capable of recording all main acceleration events. Main parachute deployment is the event with the largest instantaneous acceleration.

Table 98: NDRT Apogee Control System Requirements

Req. ID	Description	Justification
ACS.1	The ACS shall be capable of identifying the launch vehicle's current stage of flight.	Identifying the current stage of flight allows the ACS to determine when to deploy and retract its drag surfaces without compromising other phases of flight.
ACS.2	The ACS shall be capable of recording launch vehicle altitude, linear acceleration, and angular acceleration.	Collecting these measurements is the minimum necessary data-set to track vehicle position and orientation, which allows the system to calculate the projected apogee.

Table 98: NDRT Apogee Control System Requirements (continued)

Req. ID	Description	Justification
ACS.3	The ACS shall have redundant and dissimilar sensors.	Built-in redundancy both in electronic hardware and control flow creates a more reliable system that can retain full functionality with component failures.
ACS.4	The ACS shall be capable of reducing the launch vehicle's projected apogee from the maximum predicted apogee to the NDRT target apogee.	The ACS should be able to bring the launch vehicle projected apogee down to the NDRT target apogee in all NASA defined flight conditions with a margin of 100 feet. Therefore, the ACS capability must span the full range of expected apogees.
ACS.5	All electronics components shall be rated to operate between 0F and 100F.	Electronic components must be functional in all feasible launch environments. Acceptable launch day temperatures are approximated to be within the range 0F - 100F.
ACS.6	The ACS shall be secured to the launch vehicle with a connection capable of withstanding the full expected loads of flight with a factor of safety of 1.5. Calculated loads will be updated for CDR.	Ensures that the ACS stay secure inside the launch vehicle at launch

Table 98: NDRT Apogee Control System Requirements (continued)

Req. ID	Description	Justification
ACS.7	ACS flight batteries shall be sized for 3 hours of operation in all expected flight conditions, including continuous actuation of drag surfaces between motor burnout and apogee.	Sizing batteries for 3 hours of operation provides a safety factor of 1.5 from the 2 hour standby requirement given by NASA requirement 2.7. This capability should be upheld in all possible flight conditions, since batteries lose capacity in extreme cold. In addition, the system should be able to power the drag surfaces for the entire time between burnout and apogee to maximize system effectiveness.
ACS.9	The ACS motors shall have sufficient torque to actuate the drag surfaces at motor burnout with a factor of safety of 1.5.	Burnout is the point of highest velocity and is the point where fins experience the highest drag force. This ensures that motor is capable of operating in all stages of flight.
ACS.10	The ACS drag surfaces and all corresponding structural components shall be designed to withstand aerodynamic loads from full extension at motor burnout with a factor of safety of 1.5. The calculated load will be updated for CDR.	Burnout is the point of highest velocity and is the point where fins experience the highest drag force. This minimizes the risk of a structural failure in-flight.

9.2 STEM Engagement Plan

NDRT has seen a successful start to STEM Engagement events for the current school year. The team participated in five different events with local partner organizations prior to the acceptance of NDRT into this year's Student Launch. NDRT acknowledges that these events do not count toward the competition's STEM Engagement scoring. The decision was made to have STEM Engagement events prior to Proposal due to NDRT's desire to provide sustainable, recurring STEM Engagement experiences with local students and under-served organizations, a team priority. These prior events served around 80 students through weekly, direct outreach activities. NDRT members volunteered 34 hours excluding the planning of these events.

9.2.1 General Update

NDRT is excited to continue to facilitate Engagement events throughout the coming weeks. The team continues to follow current health guidelines from the University of Notre Dame and partner organizations. This includes requiring masks to be worn by volunteers and students at all events while indoors. Upcoming events will include both educational and outreach engagement experiences. NDRT will be hosting events with the Robinson Community Learning Center, local libraries, local Scout groups, and local high schools in partnership with the Society of Women Engineers at Notre Dame for the remainder of the fall semester.

9.3 Budget

NDRT's budget overview can be seen in Table 99. Rollover funds from 2020-2021 and the Boeing Company are the main sources are funding and support, as well as fundraising such as apparel sales and ND Day, a fundraising effort across University of Notre Dame's campus. NDRT intends to pair with additional sponsors and donors this year for technical support, funding, and mentorships.

Table 99: NDRT Budget Overview 2021-22

Category	Allocation	Spent	Margins
Launch Vehicle	$4,000.00	$327.66	8.19%
Recovery System	$1,000.00	$379.00	37.90%
Apogee Control System	$1,200.00	$329.53	27.46%
Launch Vehicle Identification System	$1,800.00	$93.03	5.17%
Vehicle Subtotal	***$8,000.00***	***$670.22***	***8.38%***
Safety	$300.00	$0.00	0.00%
STEM Outreach	$200.00	$39.30	19.65%
Travel	$10,500.00	$0.00	0.00%
Miscellaneous	$500.00	$0.00	0.00%
Total	**$19,500.00**	**$729.26**	**3.74%**
Total Available	$26,430.00	$26,430.00	
Remaining Funds	$6,930.00	$25,700.74	

The low amount spent as of PDR submission is due to the focus on subscale procurements ahead of CDR. All materials in the subscale vehicle have been sourced from trustworthy, reliable vendors, and have been ordered well in advance of deadlines or milestones. Tables 100 through 104 show the itemized budget for each squad that has purchased components thus far.

Table 100: Launch Vehicle Expenses

Item	Vendor	Qty	Cost/Item	Total Cost
RockSim Licenses	Apogee Rockets	4	$20.00	$80.00
G12 Fiberglass Airframe 3" ID, 60" Length	Madcow Rocketry	1	$100.00	$100.00
G12 Fiberglass Coupler 3" OD, 9" Length	Madcow Rocketry	1	$22.00	$22.00
G12 Fiberglass Coupler 3" OD, 6" Length	Madcow Rocketry	1	$15.00	$15.00
G12 Fiberglass Motor Tube 1.52" ID, 12" Length	Madcow Rocketry	1	$13.00	$13.00
Motor Retainer Assembly, 38mm - P	Madcow Rocketry	1	$25.00	$25.00
Fiberglass 3" Filament Wound Nose Cone, 4:1 Ogive	Madcow Rocketry	1	$59.95	$59.95
			Shipping and Tax	$12.71
			Total	$ 327.66

Table 101: Recovery Expenses

Item	Vendor	Qty	Cost/Item	Total Cost
GPS Tracker, Ground Station, and Battery	Featherweight	1	$352.00	$352.00
GPS Battery Charger	Featherweight	1	$17.00	$17.00
			Shipping and Tax	$10.00
			Total	$379.00

Table 102: LVIS Expenses

Item	Vendor	Qty	Cost/Item	Total Cost
DFRobot Gravity I2C	Mouser Electronics	3	$13.90	$41.70
HiLetgo MPU9250	Amazon	3	$15.99	$47.97
			Shipping and Tax	$3.36
			Total	$93.03

Table 103: ACS Expenses

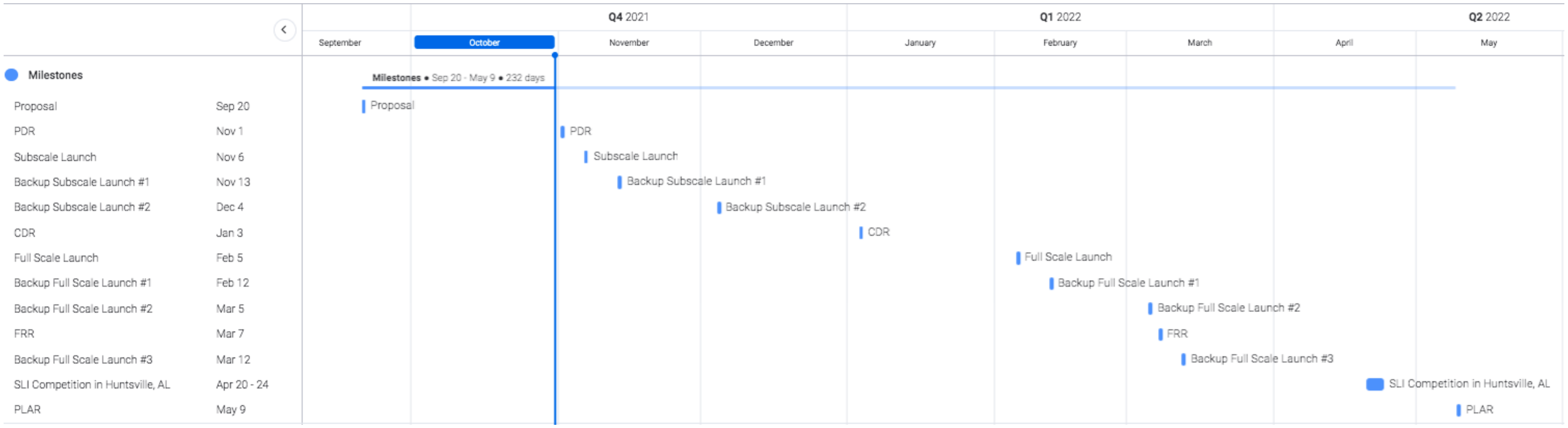
Item	Vendor	Qty	Cost/Item	Total Cost
ADAFRUIT BMP390	Digikey	2	$10.95	$21.90
Raspberry Pi Zero	Vilros	2	$7.50	$15.00
MPL3115A2 - I2C	Adafruit	2	$9.95	$19.90
ICM-20948 9-DoF	Adafruit	2	$14.95	$29.90
PowerBoost 500 Charger	Adafruit	2	$14.95	$29.90
Adafruit INA260 Voltage, Current, Power Sensor	Adafruit	2	$9.95	$19.90
PNY 32GB Elite Class 10 U1 MicroSDHC	Amazon	2	$17.99	$35.98
2 Channel DC 5V Relay Module	SunFounder	2	$6.99	$13.98
ADXL377 Accelerometer, 3 Axis Sensor	Digikey	2	$25.95	$51.90
ADXL 345	Sparkfun	2	$18.95	$37.90
			Shipping and Tax	$53.27
			Total	$329.53

Table 104: STEM Engagement Expenses

Item	Vendor	Qty	Cost/Item	Total Cost
350 Pack "Hello My Name is" Stickers	Amazon	1	$7.48	$7.48
Crayola Washable Markers	Amazon	4	$6.99	$27.96
			Shipping and Tax	$10.00
			Total	$379.00

9.4 Timeline

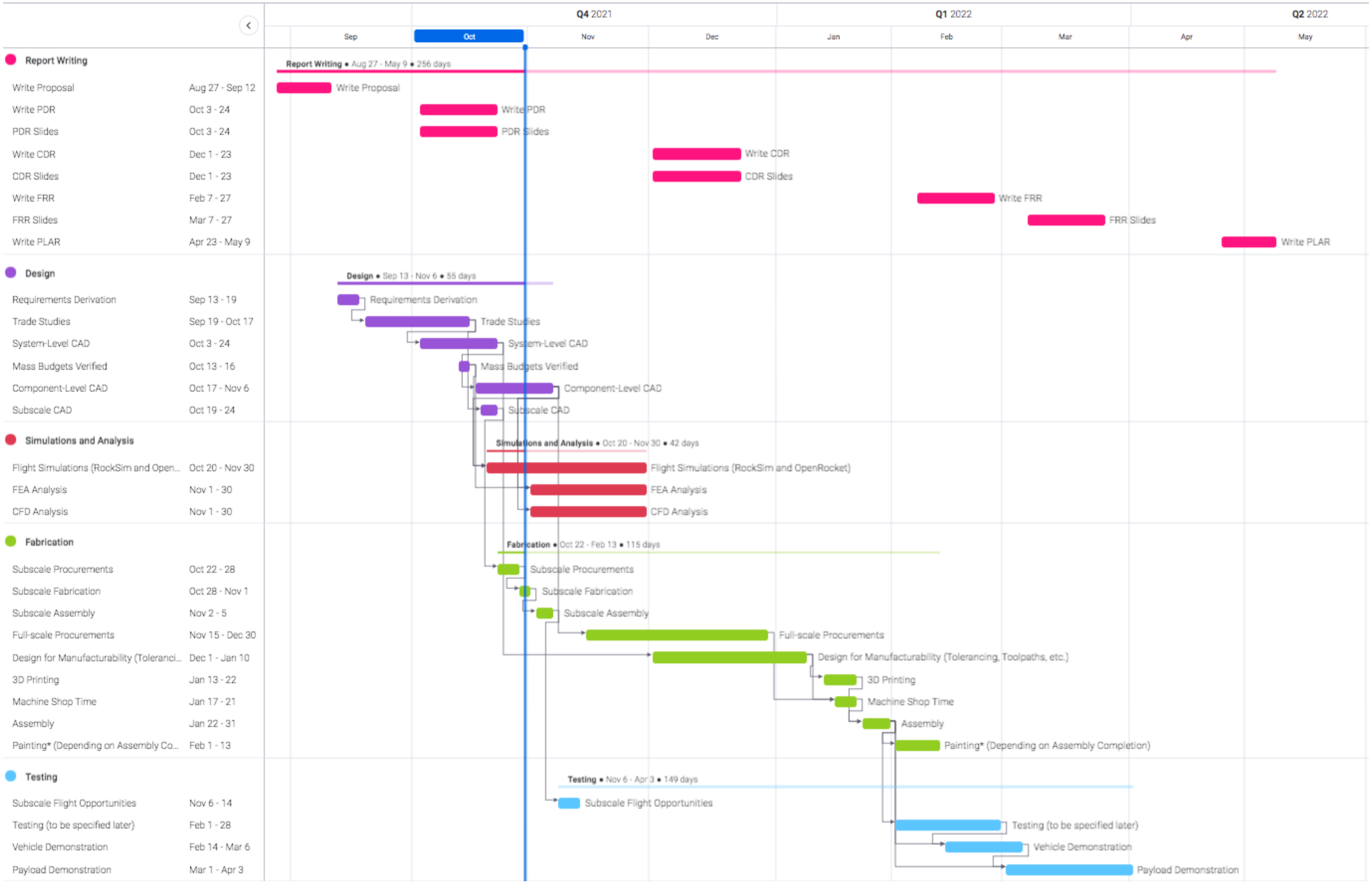
NDRT is on track to meet all milestones, and completed PDR within schedule allowances. Upcoming milestones include a subscale test flight in early November, with backups in mid-November and early-December to meet the subscale test flight requirement. Additionally, design appears to be on track to complete substantial prototyping prior to a winter break in December, prior to CDR. Figure 41 depicts the overall schedule of team milestones throughout the entire mission. Figures 42 through 46 display Gantt charts depicting progress and schedule outlooks for each squad of NDRT.



Milestones

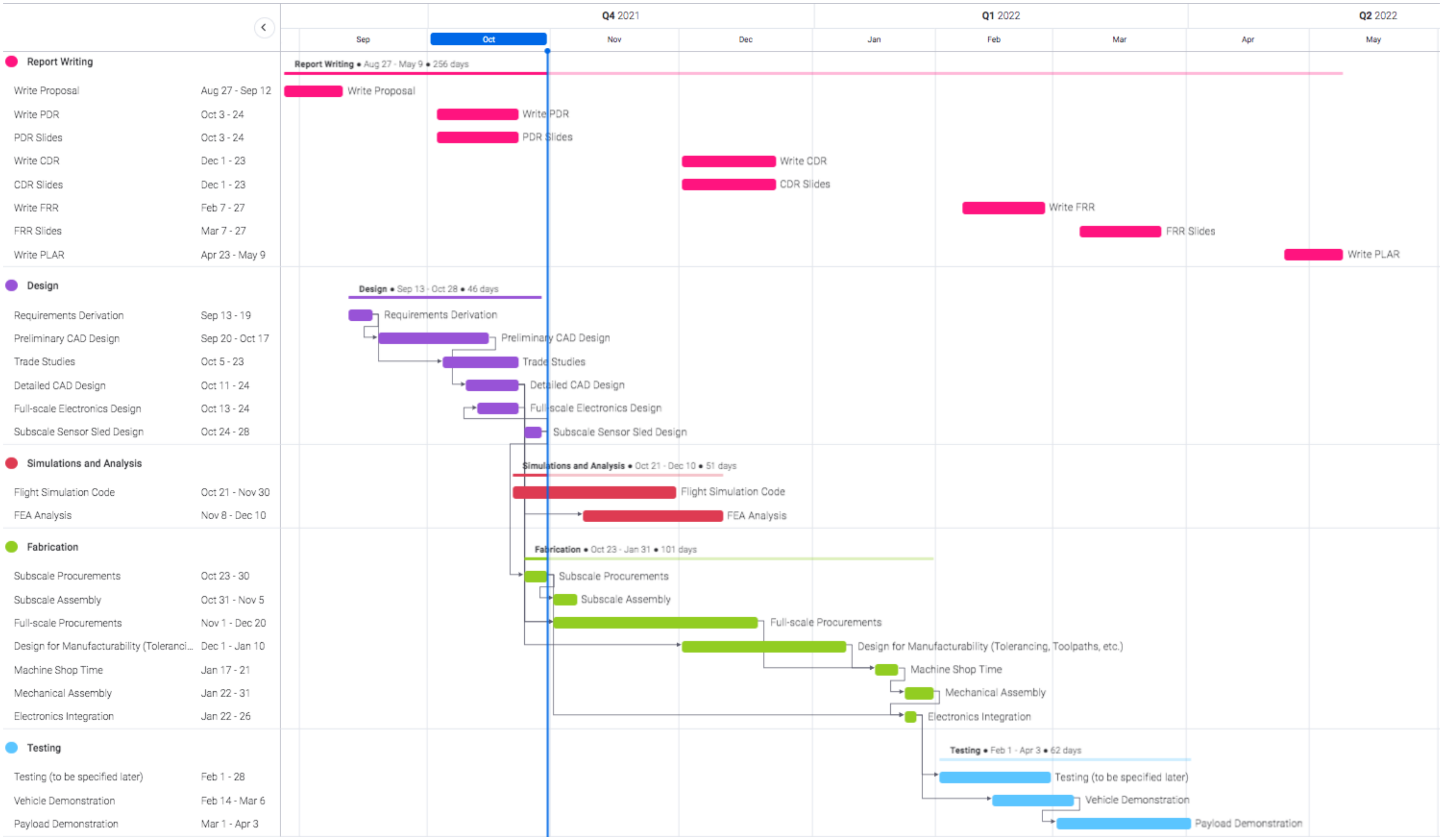
Proposal	Sep 20
PDR	Nov 1
Subscale Launch	Nov 6
Backup Subscale Launch #1	Nov 13
Backup Subscale Launch #2	Dec 4
CDR	Jan 3
Full Scale Launch	Feb 5
Backup Full Scale Launch #1	Feb 12
Backup Full Scale Launch #2	Mar 5
FRR	Mar 7
Backup Full Scale Launch #3	Mar 12
SLI Competition in Huntsville, AL	Apr 20 - 24
PLAR	May 9

Figure 41: Milestones Gantt Timeline 2021-22



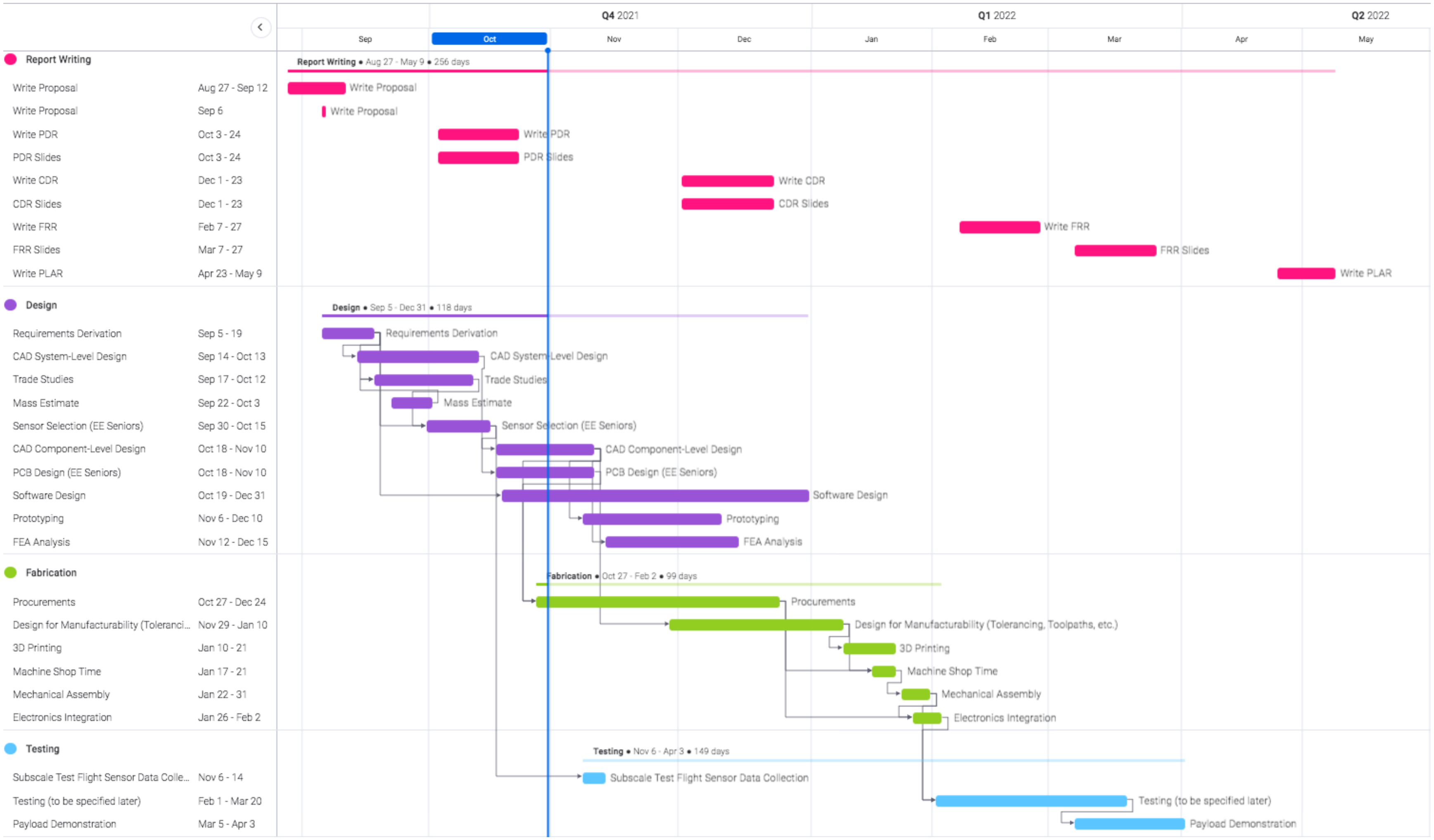
Report Writing	
Write Proposal	Aug 27 - Sep 12
Write PDR	Oct 3 - 24
PDR Slides	Oct 3 - 24
Write CDR	Dec 1 - 23
CDR Slides	Dec 1 - 23
Write FRR	Feb 7 - 27
FRR Slides	Mar 7 - 27
Write PLAR	Apr 23 - May 9
Design	
Requirements Derivation	Sep 13 - 19
Trade Studies	Sep 19 - Oct 17
System-Level CAD	Oct 3 - 24
Mass Budgets Verified	Oct 13 - 16
Component-Level CAD	Oct 17 - Nov 6
Subscale CAD	Oct 19 - 24
Simulations and Analysis	
Flight Simulations (RockSim and Open...	Oct 20 - Nov 30
FEA Analysis	Nov 1 - 30
CFD Analysis	Nov 1 - 30
Fabrication	
Subscale Procurements	Oct 22 - 28
Subscale Fabrication	Oct 28 - Nov 1
Subscale Assembly	Nov 2 - 5
Full-scale Procurements	Nov 15 - Dec 30
Design for Manufacturability (Toleranci...	Dec 1 - Jan 10
3D Printing	Jan 13 - 22
Machine Shop Time	Jan 17 - 21
Assembly	Jan 22 - 31
Painting* (Depending on Assembly Co...	Feb 1 - 13
Testing	
Subscale Flight Opportunities	Nov 6 - 14
Testing (to be specified later)	Feb 1 - 28
Vehicle Demonstration	Feb 14 - Mar 6
Payload Demonstration	Mar 1 - Apr 3

Figure 42: Launch Vehicle Gantt Timeline 2021-22



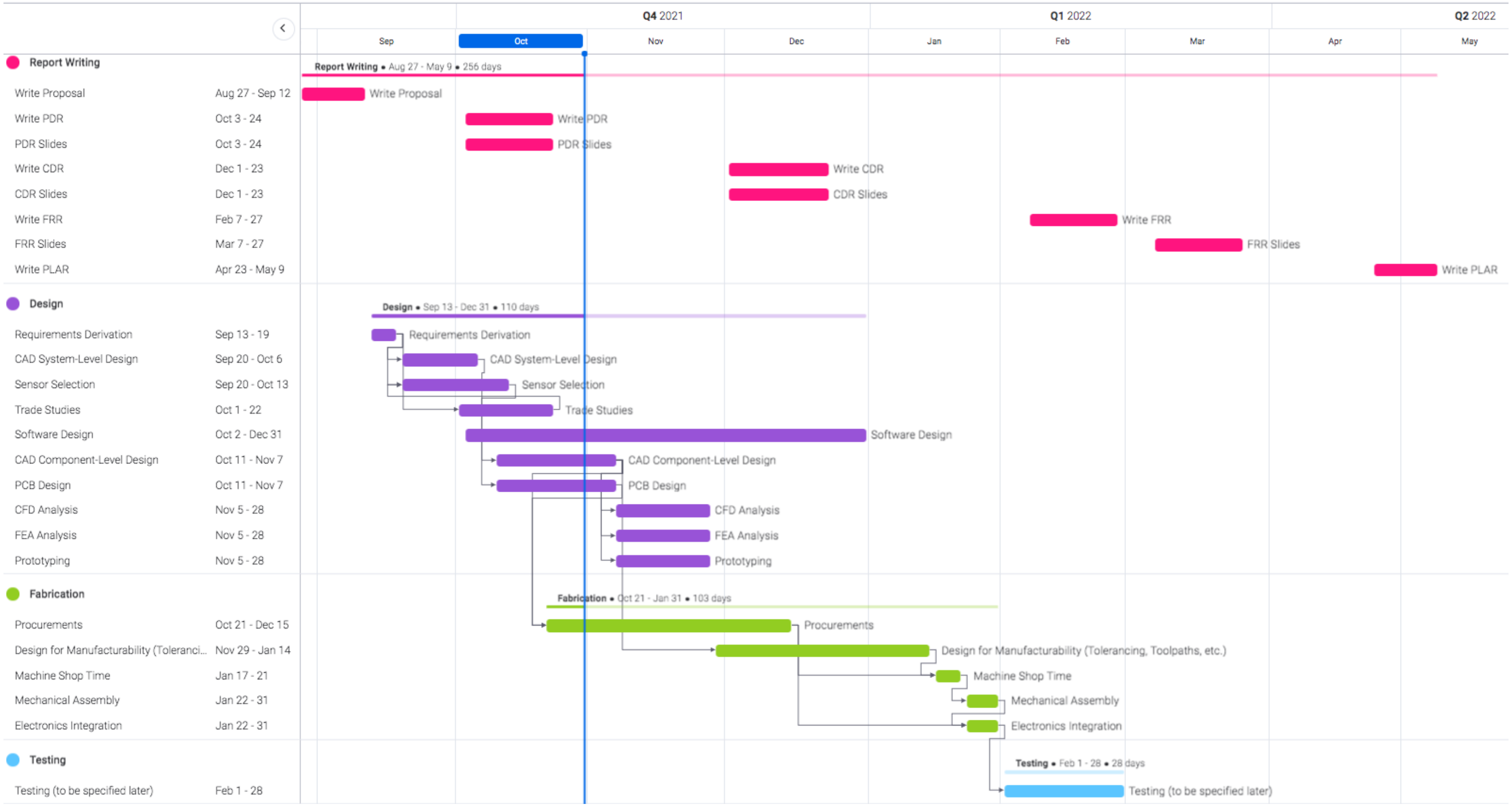
Report Writing	
Write Proposal	Aug 27 - Sep 12
Write PDR	Oct 3 - 24
PDR Slides	Oct 3 - 24
Write CDR	Dec 1 - 23
CDR Slides	Dec 1 - 23
Write FRR	Feb 7 - 27
FRR Slides	Mar 7 - 27
Write PLAR	Apr 23 - May 9
Design	
Requirements Derivation	Sep 13 - 19
Preliminary CAD Design	Sep 20 - Oct 17
Trade Studies	Oct 5 - 23
Detailed CAD Design	Oct 11 - 24
Full-scale Electronics Design	Oct 13 - 24
Subscale Sensor Sled Design	Oct 24 - 28
Simulations and Analysis	
Flight Simulation Code	Oct 21 - Nov 30
FEA Analysis	Nov 8 - Dec 10
Fabrication	
Subscale Procurements	Oct 23 - 30
Subscale Assembly	Oct 31 - Nov 5
Full-scale Procurements	Nov 1 - Dec 20
Design for Manufacturability (Toleranci...	Dec 1 - Jan 10
Machine Shop Time	Jan 17 - 21
Mechanical Assembly	Jan 22 - 31
Electronics Integration	Jan 22 - 26
Testing	
Testing (to be specified later)	Feb 1 - 28
Vehicle Demonstration	Feb 14 - Mar 6
Payload Demonstration	Mar 1 - Apr 3

Figure 43: Recovery Gantt Timeline 2021-22



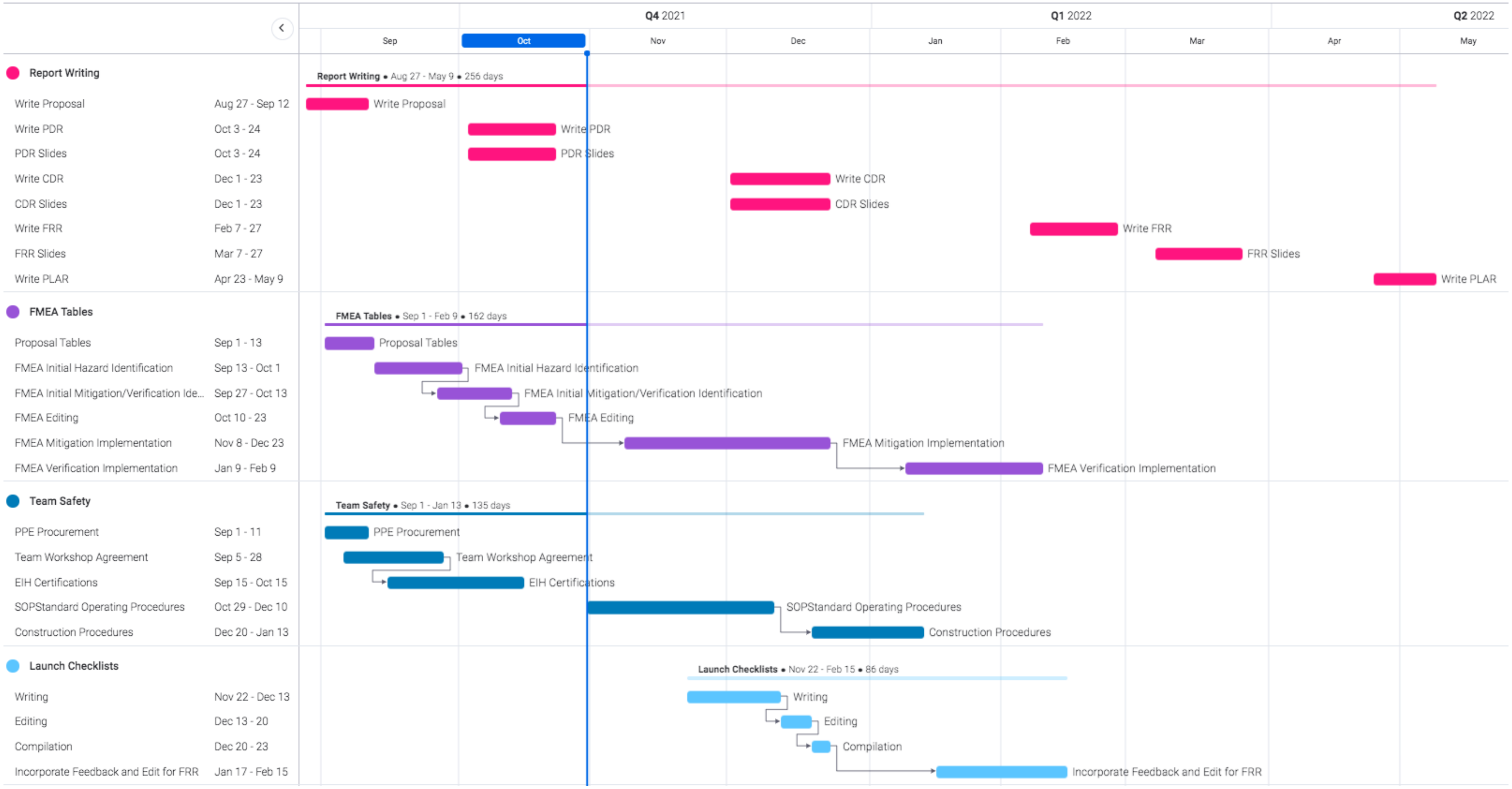
Report Writing	
Write Proposal	Aug 27 - Sep 12
Write Proposal	Sep 6
Write PDR	Oct 3 - 24
PDR Slides	Oct 3 - 24
Write CDR	Dec 1 - 23
CDR Slides	Dec 1 - 23
Write FRR	Feb 7 - 27
FRR Slides	Mar 7 - 27
Write PLAR	Apr 23 - May 9
Design	
Requirements Derivation	Sep 5 - 19
CAD System-Level Design	Sep 14 - Oct 13
Trade Studies	Sep 17 - Oct 12
Mass Estimate	Sep 22 - Oct 3
Sensor Selection (EE Seniors)	Sep 30 - Oct 15
CAD Component-Level Design	Oct 18 - Nov 10
PCB Design (EE Seniors)	Oct 18 - Nov 10
Software Design	Oct 19 - Dec 31
Prototyping	Nov 6 - Dec 10
FEA Analysis	Nov 12 - Dec 15
Fabrication	
Procurements	Oct 27 - Dec 24
Design for Manufacturability (Toleranci...	Nov 29 - Jan 10
3D Printing	Jan 10 - 21
Machine Shop Time	Jan 17 - 21
Mechanical Assembly	Jan 22 - 31
Electronics Integration	Jan 26 - Feb 2
Testing	
Subscale Test Flight Sensor Data Colle...	Nov 6 - 14
Testing (to be specified later)	Feb 1 - Mar 20
Payload Demonstration	Mar 5 - Apr 3

Figure 44: LVIS Gantt Timeline 2021-22



● **Report Writing**	
Write Proposal	Aug 27 - Sep 12
Write PDR	Oct 3 - 24
PDR Slides	Oct 3 - 24
Write CDR	Dec 1 - 23
CDR Slides	Dec 1 - 23
Write FRR	Feb 7 - 27
FRR Slides	Mar 7 - 27
Write PLAR	Apr 23 - May 9
● **Design**	
Requirements Derivation	Sep 13 - 19
CAD System-Level Design	Sep 20 - Oct 6
Sensor Selection	Sep 20 - Oct 13
Trade Studies	Oct 1 - 22
Software Design	Oct 2 - Dec 31
CAD Component-Level Design	Oct 11 - Nov 7
PCB Design	Oct 11 - Nov 7
CFD Analysis	Nov 5 - 28
FEA Analysis	Nov 5 - 28
Prototyping	Nov 5 - 28
● **Fabrication**	
Procurements	Oct 21 - Dec 15
Design for Manufacturability (Toleranci...	Nov 29 - Jan 14
Machine Shop Time	Jan 17 - 21
Mechanical Assembly	Jan 22 - 31
Electronics Integration	Jan 22 - 31
● **Testing**	
Testing (to be specified later)	Feb 1 - 28

Figure 45: ACS Gantt Timeline 2021-22



Report Writing	
Write Proposal	Aug 27 - Sep 12
Write PDR	Oct 3 - 24
PDR Slides	Oct 3 - 24
Write CDR	Dec 1 - 23
CDR Slides	Dec 1 - 23
Write FRR	Feb 7 - 27
FRR Slides	Mar 7 - 27
Write PLAR	Apr 23 - May 9
FMEA Tables	
Proposal Tables	Sep 1 - 13
FMEA Initial Hazard Identification	Sep 13 - Oct 1
FMEA Initial Mitigation/Verification Ide...	Sep 27 - Oct 13
FMEA Editing	Oct 10 - 23
FMEA Mitigation Implementation	Nov 8 - Dec 23
FMEA Verification Implementation	Jan 9 - Feb 9
Team Safety	
PPE Procurement	Sep 1 - 11
Team Workshop Agreement	Sep 5 - 28
EIH Certifications	Sep 15 - Oct 15
SOPStandard Operating Procedures	Oct 29 - Dec 10
Construction Procedures	Dec 20 - Jan 13
Launch Checklists	
Writing	Nov 22 - Dec 13
Editing	Dec 13 - 20
Compilation	Dec 20 - 23
Incorporate Feedback and Edit for FRR	Jan 17 - Feb 15

Figure 46: Safety Gantt Timeline 2021-22

A Team 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 the NDRT Google Folder.

______I agree to comply with all updated policies and statements 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 also understand that tool and machine training and certifications from previous years are no longer accepted and I must become recertified for the 2021-2022 season.

______I understand that I must receive a tool and machine certification card upon completion of the certification process in order to use the equipment. I also understand that the certification card must be in my possession at all times when using such equipment.

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

______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 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 such as the Innovation Hub. 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: ____________________