University of Notre Dame

2021-2022

Notre Dame Rocketry Team
Flight Readiness Review

NASA Student Launch 2022

Launch Vehicle Identification System and Apogee Control System

Submitted March 6, 2022

365 Fitzpatrick Hall of Engineering
Notre Dame, IN 46556

Contents

Table 1: Commonly-Used Acronyms

Acronym	Meaning
ABS	Acrylonitrile Butadiene Styrene
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
EE	Electrical Engineering
EMF	Electromotive Force
FEA	Finite Element Analysis
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
PML	Public Missles Limited
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

1 Team Summary

Team Information: Notre Dame Rocketry Team (NDRT)
University of Notre Dame
365 Fitzpatrick Hall of Engineering
Notre Dame, IN 46556
Mentor: Dave Brunsting, NAR # 85879 (Level 3), TRA # 12369 (Level 3)
e: dacsmema@gmail.com, p: (269) 838-4275
NAR/TRA Section: TRA #12340, Michiana Rocketry
Team Hours Logged: 1579 (NASA 1.14)
Final Launch Location: Huntsville, AL on April 23, 2022
Backup Final Launch: Three Oaks, MI on April 9, 2022 (Michiana Rocketry, TRA #12340)
Jerry Vida (NAR/TRA Level 3), President
e: jerry.vida@gmail.com
STEM Engagement: 19 Events, 470 Participants Reached (318 Direct Educational) (NASA 1.5)
Activities: Parachute Design: Create a parachute in an iterative design challenge
Paper Helicopter: Create a paper helicopter and learn about the forces acting on it
Mars and Rovers: Learn about Mars, solve a rover puzzle, and create a paper helicopter
Marshmallow Towers: Learn about structures by creating towers with various objects
Exhibition: Learn about rocketry and space exploration by meeting NDRT members
Legos: Build Legos with NDRT members
Artemis Explorer: Learn about the Artemis missions and complete a play and learn activity
Coding: Complete a coding tutorial from coding.org
Paper Straw Rockets: Build, launch, and decorate a paper rocket attached to a straw

1.1 Launch Vehicle Summary

A brief summary of the launch vehicle design is provided in Table 2. An overview of the masses and lengths of each section is provided in Table 3. The vehicle is recovered using a dual deploy parachute recovery configuration. The Primary Recovery Module (PRM) controls drogue parachute separation at apogee and main parachute separation at 576 ft. The drogue parachute is a 2 ft diameter, 1.6 C_d Rocketman elliptical parachute and the main parachute is a 12 ft diameter, 0.97 C_d Rocketman parabolic parachute. Both are connected to a 30 ft braided kevlar shock cord. A 2 ft, 1.6 C_d FruityChutes elliptical pilot parachute assists in main deployment. The Secondary Recovery Module (SRM) controls fin can separation at 800 ft to decrease section kinetic energy at landing. No parachute is deployed by the SRM.

Table 2: Launch Vehicle Summary

Feature	Value
Target altitude (ft)	4800
Selected Motor	Aerotech L2200G-P
Length (in.)	134
Outer diameter (in.)	6.17
Total Mass (oz)	823.0
Rail Size	12-foot 1515

Table 3: Recovery Summary

Section	Mass (oz)	Length (in)
Nose Cone + Payload Bay	141.0	36
Recovery Bay	97.7	34
ACS Bay	167.4	29
Fin Can Bay	216.6	34.5

1.2 Payload Summary

The Launch Vehicle Identification System (LVIS) will use an inertial navigation system (INS) during 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. Additionally, the Apogee Control System (ACS) is a non-scoring payload designed to extend drag flaps to reduce apogee to the target of 4800 ft.

2 Changes Made Since CDR

A summary of all changes made to the launch vehicle criteria, payload criteria, and project plan criteria is provided in Table 4.

Table 4: Summary of changes made since CDR

Section	Change	Justification
Changes Made to Vehicle Criteria		
Airframe Sections 3.3.2	Couplers lengthened from 9 inches to 11.75 inches	Increase epoxy surface area on fixed side of separation point.
Changes Made to Recovery Subsystem		
Main Parachute Assembly 4.4.1	Sewed tubular nylon around the braided kevlar harnesses where they interface with the body tube.	Prevents fraying from rubbing against the body tube.
Main Structural Elements 4.5.1	Steel brackets epoxied to corners of U-bolts.	Guides the main recovery quicklinks back to center.
Changes Made to Payload Criteria		
Post-Flight Software Design Features 6.5.1.2	Post-flight sensor fusion algorithm changed to Extended Kalman Filter.	Increase in resources available for the filter.
Power Distribution and Transmission Board 6.4.2	1S2P battery switched to a 2S1P battery. Boost converter to power 5V rail switched to buck converter	More adequate power distribution.
Apogee Control System Mechanism 7.2	Lead screw resized, central nut redesigned	Ensured minimum factor of safety of the leadscrew of 2.0
Apogee Control System Mechanism 7.2	Length of pusher arm reduced from 6.25 inches to 5.25 inches	Increased mechanism speed
Apogee Control System Pressure Iso 7.2	Pressure isolation component removed	Not necessary based on vehicle demonstration flight data
Changes Made to Project Plan		
Vehicle Demonstration Flight 8.1	A Vehicle Demonstration Re-Flight will be required, which will occur on the same flight as the Payload Demonstration Flight	A successful VDF is required for competition launch in April.
Budget 10.3	The LVIS budget has been decreased, while the vehicle, recovery, and ACS budgets have increased.	Mechanical complexity of the LVIS has decreased. Supply chain issues increased cost for the other systems.

2.1 CDR Action Items

The following points were given as CDR action items:

- CDR report late due to updated gridded map needed,
- Professionalism score is due to 7 minutes late and running over time on presentation,
- Math equations need to have numbers.

This feedback has been passed onto the team for implementation in this and future reports and presentations.

3 Launch Vehicle Design

3.1 Mission Statement and Success Criteria

The overall mission of the launch vehicle is to safely and reliably facilitate the mission goals of each payload. The vehicle design is driven by NASA-specified requirements and 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 ft and 6,000 ft (NASA 2.1) with a maximum motor impulse of 5,120 N-s (NASA 2.12), and to reach a minimum velocity of 52 ft/s (NASA 2.17) with a static stability margin of at least 2.0 at launch rail exit.

The team-derived requirements that drive the vehicle design are in regards to the scoring payload, the LVIS, and the nonscoring payload, the ACS. The LVIS requires that the vehicle performs close to nominally and is not overly-sensitive to wind gusts such that the vehicle drifts too far from the launch site. The ACS 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. All vehicle components must be designed such that they can withstand loads sustained during motor burn, recovery events, and landing. The vehicle is designed specifically for this competition cycle (NASA 2.19.1.2).

A successful mission for the launch vehicle system includes meeting the following 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

3.1.1 Separation Points and Energetics

The three separation points on the launch vehicle are at the interface points of the payload and recovery bays, the recovery bay and the ACS bay, and the ACS bay and the fin can. Accordingly, the recovery design includes black powder charges placed in the vehicle at each separation point to induce the pressure necessary for separation. An OpenRocket diagram illustrating the separation points and black powder locations is featured in Figure 1, and the distances of these from the tip of the nosecone are shown in Table 5.

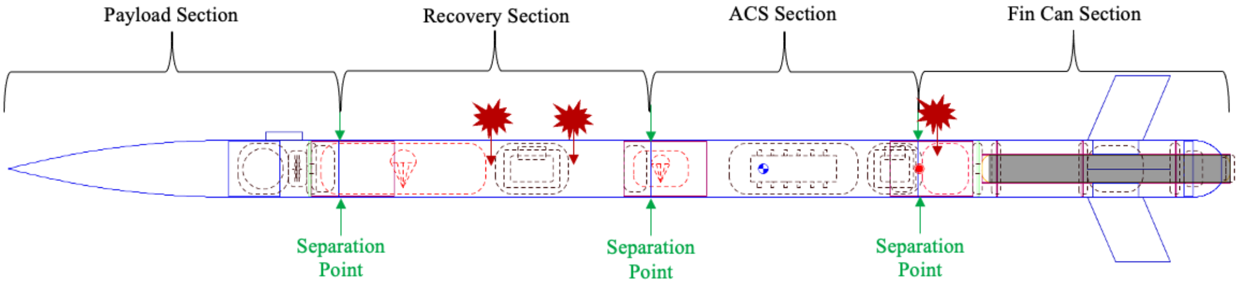


Figure 1: OpenRocket diagram with separation points and black powder charges

Table 5: Distances of Separation Points and Black Powder Locations from Nosecone Tip

Separating Components	Separation Point Location (in.)	Black Powder Location (in.)
Payload Bay & Recovery Bay	36	53
Recovery Bay & ACS Bay	70	61
ACS Bay & Fin Can	99	99

3.2 Launch Vehicle Design Overview

The CAD model and as-built photo of the final full scale launch vehicle can be seen in Figures 2 and 3.

Figure 2: Final Launch Vehicle CAD Model

Figure 3: Final Launch Vehicle As-Built

A summary of the contents and materials of each of the four vehicle sections is included in Table 6.

Table 6: Breakdown of launch vehicle components with materials and internal systems

Section	Material	Contains
Payload Section	G12 Fiberglass	Nosecone, LVIS, Bulkhead, Eye Bolt, Coupler, Camera
Recovery Section	Carbon Fiber	PRM, Main Parachute, Drogue Parachute, Coupler
ACS Section	Carbon Fiber	ACS, SRM, Coupler
Fin Can Section	Carbon Fiber	Bulkhead, Eye Bolt, Centering Rings, Motor Mount Tube, Tail Cone, Motor Retainer

3.3 Component Design

The following section outlines the final component design selections and specifications for the full scale launch vehicle.

3.3.1 Nosecone and Payload Section

The nosecone section consists of two subsections: the nosecone itself and the payload body tube. The nosecone for this launch vehicle is a FNC-6.0 Fiberglass nosecone purchased from Public Missiles LTD. The tangential ogive shape of the nosecone allows the launch vehicle a low-drag leading edge. The outer shoulder diameter of 6 in. matches the inner diameter of the payload bay. The nosecone shoulder is not an in-flight separation point. It is screwed into the fore end of the payload bay after integration. The specifications of the nosecone are outlined in Table 7, and the nosecone is shown in Figure 4. A dimensioned drawing of the nosecone can be seen in Figure 5.

Table 7: Nosecone Characteristics

Feature	Value
Exposed Length (in.)	24.00
Shoulder Length (in.)	5.50
Shape parameter (in.)	4:1 Ogive
Weight (oz)	4:1 Ogive
Material	Fiberglass
Total	34.0

Figure 4: Image of purchased nosecone

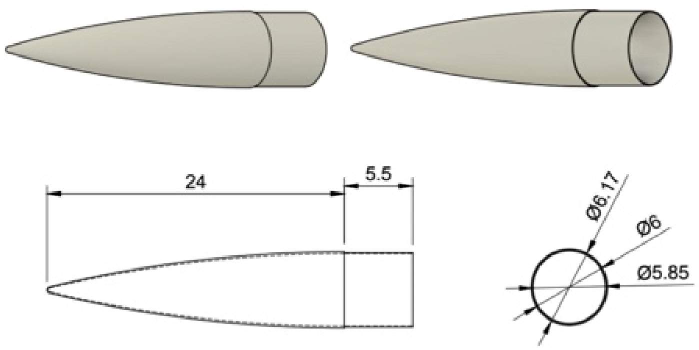


Figure 5: CAD drawing of nosecone

The payload tube, located at the fore end of the vehicle aft of the nosecone, contains the LVIS. The camera shroud is also epoxied to the outside of the tube. G12 Fiberglass was used for the payload bay due to its RF transparency, high yield strength, and high durability. The coupler was epoxied to the aft end of the payload bay to insert this section into the recovery bay. The payload bay specifications are shown in Table 8. The payload bay is shown in Figure 7 and a dimensioned drawing can be seen in Figure 6.

Table 8: Payload Bay Specifications

Parameter	Value
Length (in.)	12
Inner Diameter (in.)	6.00
Outer Diameter (in.)	6.17
Weight (oz)	25.7
Material	G12 Fiberglass
Coupler Length (in.)	12
Coupler Inner Diameter (in.)	5.8
Coupler Outer Diameter (in.)	5.998
Coupler Weight (oz)	25.3
Coupler Material	G12 Fiberglass

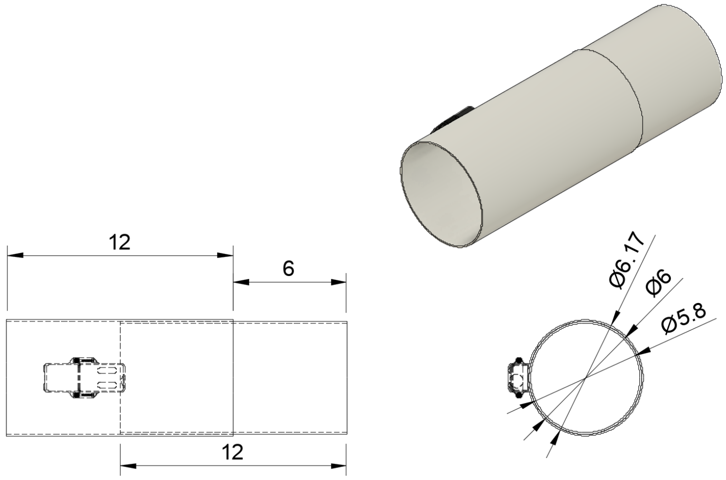


Figure 6: CAD drawing of payload bay

Figure 7: Image of payload bay

3.3.2 Airframe Sections

There are three independent sections of tubing following the payload bay that make up the main airframe: the recovery bay, the ACS bay, and the fin can. These three tubes are made of carbon fiber due to its high yield strength, low weight, and high durability and were purchased from LOC/PML.

The recovery bay holds the main recovery subsystem including the PRM, the main parachute, and the drogue parachute. It is located aft of the payload bay and fore of the ACS bay. The payload coupler is able to slide into the fore end of the recovery bay. The recovery coupler, with a length of 11.75 in., is epoxied 6 in. into the aft end of recovery bay in the aft end for insertion into the ACS bay. The recovery bay specifications are outlined in Table 9.

The engineering drawing and the recovery bay are shown in Figures 8 and 9 respectively.

Table 9: Recovery Bay Specifications

Parameter	Value
Length (in.)	34
Inner Diameter (in.)	6.00
Outer Diameter (in.)	6.17
Weight (oz)	42.1
Material	Carbon Fiber
Coupler Length (in.)	11.75
Coupler Inner Diameter (in.)	5.8
Coupler Outer Diameter (in.)	5.998
Coupler Weight (oz)	9.1
Coupler Material	Carbon Fiber

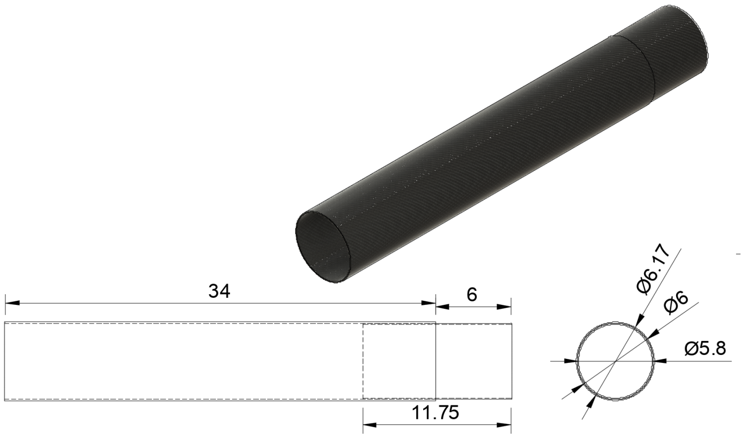


Figure 8: CAD drawing of recovery bay

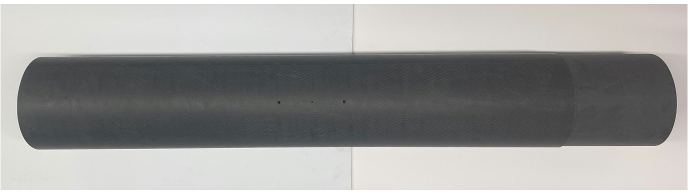


Figure 9: Image of the recovery bay

The ACS bay, located directly aft of the recovery bay, houses the ACS and the SRM in a configuration that can interface with and separate from the recovery tube and fin can. This bay transfers the drag loads from the ACS to the rest of the vehicle. ACS flap slots are machined in the side of the tube with in-house machinery. The ACS coupler is epoxied 6 in. into the ACS tube, leaving 6 in. to interface with the fin can. The ACS bay specifications are outlined in Table 10. The engineering drawings and the recovery bay are shown in Figures 10 and 11 respectively.

Table 10: ACS Bay Specifications

Parameter	Value
Length (in.)	29
Inner Diameter (in.)	6.00
Outer Diameter (in.)	6.17
Weight (oz)	33.1
Material	Carbon Fiber
Coupler Length (in.)	11.75
Coupler Inner Diameter (in.)	5.8
Coupler Outer Diameter (in.)	5.998
Coupler Weight (oz)	9.1
Coupler Material	Carbon Fiber

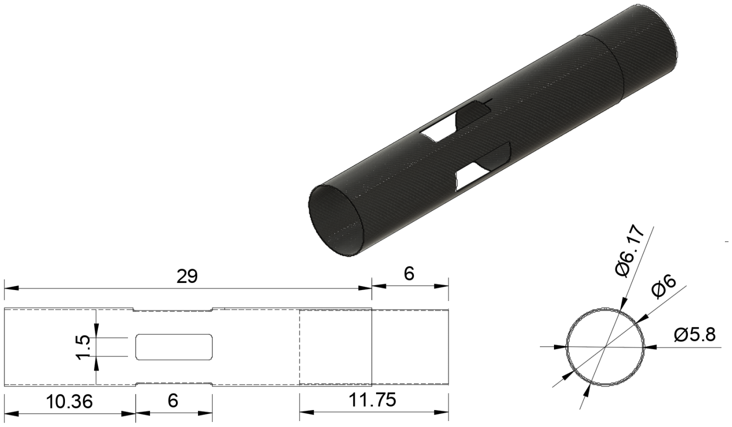


Figure 10: CAD drawing of ACS bay

Figure 11: Image of ACS bay

The fin can, the aft-most airframe tube, is constructed from several components and assembled using epoxy. The motor retention assembly is attached to the interior of the fin can with centering rings. The fin can is secured to the ACS tube with the ACS coupler during launch, and an eyebolt connected to a bulkhead near the fore end of the fin can is used to tether the tubes after separation. Also attached to the fin can are the rail buttons, tail cone, and fins secured into fin slots machined in the body tube. The fin can specifications are outlined in Table 11. The engineering drawings and complete fin can are shown in Figures 12 and 13 respectively.

Table 11: Fin Can Specifications

Parameter	Value
Length (in.)	30
Inner Diameter (in.)	6.00
Outer Diameter (in.)	6.17
Weight (oz)	38.2
Material	Carbon Fiber

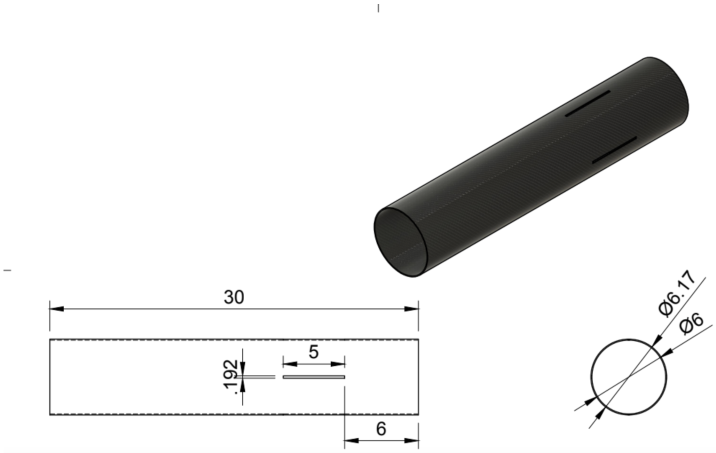


Figure 12: CAD drawing of fin can

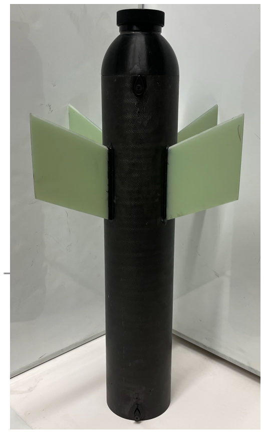


Figure 13: Complete constructed fin can

3.3.3 Tail Cone

The tail cone is used to create a smooth transition from the airframe to the motor mount tube to lessen the size of the low-pressure wake created by flow separation. The tail cone on the vehicle has an outer diameter made to fit the 6.17 in. diameter of the fin can. The inner diameter is 3.112 in. and allows the motor mount tube to fit inside. The 3 in. transition length allows the tail cone to not interfere significantly with the centering ring and fin assembly of the motor retention system. The characteristics of the tail cone are shown in Table 12 and Figure 14 shows the CAD drawing and images of the tail cone.

Table 12: Tail Cone Characteristics

Characteristic	Value
Length (in.)	3
Fore Diameter (in.)	6.17
Aft Diameter (in.)	3.00
Weight (oz)	6.3
Shape	Ogive
Material	3D-printed ABS

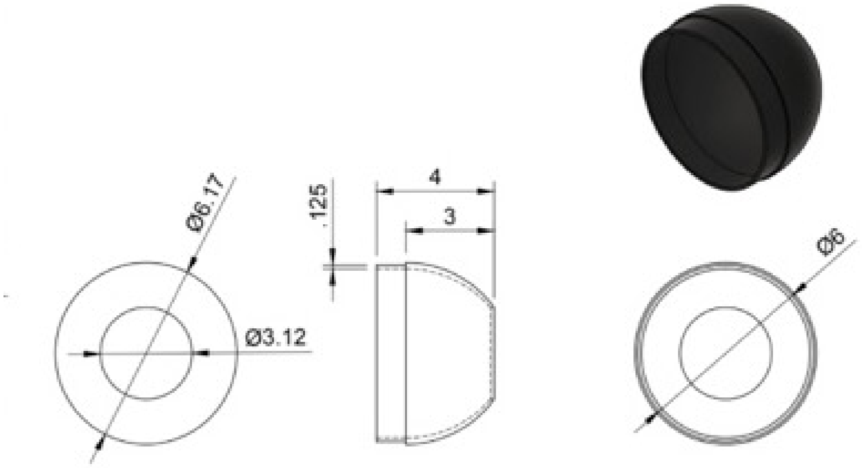


Figure 14: CAD drawing of 3D printed tail cone

3.3.4 Motor Retention Assembly

The motor retention assembly consists of the motor mount tube, three centering rings, and the motor retainer (NASA 2.23.5). A drawing of this assembly can be seen in Figure 15. The motor retention assembly directs the thrust force of the motor into the body of the launch vehicle, while also keeping the thrust force vector directed through the center of mass. Additionally, it secures the motor to the fin can after burnout. The motor mount tube was purchased from LOC/PML, and is constructed from carbon fiber due to its heat tolerance and high yield strength. The motor retainer was manufactured by AeroPack. Both the motor mount tube and the motor retainer were designed for 75 mm motors such as the AeroTech L2200G. J-B Weld was used in all joints with the motor mount tube due to its high heat tolerance (NDRT LV.5. The masses of each component can be seen in Table 13.

Table 13: Motor Retention Assembly Masses

Component	Mass (oz)
Motor Mount Tube	11.7
Centering Rings (3)	13.8
Motor Retainer	3.2
Motor Retention Epoxy	5.3
Total	34.0

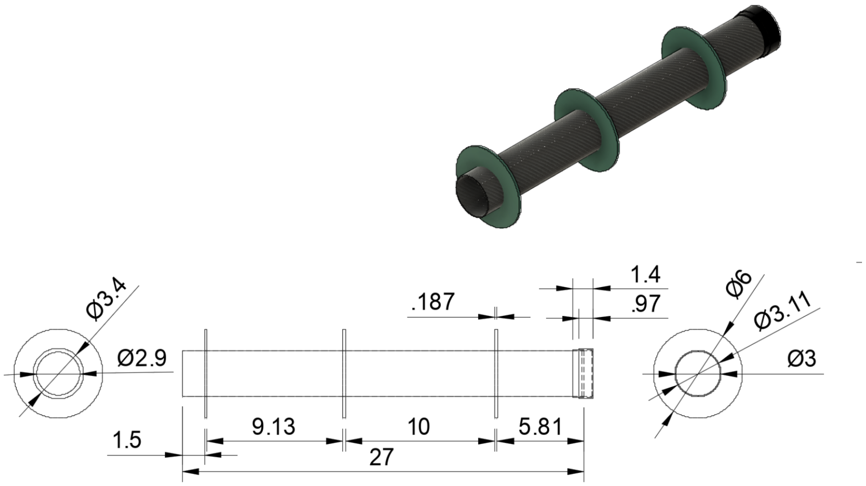


Figure 15: Motor mount assembly drawing

3.3.5 Fins

Fins are crucial to the stability of the launch vehicle, specifically by controlling the center of pressure of the launch vehicle through their shape and size. The swept rectangular shape can be seen in Figure 16. The fins were constructed from G10 Fiberglass due to its durability and low weight. The fins were given an airfoil cross sectional shape in order to minimize drag, as seen in Figure 17. The overall design of the fins can be seen in Figure 18.The characteristics of the as-built fins are shown in Table 14.

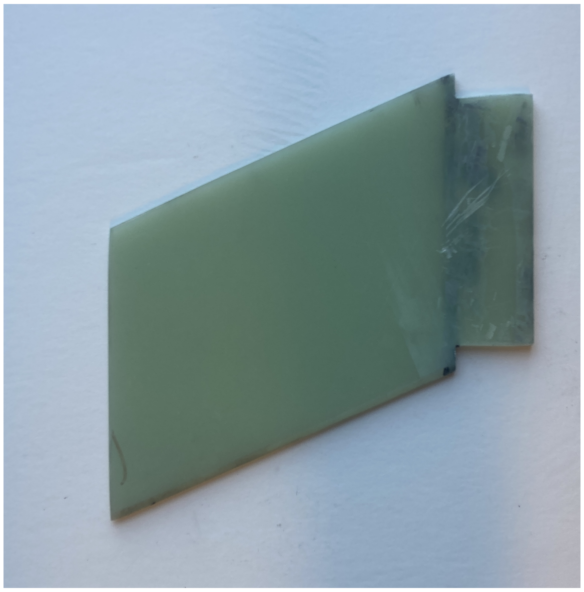


Figure 16: Side view of fin

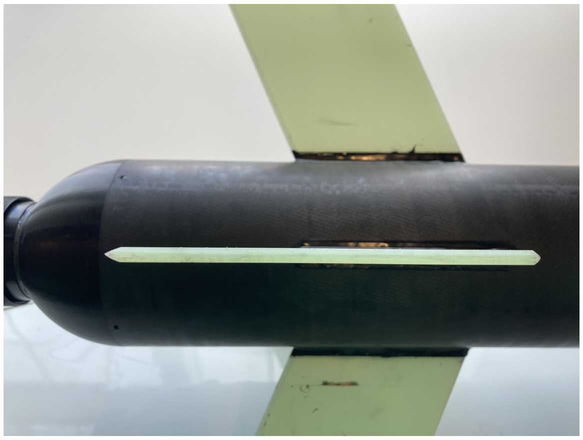


Figure 17: Cross section of fin

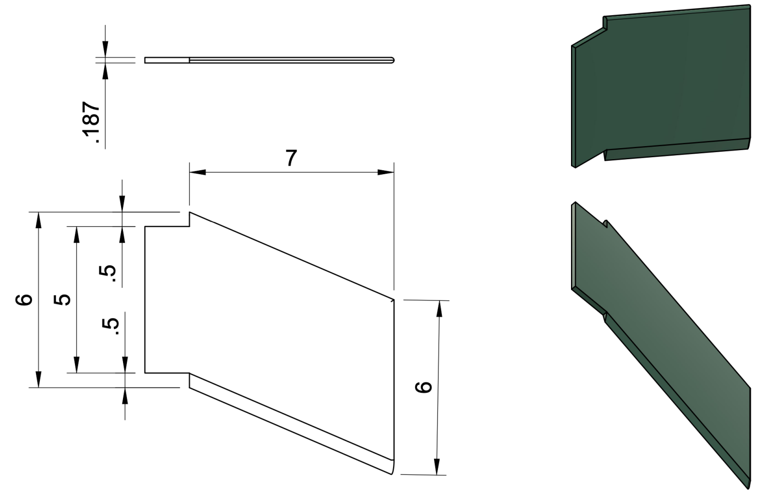


Figure 18: Dimensioned CAD drawing of fin

Table 14: Characteristics of As-Built Fins

Characteristic	Value
Number of fins	4
Cross-section	Airfoil
Material	G10 Fiberglass
Measured Total Weight (oz)	42.8

3.3.6 Bulkheads

Bulkheads provide structure and serve as a recovery harness connection points able to withstand the forces experienced during deployment of the main parachute. The bulkheads were constructed from G10 fiberglass due to its high yield strength and relatively low weight. The diameter of each plate is 6 in. and the thickness is 0.187 in. Each bulkhead has a 0.375 in. hole in the middle in order to fit an eyebolt. The overall design of the bulkheads can be seen in Figure 19. The first bulkhead is mounted at the aft end of the payload bay, as seen in Figure 20, and the second bulkhead is located on the fore side of the fin can, as seen in Figure 21.

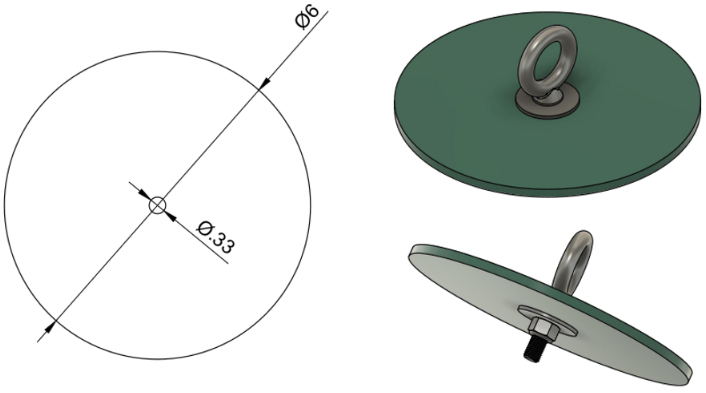


Figure 19: Dimensioned bulkhead CAD drawing

Figure 20: Payload bay bulkhead

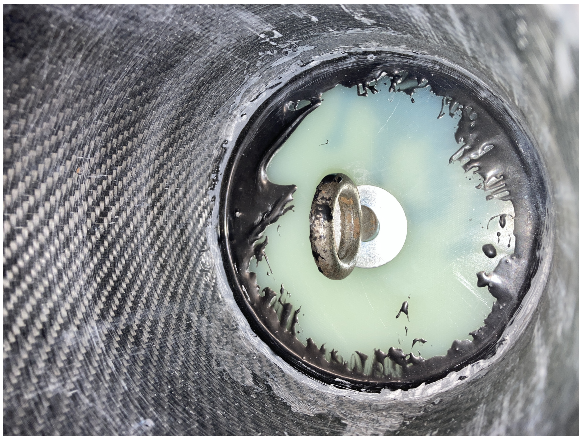


Figure 21: Fin can bulkhead

3.3.7 Camera Shroud

The camera shroud secures the camera to the body tube and also creates an aerodynamic shape, resulting in minimal drag. The shroud is angled away from the body tube by 3 degrees, which will allow for a greater field of view for the camera. The Mobius 2 Action Cam is the camera that will be used. The design of the shroud allows for a large surface area to secure the shroud to the body tube. A dimensioned drawing of the camera shroud design can be seen in Figure 22. Additionally, the controls for the camera are accessible while the camera is installed in the shroud. Threaded inserts were used on the cover for easy removal of the camera. The complete camera shroud assembly can be seen in Figure 23.

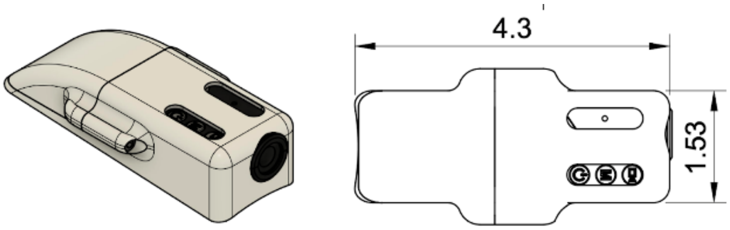


Figure 22: Dimensioned CAD drawing of camera shroud

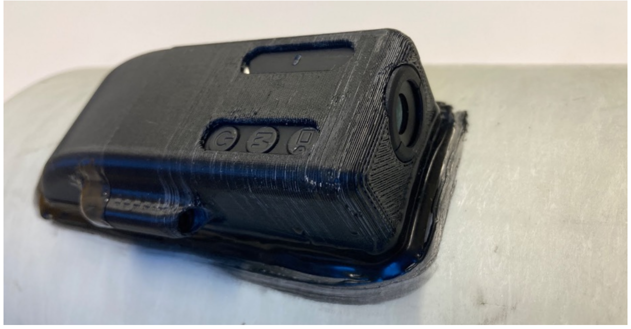


Figure 23: Camera shroud assembly

3.4 Construction

The following section outlines the use of multiple tools and methods in the construction of the launch vehicle.

3.4.1 Bandsaw and Belt Sander

The belt sander, pictured in Figure 24, was used to sand the payload bay coupler and four fins. A rounded edge was sanded on the fore and outer edges of the fins, while a sharp edge was sanded on the aft side. The belt sander was used on the payload bay coupler to more efficiently sand the tough fiberglass to fit into the recovery tube. The bandsaw, pictured in Figure 25, was used to cut the airframe tubes to the correct sizes. These tubes include the ACS tube (29 in.), the fin can (30 in.), and the recovery tube (34 in.). These tubes were purchased as 60 in. pieces, rough cut with a hacksaw, and then clean cut with the bandsaw to their respective sizes.

Figure 24: Image of belt sander

Figure 25: Image of bandsaw

3.4.2 CNC Waterjet

A CNC waterjet is a computer-controlled machine that uses a concentrated high-pressure stream of water and particulate to cut through materials such as fiberglass. To cut the material into specific shapes, the waterjet accepts a pre-programmed tool path and then cuts the material with high precision. The waterjet was used to cut the fins, centering rings, and the bulkheads. Figure 26 shows the waterjet, and Figure 27 is an image of the water jet cutting the bulkheads and centering rings.

Figure 26: Image of waterjet

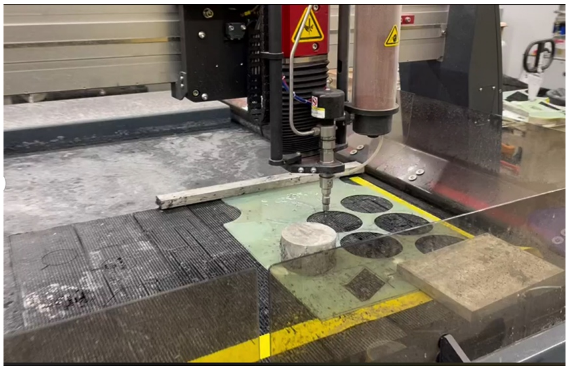


Figure 27: Image of waterjet cutting bulkheads and centering rings

3.4.3 CNC Mill

A CNC mill is a computer-controlled vertical milling machine which can accurately and repeatedly make cuts based on a pre-programmed tool path. The CNC mill was used to cut slots in the body tubes for the ACS flaps and for the fins. Jigs, shown in Figure 28, were 3D printed in order to index and secure the body tubes while they were machined. The body tube secured in the jigs can be seen in Figure 29, and the body tube being machined in the CNC mill can be seen in Figure 30 and Figure 31. Holes were drilled in the body tubes to align them with heat-set threaded inserts in the jigs.

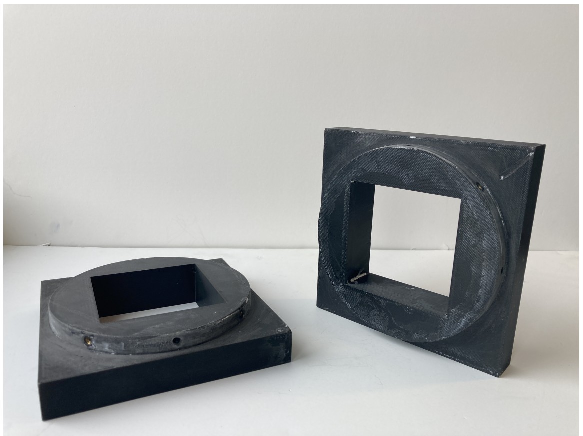


Figure 28: Airframe CNC mounting jigs


Figure 29: Body tube in CNC mounting jigs

Figure 30: Body tube mounted in CNC mill

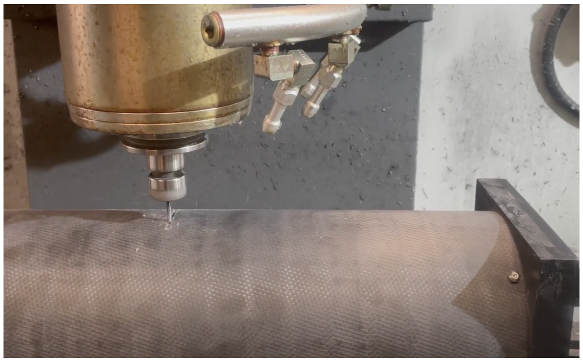


Figure 31: CNC mill working on body tube

3.4.4 Couplers

Two types of couplers were used in the launch vehicle. The coupler between the payload bay and the recovery bay, as seen in Figure 32, was constructed from G12 fiberglass and was purchased from Composite Warehouse. The other two couplers were purchased from LOC/PML, and were constructed from carbon fiber. Figure 33 shows the coupler between the recovery bay and the ACS tube. The couplers have an outer diameter of 6 in. to match the inner diameter of the body tubes. The carbon fiber couplers have a length of 11.75 in., while the fiberglass coupler has a length of 12 in. The couplers were sanded to fit with their respective body tubes. To secure the couplers to the body tubes, epoxy was applied heavily to the inner edge of the body tubes, allowing for the epoxy to spread between the inner surface of the body tube and the outer surface of the coupler when sliding the couplers to their target positions.

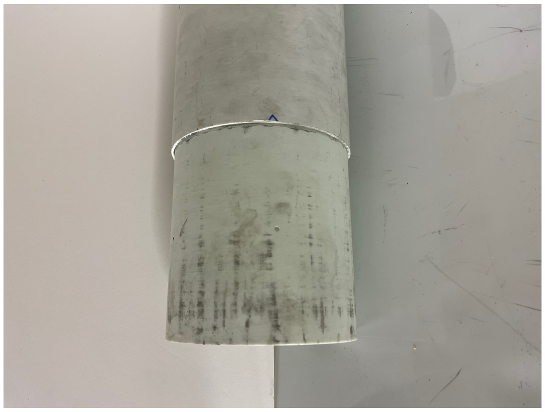


Figure 32: Payload bay coupler

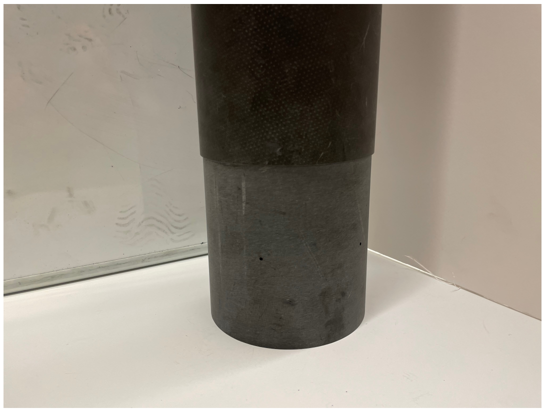


Figure 33: Recovery bay coupler

3.4.5 Bulkheads and Centering Rings

The bulkheads and centering rings were cut out of fiberglass using the waterjet as seen in Figure 36. Each bulkhead and centering ring, once cut on the waterjet, was measured for accuracy with calipers and against the body tubes and the motor mount tube. They were then sanded as needed using sandpaper to fit properly. The bulkheads and centering rings were then attached to the body tubes and motor mount tubes respectively using epoxy adhesive. The epoxied bulkheads can be seen in Figure 34 and Figure 35.

Figure 34: Payload Bulkhead epoxied into body tube

Figure 35: Fin Can Bulkhead epoxied into body tube

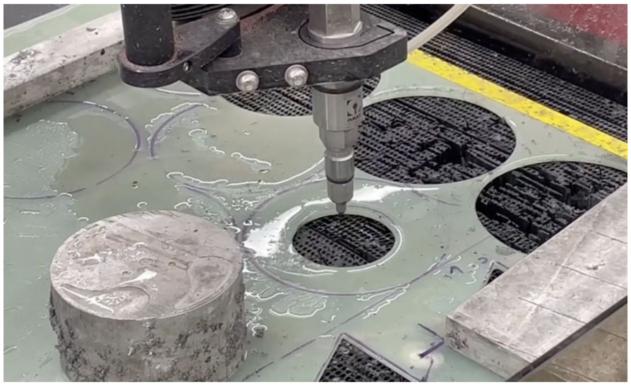


Figure 36: Using the waterjet to cut out the bulkheads and centering rings

3.4.6 Fin Can Assembly

Construction of the fin can assembly began with the attachment of a centering ring to the motor mount tube using J-B Weld. The centering ring was then attached to the fin can's inside RocketPoxy, shown in Figure 37. Additional epoxy was added to the opposite side of the centering ring.

The team used RocketPoxy and J-B Weld to attach the second centering ring at the fore of the fin can. The second centering ring was slid onto the motor mount tube, and additional epoxy was added to both the outer and inner joints of the centering ring to secure it to the fin can.

The fins were then inserted into the fin can and epoxied to the motor mount tube and the fin can. J-B Weld was used to connect the bottom of the fin insert to the motor mount tube, and the fins were secured to the fin can with RocketPoxy on both the inside and outside of the fin can.

Once all fins were inserted, the third and final centering ring was added using the same process as the second centering ring. The tail cone was epoxied onto the rear of the fin can by spreading RocketPoxy on the inside of the fin can, and J-B Weld was used to epoxy the motor retainer to the motor mount tube, shown in Figure 38.

Figure 37: Motor Mount being secured in fin can

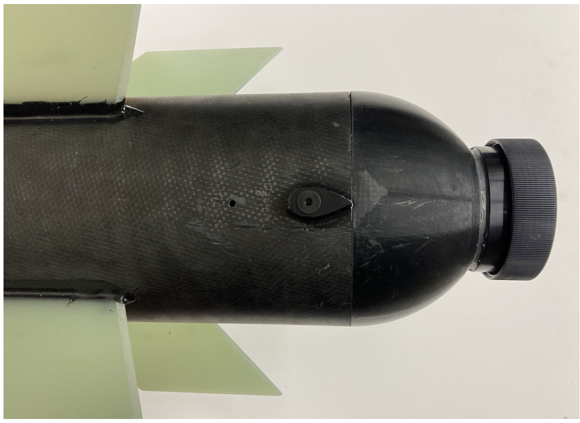


Figure 38: Motor retention assembly with tail cone and retainer

3.4.7 Fin Alignment

The fin edges were sanded and shaped with the belt sander to create a more aerodynamic shape. The fins were then installed into slots machined into the fin can. Each fin was attached to the motor mount tube using epoxy. A fillet was created for each fin around the slots of the can with RocketPoxy to interface with the fin can. A wooden laser-cut alignment jig was used to hold the fins 90 degrees apart from each other while the epoxy cured. After the epoxy cured, the excess epoxy was removed with sandpaper to minimize drag. A total of 3 ounces of epoxy was used to attach the fins to the vehicle. This process is shown in Figure 39.

Figure 39: Fins held in place by wooden alignment jig

3.4.8 Rail Buttons and Camera Shroud

The rail buttons were added to the outer surface of the fin can, one at the fore end and the other at the aft end of the body tube. A long string was used to determine the exact placement and alignment of the rail buttons. Holes were drilled in the fin can for screws and epoxy was placed around the holes with the rail buttons placed on top. The screws were used once the holes were properly aligned.An installed rail button can be seen in Figure 40.

Figure 40: Rail button secured to fin can

Figure 41: Camera shroud secured on payload bay

The camera shroud was epoxied onto the payload body tube, and its position was placed so as not to be aligned with the rail buttons or the fins. It was placed this way so as not to interfere with the flow on the fins and so that it does not interfere with the launch rail. The installed camera shroud can be seen in Figure 41.

3.4.9 System and Component Integration

Each body tube had to be mated to its respective system to fully integrate the launch vehicle. The ACS, LVIS, PRM, and SRM all used the same machined mounting blocks with holes drilled into the airframe for easy access and removal. The ACS system was aligned with the slots machined in the ACS bay, and the PRM and SRM had holes drilled for access to the keyed altimeter switches. Five holes were drilled through both the coupler and the body tube at each separation point to install shear pins.

3.5 Launch Vehicle Detailed Design

The following sections details the constructed launch vehicle, including mass statements and reliability confidence.

3.5.1 Constructed Vehicle

A picture of fully constructed vehicle is shown in Figure 42 along with the dimensioned design drawing in Figure 43. Additionally, Table 15 contains the material used for each part of the launch vehicle.

Figure 42: As-Constructed Launch Vehicle

Table 15: Summary of Launch Vehicle Component Material

Component	Material
Nosecone	G12 Fiberglass
Payload Bay	G12 Fiberglass
Payload Coupler	G12 Fiberglass
Recovery Bay	Carbon Fiber
ACS Bay	Carbon Fiber
ACS and Recovery Couplers	Carbon Fiber
Fin Can	Carbon Fiber
Bulkheads	G10 Fiberglass
Fins	G10 Fiberglass
Motor Mount Tube	Carbon Fiber
Centering Rings	G10 Fiberglass
Tail Cone	ABS Plastic

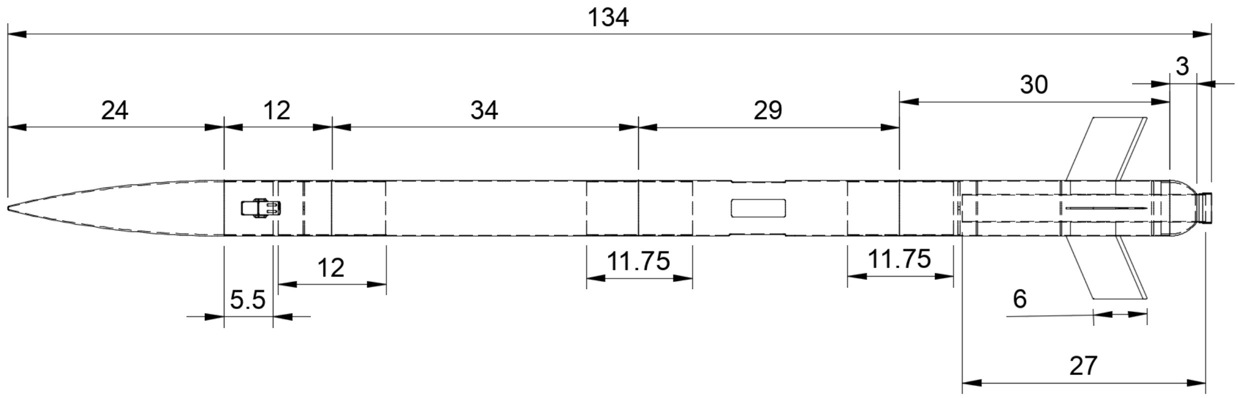


Figure 43: As-Constructed Launch Vehicle

3.5.2 Mass Statement

Table 16 shows the actual and predicted masses for the overall launch vehicle and all subsystems. All mission performance prediction simulations were done with these measured masses.

Table 16: Overall Mass Statement

Component/Subsystem	Measured Mass (oz)	Predicted Mass (oz)
Vehicle	318.3	350.4
Recovery (PRM)	139.3	122.4
Recovery (SRM)	50.7	52.5
Payload	38	51.8
ACS	73.2	75.8
Motor	168	168
Ballast	36.4	N/A
Total	823	820.98

3.5.3 Flight Reliability Confidence

The team performed FEA on all of the vehicle components during CDR to ensure that they could withstand the predicted loads with a factor of safety of at least 2. Table 17 shows the results of the FEA testing of each component. These safety factors combined with launch testing give the team good confidence that the vehicle can reliably withstand all flight loads.

Table 17: FEA Results for Vehicle Primary Structures

Component	Material	Loading Scenario	F.O.S.
Motor Mount Tube	Carbon Fiber	Peak Thrust	(63.4)
Recovery Tube	Carbon Fiber	Peak Thrust	(336.5)
ACS Tube	Carbon Fiber	Peak Thrust	(92.6)
Fin Flutter	G10 Fiberglass	(scenario)	(39)
Payload Bulkhead	G10 Fiberglass	Main Deployment	(2.42)
Centering Ring	G10 Fiberglass	Peak Thrust	(6.27)

4 Technical Design and Construction: Vehicle Recovery System

4.1 Mission Statement and Success Criteria

The primary mission of the recovery system is to ensure a safe and undamaged flight of every vehicle and payload component and ensure the launch vehicle is ready for reuse after landing. The recovery system also tracks and logs the flight path of the vehicle for data analysis and verification of the payload and ACS missions. The following criteria were 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 away from the launch pad.
- The launch vehicle will land within 90 seconds of reaching apogee.
- As proof of flight, battery powered altimeters housed within the recovery system will collect official altitude readings.
- The GPS system within the recovery system will transmit the location of the launch vehicle to a ground receiver to verify the results of the payload mission.

4.2 Design Overview

The recovery system for the launch vehicle will initiate three separation events from two separate avionics modules. Drogue deployment at apogee and main deployment at 576 ft AGL will be initiated by the altimeters housed in the Primary Recovery Module (PRM). Another separation event will occur at 800 ft AGL with the sole purpose of reducing the kinetic energy of the remaining vehicle sections. This event will be initiated by a Secondary Recovery Module (SRM) and no parachute will be deployed; however, the sections involved will remain tethered to the vehicle. The PRM and SRM share nearly identical structural designs, which will be further detailed in Section 4.5.1, and the internal avionics will be armed on the launch pad with keylock switches (NASA 3.6, NASA 3.7). Further description of the separation method and deployment sequence are located in Section 4.3, and further description of the avionics are located in Section 4.6.

4.3 Separations and Deployments

The following sections detail the multiple separation and deployment stages of the launch vehicle.

4.3.1 Separation and Deployment Sequence

The first separation event will occur at apogee and initiate the deployment of the drogue parachute. The separation point is located between the recovery and ACS bays. The primary ejection charge will be triggered by the altimeter at apogee, and the secondary and tertiary charges will be triggered at 1 s delays, ensuring that the drogue parachute deployment will occur no more than 2 s after apogee (NASA 3.1.2).

The second separation event will occur at 800 ft AGL and will not initiate the deployment of any parachutes. This event will cause the separation of the fin can from the ACS bay and these two sections will remain tethered by a recovery harness. The backup charges will be triggered at 750 ft and 700 ft, approximately 0.5 s intervals.

The third separation event will occur at 576 ft AGL and initiate the deployment of a pilot parachute and the main parachute. The separation point will be located between the recovery and payload bays. The primary ejection charge will be triggered by the altimeter at 576 ft AGL. This altitude was chosen primarily due to altimeter limitations since the Raven4, the primary altimeter, can only set ejection charge altitudes at 32-ft intervals. The backup charges will be triggered by the Stratologgers, which have can set ejection charges at 1-ft intervals, at 535 ft and 500 ft ensuring that the main parachute will not deploy lower than 500 ft (NASA 3.1.1). Figure 44 shows the sequence of separation events along the launch vehicle's flight path.

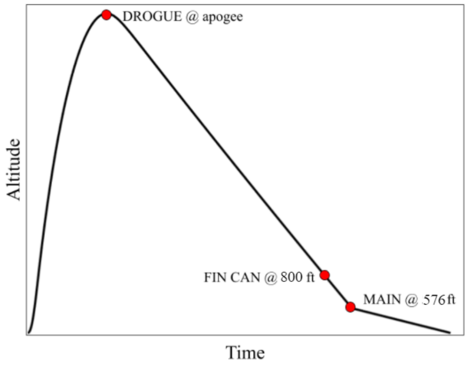


Figure 44: Separation Events Along Flight Path

4.3.2 Ejection Charge Sizing

Figure 45 shows location of the ejection charges in the vehicle as well as the pressurized sections S1, S2, and S3 that correspond to the first, second, and third separation events.

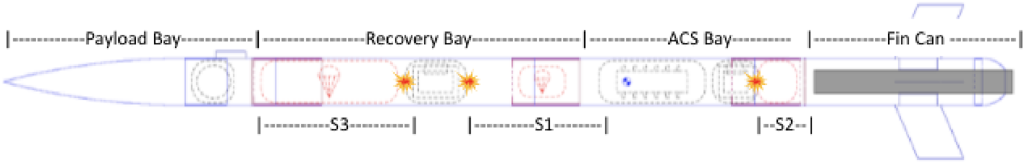


Figure 45: Launch Vehicle Separation Points

Table 18 lists the dimensions of each of the pressurized sections.

Table 18: Dimensions of Pressurization Sections

Section	Length (in)	Cross Sectional Area (in^2)	Volume (in^3)
S1	28.75	28.27	812.9
S2	8.625	26.69	230.2
S3	19.19	28.27	542.5

Five 4-40 nylon shear pins will be used at each separation point to secure the vehicle sections until the deployment events, satisfying NASA 3.9. The size and number of shear pins were sized in order to exceed the maximum drag produced by the ACS system, detailed in Section 7, by a factor of two. The size of primary ejection charges, g_{bp}, is given by

$$\text{Force to Break Shear Pins}: \; F_{\text{shear}} = \tau_{\text{max}} A_{\text{pin}} N_{\text{pins}} = 360 \text{ lbf}$$

$$\text{Moles of Gas Needed}: \; n_{\text{gas}} = \frac{F_{\text{shear}} L_{\text{sect}}}{RT}$$

$$\text{Grams of Carbon Needed}: \; g_{\text{C}} = \frac{3}{4} n_{\text{gas}} \times \frac{12 \text{ g C}}{\text{mol C}}$$

$$\text{Grams of Sulfur Needed}: \; g_{\text{S}} = \frac{1}{4} n_{\text{gas}} \times \frac{32.1 \text{ g S}}{\text{mol S}}$$

$$\text{Grams of Potassium Nitrate Needed}: \; g_{\text{KNO}_3} = \frac{2}{4} n_{\text{gas}} \times \frac{101.1 \text{ g KNO}_3}{\text{mol KNO}_3}$$

$$\text{Grams of Black Powder Needed}: \; g_{\text{bp}} = g_{\text{C}} + g_{\text{S}} + g_{\text{KNO}_3}$$

Table 19: Shear Pin Parameters

Parameter	Value
Size	#4-40
Length [in]	0.75
Diameter [in]	0.096
Material	Nylon
Shear Strength [psi]	10,000

where τ_{max} is the shear strength of nylon, A_{pin} is the cross-sectional area of one 4-40 pin, N_{pins} is the number of pins at each separation point, A_{bh} is the bulkhead area, L_{sect} is the length of each pressurization section, and T is the ignition temperature of black powder. Redundant ejection charges include an additional 0.5 g of black powder based on the suggestion of the Team's mentor. Table 20 shows a summary of the separation events, including the ejection charge sizes for the primary, secondary, and tertiary charges.

Table 20: Summary of Separation Events

Separation Event	Altimeter Location	Parachute Deployment	Ejection Altitude	Ejection Charge Size (g)
Drogue Deployment	PRM	✓	Apogee	5
			Apogee + 1 s	5.5
			Apogee + 2 s	5.5
Main Deployment	PRM	✓	576 ft	4
			535 ft	4.5
			500 ft	4.5
Fin Can Separation	SRM		800 ft	2
			750 ft	2.5
			700 ft	2.5

4.4 Drag Elements

The launch vehicle's various drag elements are detailed in the following sections.

4.4.1 Main Parachute Assembly

The main parachute assembly is deployed at 576 ft to slow the vehicle during the final stage decent to ensure landing with a kinetic energy of less than 75 ft-lbf (NASA 3.3) and within the required descent time of 90 s (NASA 3.10). The parameters of the parachute used in the main assembly are shown in Tables 21 and 22. Figures 46 and 47 show the inflated main and pilot parachutes.

Table 21: Main Parachute Parameters

Parameter	Main
Drag Coefficient, C_d	0.97
Diameter (ft)	12
Shroud Lines Material	200 lb Nylon
No. Shroud Lines	4
Weight (oz)	17
Packing Volume (in^3)	138.2

Figure 46: Inflated Main Parachute

Table 22: Pilot Parachute Parameters

Parameter	Pilot
Drag Coefficient, C_d	1.6
Diameter (ft)	2
Shroud Lines Material	220 lb Nylon
No. Shroud Lines	8
Weight (oz)	2.2
Packing Volume (in^3)	12.2

Figure 47: Inflated Pilot Parachute

The main parachute is stored in a deployment bag that is guided open by a pilot parachute to mitigate failure during the deployment. The event begins with the payload bay and recovery bay separating followed by the deployment of the pilot and main parachutes. The vehicle sections remain connected via a braided kevlar recovery harness and quicklinks. A swivel is used between two quicklinks and the parachute that allows the parachute to rotate without tangling. The harness parameters are shown in Table 23 and the harness is shown in Figure 48.

Table 23: Main Recovery Harness Parameters

Parameter	Value
Material	Braided Kevlar
Width (in)	0.200
Length (ft)	30
No. Loops	3
Breaking Strength (lbs)	2520
Weight (oz)	4.5

Figure 48: Main Parachute Harness

The main parachute harness was modified to protect against possible fraying due to rubbing on the body tube during flight. A sleeve of 3/4 in. tubular nylon was sewn to the kevlar where the harness interfaces with the airframe, as shown in Figure 49.

(a) Modified Kevlar Harness (b) Modified Harness in Flight

Figure 49: Modified Kevlar Harness

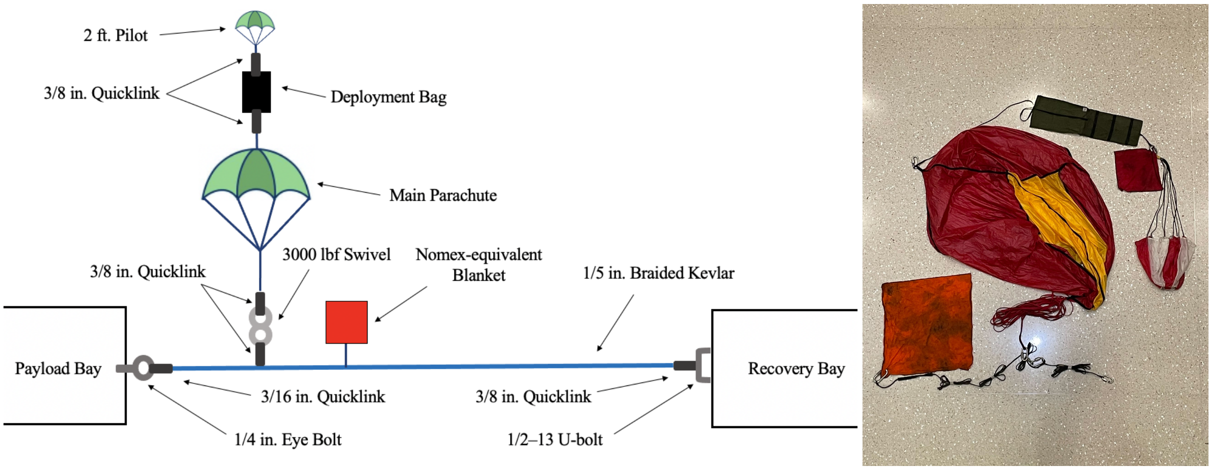
The parachute and recovery harness are protected with a fire-retardant blanket, satisfying NASA Requirement R.2. Parameters of the parachute protection are shown in Table 24 and the parachute protector is shown in Figure 50.

Table 24: Main Parachute Protector Parameters

Parameter	Value
Brand	Dino Chutes
Material	Nomex-equivalent
Size	24 in. Square
Weight (oz)	9

Figure 50: Main Parachute Protector

The structural verification of the main parachute assembly is further described in Section 5.6. Figure 51 shows the as-designed and as-built main parachute assembly.



(a) As-Designed (b) As-Built

Figure 51: Main Parachute Assembly

4.4.2 Drogue Parachute Assembly

The drogue parachute is deployed after the altimeters detect apogee. The properties of the parachute selected are shown in Table 25 and the parachute is shown in Figure 52.

Table 25: Drogue Parachute Parameters

Parameter	Value
Shroud Lines Material	250 lb Nylon
No. Shroud Lines	8
C_d	1.6
Diameter (ft)	2
Weight (oz)	2.1
Packing Volume (in^3)	12.16

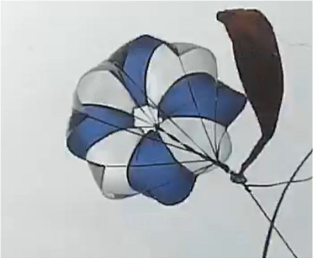


Figure 52: Drogue Parachute

The drogue parachute is attached to the recovery harness using a quicklink. Table 26 shows the parameters for the drogue recovery harness. The parachute and harness are protected from the black powder charges with a Nomex-equivalent blanket. The parameters of the drogue parachute protection can be seen in Table 27. The drogue harness and parachute protector are nearly identical to those used for the main parachute assembly and pictured in Figures 48 and 50.

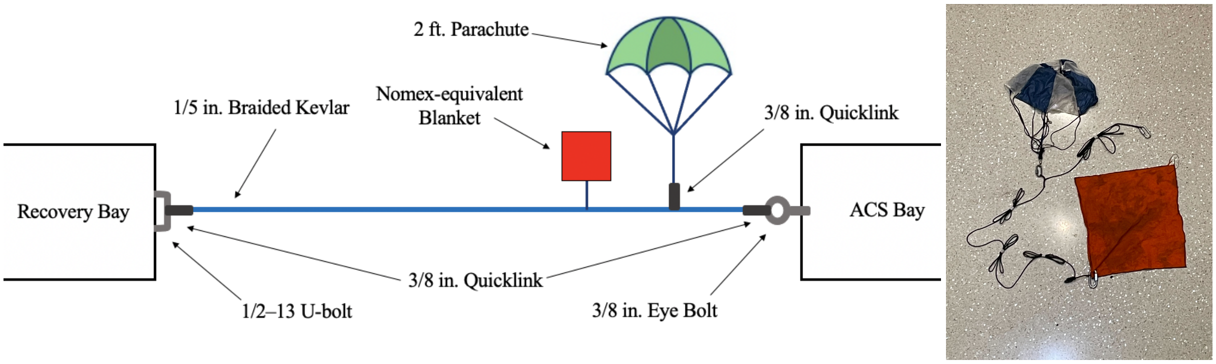
Table 26: Drogue Recovery Harness Parameters

Parameter	Value
Brand	Rocketman
Material	Braided Kevlar
Width (in)	0.200
Length (ft)	30
No. Loops	3
Breaking Strength (lbs)	2520
Weight (oz)	3.39

Table 27: Drogue Parachute Protection Parameters

Parameter	Value
Brand	Dino Chutes
Material	Nomex-equivalent
Size	24 in. Square
Weight (oz)	9

The full assembly of the drogue system includes a U-bolt connected to the recovery bay and an eye bolt connected to the ACS bay, which provide connection points for the braided Kevlar harness. The as-designed and as-built assembly for the drogue parachute is shown in Figure 53.



(a) As-Designed (b) As-Built

Figure 53: Drogue Parachute Assembly

Detailed structural verification of the recovery components is located in Section 5.6.

4.4.3 Fin Can Separation Assembly

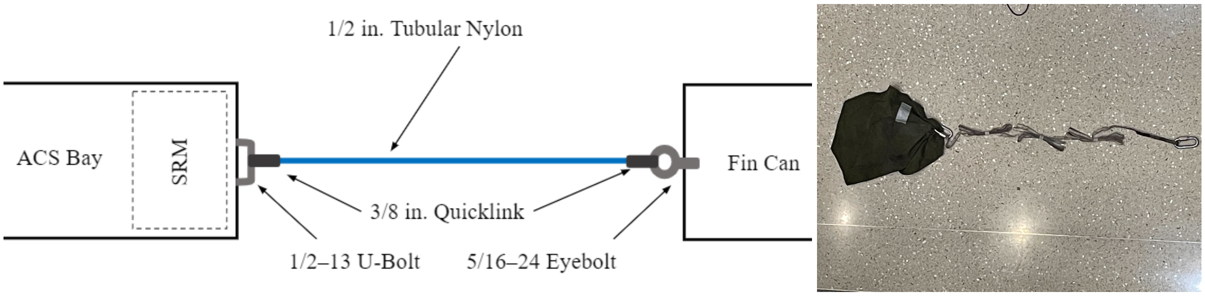
The fin can separation assembly is used to separate the ACS bay and fin can during the final stage of descent. The primary deployment for this event occurs before main deployment at 800 feet AGL. The vehicle bays are connected with a kevlar harness that attaches to each bay with quicklinks. Table 28 shows the parameters of the recovery harness attaching the two bays.

Table 28: Fin Can Recovery Harness Parameters

Parameter	Value
Material	Nylon
Width (in)	1/2"
Length (ft)	20
No. Loops	2
Breaking Strength (lbs)	2200

Figure 54: Fin Can Parachute Harness

Figure 55 below shows the configuration of the final fin can separation assembly. The structural verification of the assembly is shown in Section 5.6.

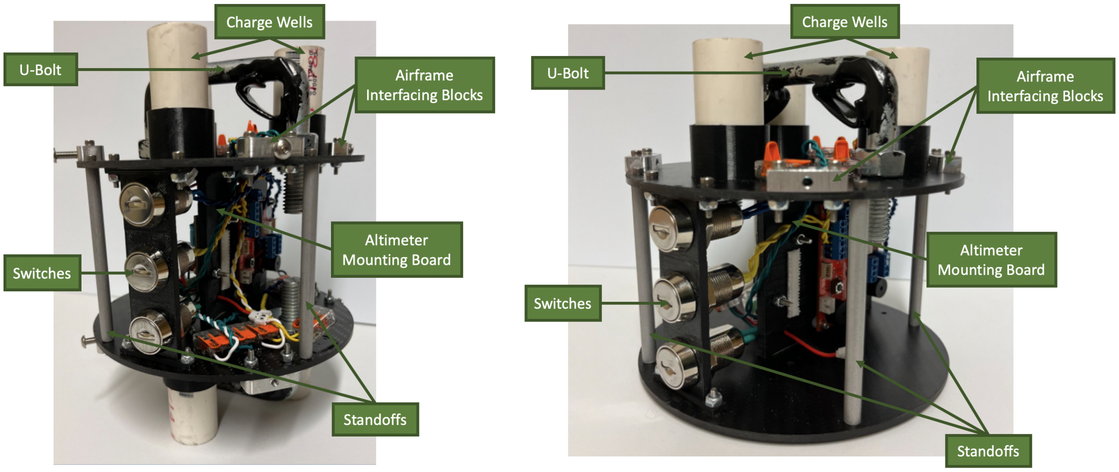


(a) As-Designed (b) As-Built

Figure 55: Fin Can Harness Assembly

4.5 Primary and Secondary Recovery Modules

The primary and secondary recovery modules (PRM and SRM) provide a structural interface between the recovery hardware and the launch vehicle as well as a housing for the recovery avionics. Both the PRM and SRM consist of two carbon fiber bulkheads which enclose four minimally load-bearing aluminum standoffs and the avionics mounting. Both modules contain three altimeters with their respective switches, batteries, and wiring. Charge wells and structural elements were affixed to both bulkheads of the primary recovery module and to only the aft bulkhead of the SRM. The final constructed PRM and SRM assemblies are shown in Figure 56. The following sections outline the design and construction of both recovery modules.



(a) PRM (b) SRM

Figure 56: As-Built PRM and SRM Assemblies

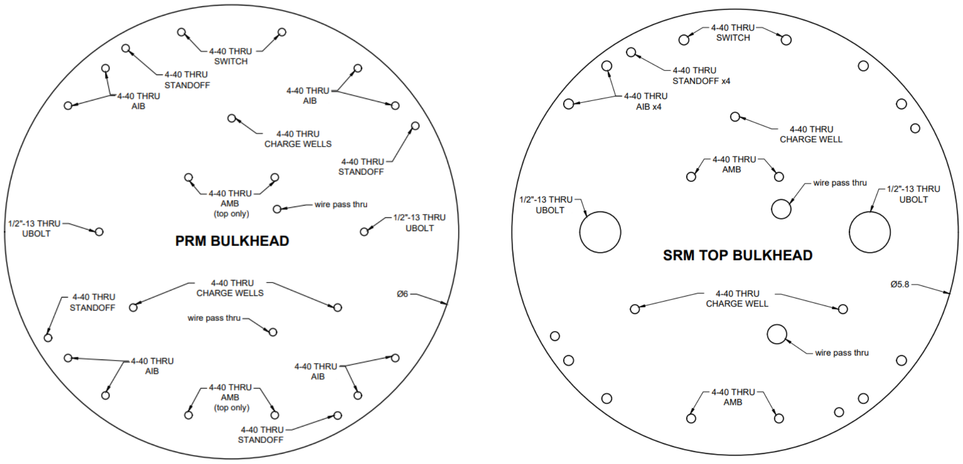
4.5.1 Main Structural Elements

The primary Recovery Module and Secondary Recovery Module both experience a main load path through the respective recovery harnesses and into the 1/2" - 13 U-Bolts attached to the bulkheads with washers and nuts. The U-Bolt parameters are listed in Table 29.

Table 29: U-bolt Parameters

Parameter	Value
Material	Zinc Plated Steel
Thread	1/2"-13
Breaking Strength (lbs)	2000

These U-Bolts have been modified to accommodate an angled force from the recovery harness at the parachute deployment which would result in the force being applied to a turn in the U-Bolt mechanism as opposed to the center. Steel brackets were epoxied using J-B Weld (NDRT R.5) into the corners of the U-Bolt to ensure the force is applied to the center of the mechanism as modeled. The 1/8 in. carbon fiber bulkheads were cut from a single 24 in. by 48 in. sheet. Square sections were cut using a band saw. The bolt holes were spotted and the bulkhead profile was cut using a 2.5 Axis HAAS. The holes were drilled to the proper diameter using a drill press using the PRM and SRM drill guides, shown in Figure 57.



(a) PRM (b) SRM

Figure 57: PRM and SRM Drill Guides

The airframe interfacing blocks (AIBs) were machined from aluminum stock using the HAAS 2.5-axis mill. The 8-32 holes were then tapped by hand. The drawing for the part and the as-built part are shown in Figure 58.

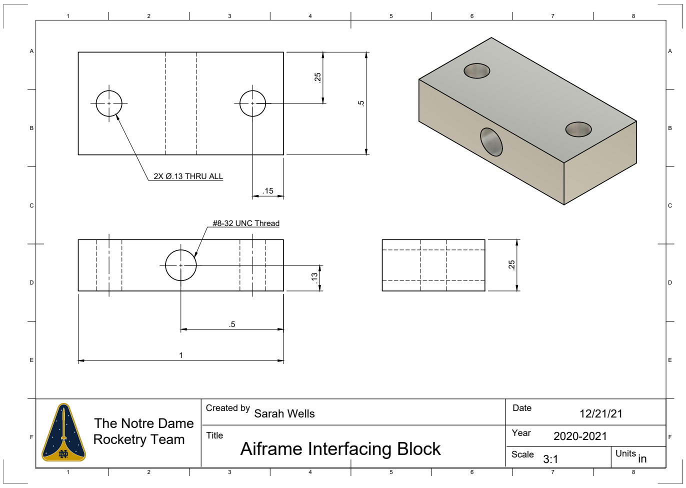


Figure 58: Airframe Interfacing Block

The airframe interfacing blocks were affixed to the outward faces of the primary load bearing bulkheads using two 4-40 screws and interface with the body tube of the launch vehicle with 8-32 screws.

4.5.2 Secondary Structural Elements

Secondary minimally load bearing elements are also present in the primary and secondary recovery modules. Three charge wells are affixed to the bulkheads on both outward facing surfaces of the PRM and one of the faces of the SRM. The charge wells, shown in Figure 59, hold the energetics for the recovery separation event and interface with the bulkhead through 3D printed end caps made of ABS plastic bolted directly into the carbon fiber bulkheads with 4-40 screws. The PVC piping used for the charge wells themselves were cut to size using a bandsaw and epoxied into the end cap.

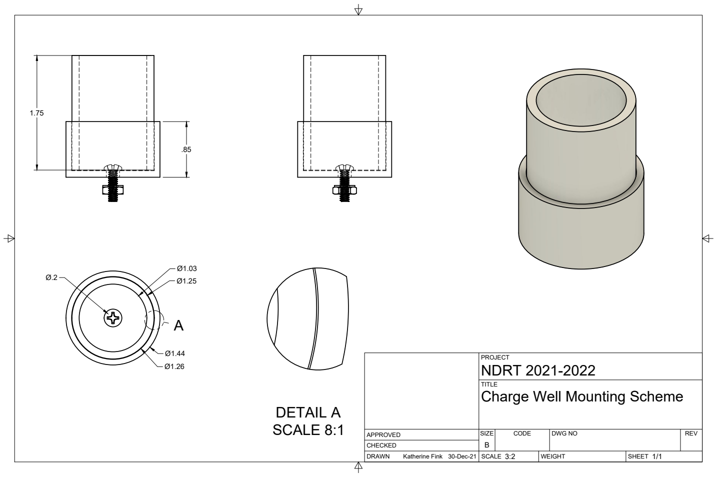


Figure 59: Charge Well

Four minimally load bearing standoffs provide the structure between the bulkhead pairs for the primary and secondary recovery modules. The bulkheads enclose the altimeter mounting boards and switchboards. The altimeter mounting board was 3D printed and bolted into the carbon fiber bulkheads with 4-40 screws. The switchboard was 3D printed and bolted into the bulkheads using 4-40 screws. A 3D printed jig stabilizes the switchboard against the inner face of the bulkhead.

4.6 Electronics

The recovery system's electronics are detailed in the following sections.

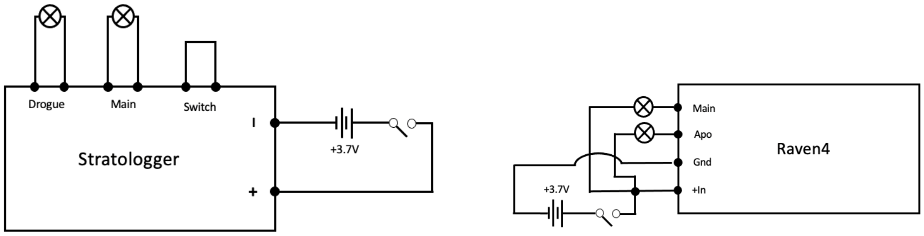
4.6.1 Altimeters

Six altimeters are used in total to control the three separation events to ensure redundancy within the system: two Featherweight Raven4, two Stratologger SL100s, and two Stratologger CFs. Using three altimeters per recovery module allows for the team to launch even if one altimeter is malfunctioning, satisfying NASA Req. 2.3.

The parameters for each of the altimeters are shown within Table 30, and final electrical schematics for each altimeter are shown in Figure 60. Before integration into the PRM and SRM systems, altimeters were tested following the procedure outlined in NDRT RT.4 to ensure their ability to deploy at the desired altitudes. Deployment at expected altitudes was verified by the LEDs lighting up at expected altitudes programmed into the Raven4s and the Stratologgers for both the drogue and main parachutes.

Table 30: Properties of Selected Altimeters

Property	SL100	SLCF	Raven 4
Dimension (in.)	2.75 x 0.9 x 0.5	2 x 0.84 x 0.5	1.8 x 0.8 x 0.5
Power (V)	4-16	4-16	3.8-16
Max Output Current (A)	10	5	9
Max Capacity (mAh)	N/A	N/A	170
Mass (oz)	0.45	0.38	0.23
Current Draw (mA)	1.5	1.5	<5



(a) Perfectflite StratoLogger (b) Featherweight Raven

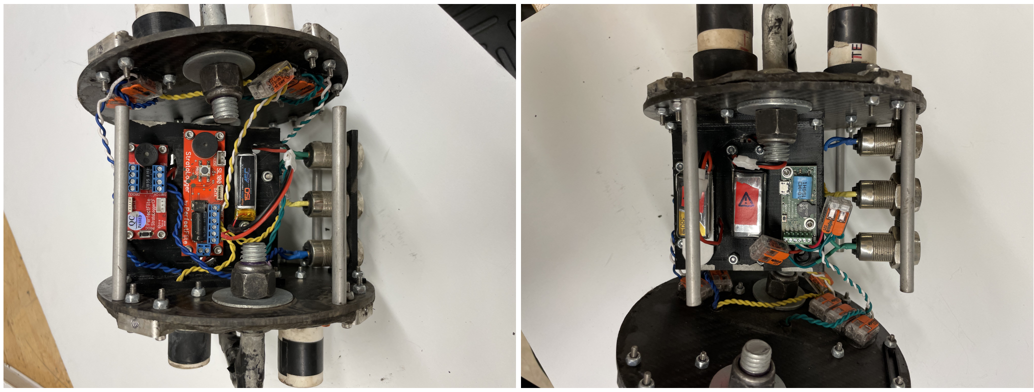
Figure 60: Recovery Electrical Schematics

The altimeters were screwed into the altimeter mounting board using 4-40 screws. Standoffs were placed between the altimeters and the mounting board to prevent any accidental short-circuiting. The altimeter batteries were secured to the mounting block using two-way velcro and adhesive strips. Batteries were wired to the altimeters using Molex connectors. One battery was wired to each altimeter for six total batteries, three for altimeters on the PRM and three for the SRM. The Featherweight Raven4 altimeters are powered by E-Flite 1S Lithium batteries and the Stratologgers are powered by Tattu 1S Lithium Polymer batteries with specifications in Figure 31. The battery life for each altimeter is also shown in the table, and each batteries meet NASA Req 2.7.

Table 31: Battery Specifications

Battery Parameter	Tattu 1S	E-Flite 1S
Capacity (mAh)	350	150
Voltage (V)	3.7	3.7
Constant Discharge Rate (C)	25	45
Battery Life (days)	30	9.72

WAGO 221 connectors epoxied to the bulkheads were used to directly connect each of the components in the circuit. The connections to the keyed switches were soldered and protected with heat shrink. All wire pairs were twisted to reduce common noise. A digital multimeter was used to test the integrity of the connections after the circuit's completion. Images of the physical circuit and connections on the PRM are shown in Figure 61.



(a) Stratologger SL100 and CF (b) Featherweight Raven4

Figure 61: Physical Electrical Circuit and Connections

4.6.2 GPS

A GPS transmitter is secured to a bulkhead in the payload system (3.12). The Featherweight GPS Tracker was chosen due its accuracy, reliability, and ease of use. It relays real time altitude and location data to an iPhone to expedite GPS data collection both during and after flight. The Featherweight is the only GPS included in the launch vehicle, which fulfills 3.12.1 since all vehicle sections remain tethered together throughout the flight.

The Featherweight GPS Tracker is powered by a commercially obtained 1S Lithium Polymer battery (3.5). The battery, with specifications given in Table 32, was selected in keeping with requirements listed in the GPS manual. The GPS battery life is expected to be about four to six hours, meeting NASA Req 2.7.

Table 32: Battery Specifications

Battery Parameter	Value
Capacity (mAh)	400
Voltage (V)	3.7
Battery Life (hrs)	4-6

5 Mission Performance Predictions

5.1 Flight Ascent Analysis

The flight ascent was predicted using two methods: OpenRocket and RockSim. OpenRocket and RockSim are both full flight simulators, which output flight profiles for a range of inputs. These inputs include launch vehicle geometry, motor type, launch rail cant, wind speed, launch vehicle surface roughness, and recovery system details. However, each simulation relies on a number of simplifications which can introduce errors. Error sources analyzed in the OpenRocket simulation include:

- 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, which may add an additional 3-14% error. Overall, the creators of OpenRocket estimate the simulation over-approximates apogee by about 29%, though it may be up to 43%.

RockSim is a proprietary software and as such it is difficult to assess specific sources of error. The creators of OpenRocket performed 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 uncertainty analysis.

5.2 Simulation Results

Both OpenRocket and RockSim were used to simulate critical values at launch angles of 5°, 7°, and 10° with wind speeds of 0 to 20 mph. All flight simulations were performed with the Aerotech L2200G-P motor, which was chosen for the demonstration flight and competition. The simulations use the measured CG location, measured mass of components, measured dimensions of components, and simulated CP. All simulations predict an apogee between 4,000 and 6,000 feet above ground level (NASA 2.1), and a minimum off-rail velocity of 75.4 ft/s (NASA 2.17). Table summaries and data plots of the simulation results at each angle and in each simulation software are included below in the following three sections.

5.2.1 5 Degree Rail Angle

Table 33: 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	76.4	5554	655	419
5	76.4	5518	655	419
10	76.4	5477	654	420
15	76.4	5440	654	420
20	76.4	5384	653	420

Table 34: 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	75.4	5892	661	423
5	75.4	5916	661	423
10	75.4	5929	661	423
15	75.4	5931	660	423
20	75.4	5924	659	423

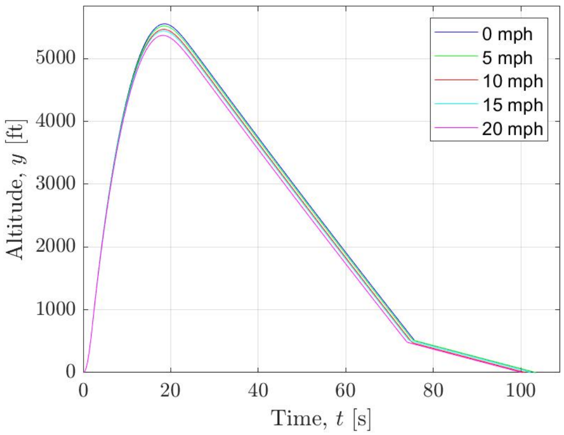


Figure 62: Altitude Flight Profiles from OpenRocket Simulations for Launch Angle of 5°

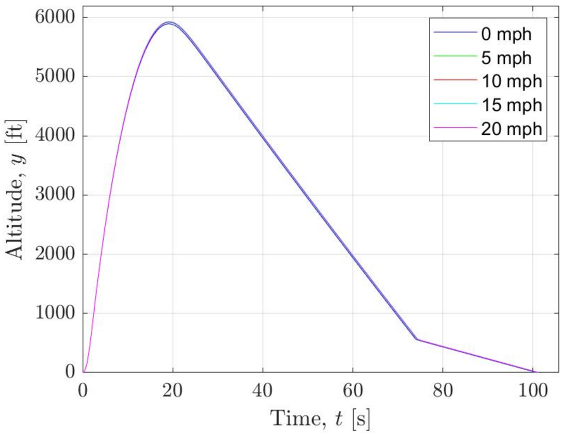


Figure 63: Altitude Flight Profiles from RockSim Simulations for Launch Angle of 5°

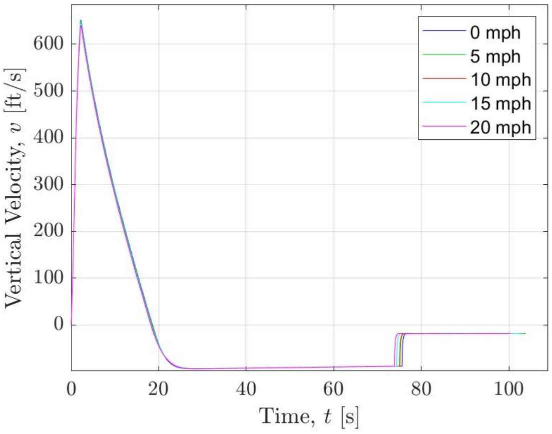


Figure 64: Velocity Flight Profiles from OpenRocket Simulations for Launch Angle of 5°

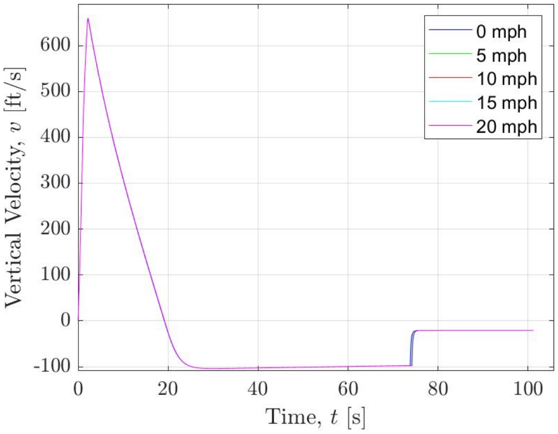


Figure 65: Velocity Flight Profiles from RockSim Simulations for Launch Angle of 5°

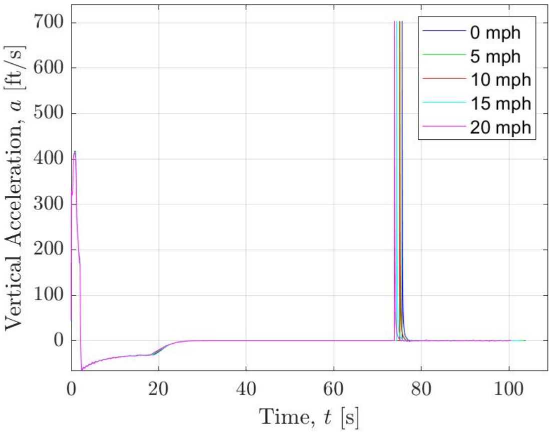


Figure 66: Acceleration Flight Profiles from OpenRocket Simulations for Launch Angle of 5°

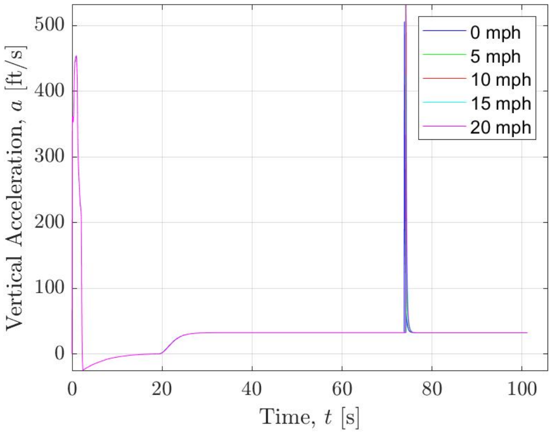


Figure 67: Acceleration Flight Profiles from RockSim Simulations for Launch Angle of 5°

5.2.2 7 Degree Rail Angle

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	76.4	5509	655	419
5	76.4	5465	655	420
10	76.4	5420	655	420
15	76.4	5378	654	420
20	76.4	5286	653	420

Table 36: 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	75.8	5842	661	423
5	75.8	5878	661	423
10	75.8	5902	661	423
15	75.8	5914	660	423
20	75.8	5917	660	423

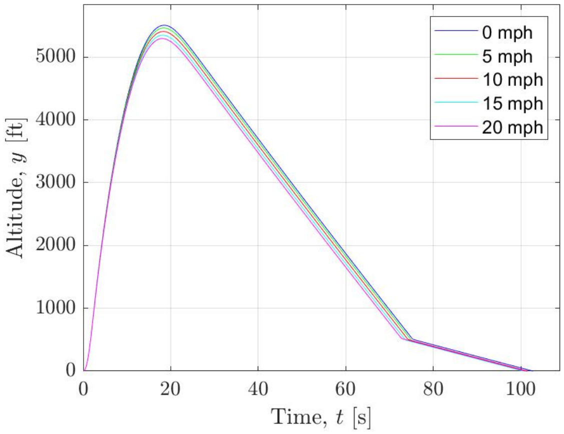


Figure 68: Altitude Flight Profiles from OpenRocket Simulations for Launch Angle of 7°

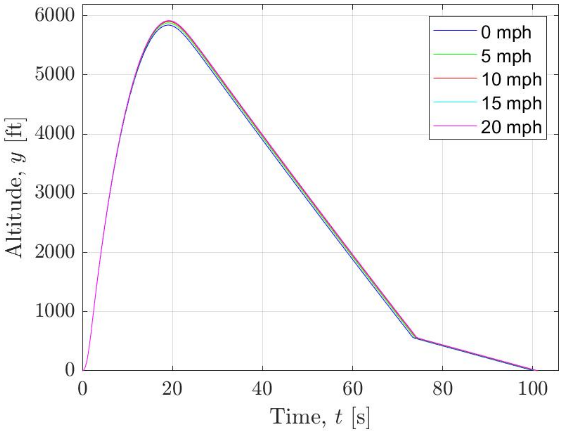


Figure 69: Altitude Flight Profiles from RockSim Simulations for Launch Angle of 7°

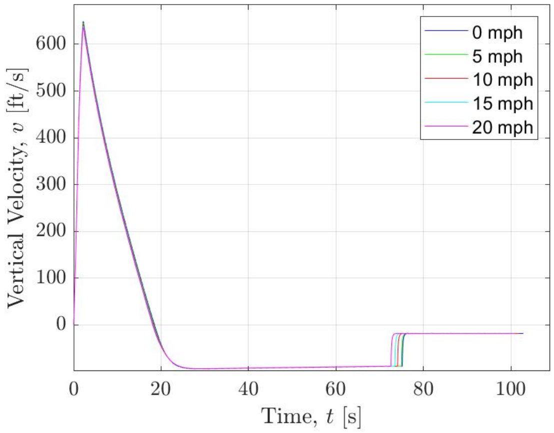


Figure 70: Velocity Flight Profiles from OpenRocket Simulations for Launch Angle of 7°

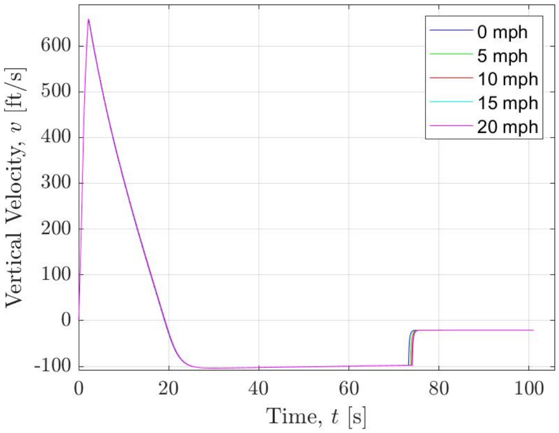


Figure 71: Velocity Flight Profiles from RockSim Simulations for Launch Angle of 7°

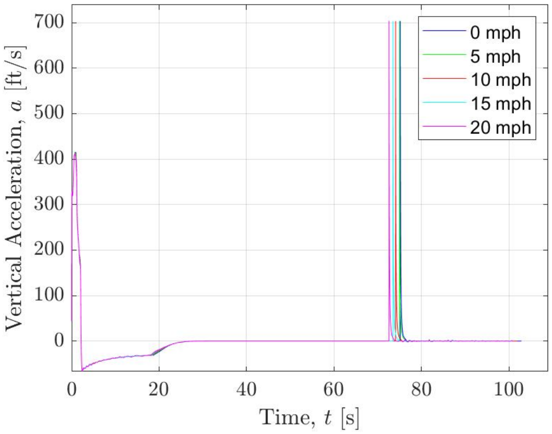


Figure 72: Acceleration Flight Profiles from OpenRocket Simulations for Launch Angle of 7°

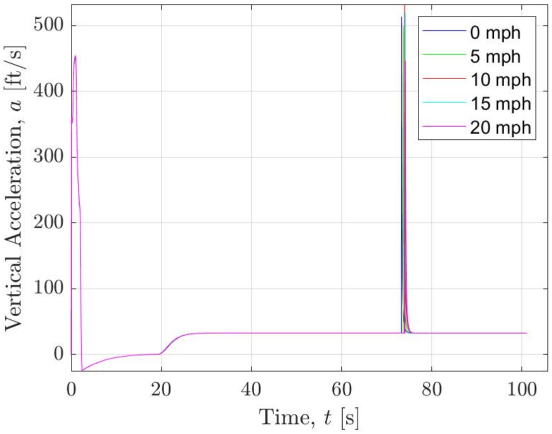


Figure 73: Acceleration Flight Profiles from RockSim Simulations for Launch Angle of 7°

5.2.3 10 Degree Rail Angle

Table 37: 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	76.5	5411	656	420
5	76.5	5356	656	420
10	76.5	5288	655	420
15	76.5	5234	655	420
20	76.5	5188	654	420

Table 38: 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	75.8	5737	662	423
5	75.8	5790	662	423
10	75.8	5830	661	423
15	75.8	5850	661	423
20	75.8	5875	660	423

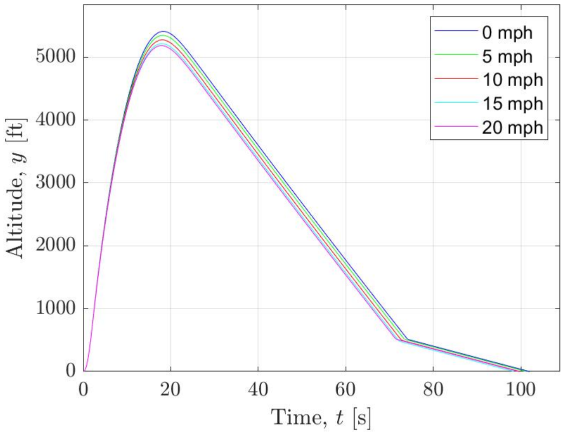


Figure 74: Altitude Flight Profiles from OpenRocket Simulations for Launch Angle of 10°

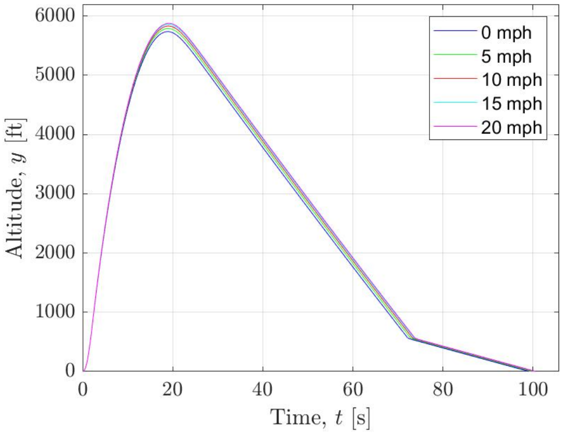


Figure 75: Altitude Flight Profiles from RockSim Simulations for Launch Angle of 10°

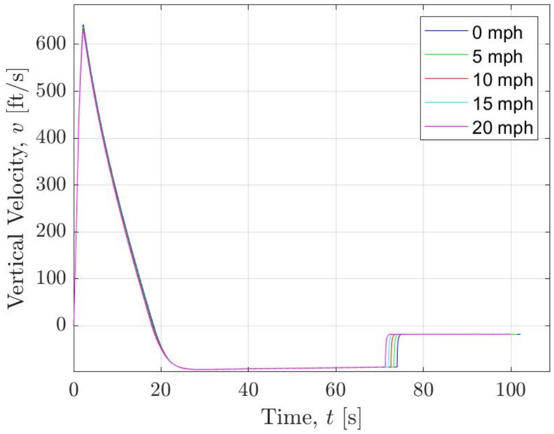


Figure 76: Velocity Flight Profiles from OpenRocket Simulations for Launch Angle of 10°

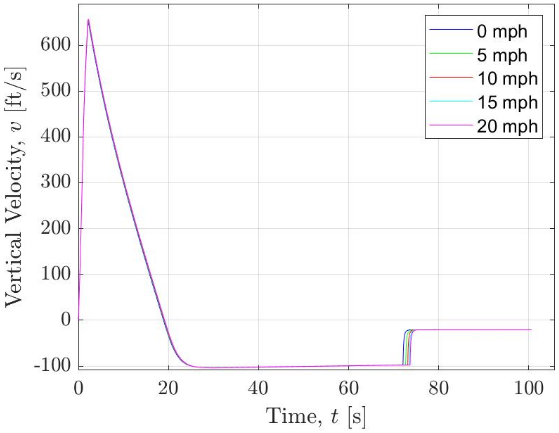


Figure 77: Velocity Flight Profiles from RockSim Simulations for Launch Angle of 10°

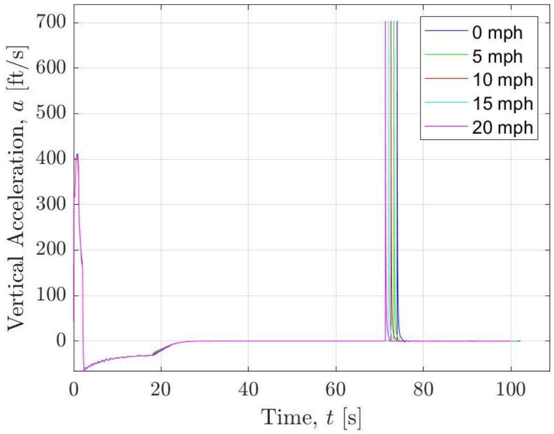


Figure 78: Acceleration Flight Profiles from OpenRocket Simulations for Launch Angle of 10°

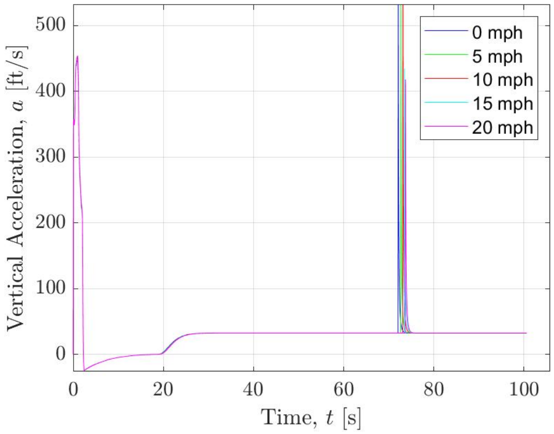


Figure 79: Acceleration Flight Profiles from RockSim Simulations for Launch Angle of 10°

The simulation results proved similar to the CDR phase in that the RockSim apogees are consistently higher than those in OpenRocket. Because the team saw high accuracy in the OpenRocket simulation for subscale, the OpenRocket simulations were given more weight as the design progressed. However, the vehicle is designed to meet the mission success criteria for the apogees predicted by both softwares.

5.2.4 Thrust

The thrust from 0 to 2.5 seconds for the Aerotech L2200G-P motor was found using OpenRocket simulations, shown in 80.

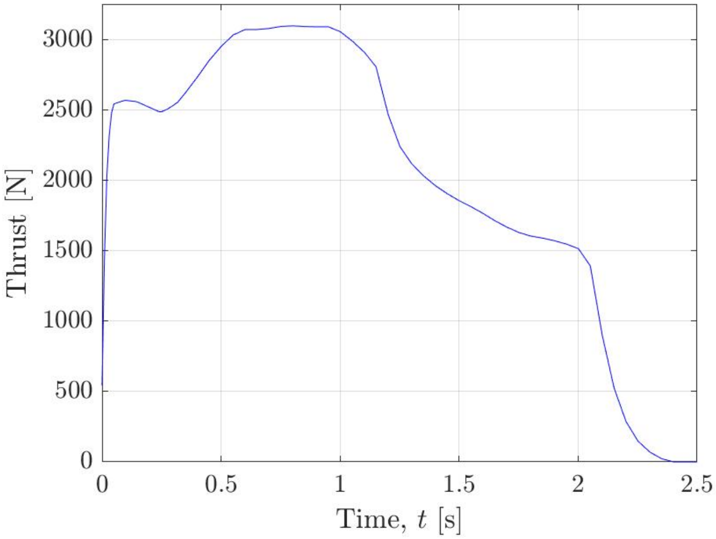


Figure 80: Thrust curve from OpenRocket Simulations

5.3 Stability Analysis

OpenRocket was used to calculate the static stability of the rocket at the rail exit, which was found to be 2.71 cal when launched vertically and with zero wind. This stability is desirable based on literature for pencil-like launch vehicles and the team's subscale launch. The launch vehicle has a height to diameter ratio of 21.7:1. The simulated rail exit velocity is 75 ft/s.

As the fuel burns, the reduction in mass at the aft end of the rocket causes the CG to shift forwards, increasing the static stability from rail exit to burnout. Since the ACS flaps are located 2.25 inches aft of the burnout CG, the deployment of ACS flaps will not decrease stability during flight. OpenRocket was used to plot the simulated stability, CP location, and CG location from 0 to 4 seconds, which includes the times of rail exit and motor burnout, shown in Figure 81.

The center of pressure (C_P) as a distance from the nose cone tip was found to be 99.153 in. using the OpenRocket Barrowman stability equations. The center of gravity, (C_G) as a distance from the nose cone tip, was found to be 82.152 in. when found by balancing the launch vehicle at the launch site. The outer diameter of the launch vehicle (D_{outer}) is 6.17 in. The stability (S) was found to be 2.67 cal using the following equation, fulfilling NASA 2.14:

$$S = \frac{C_P - C_G}{D_{outer}}$$

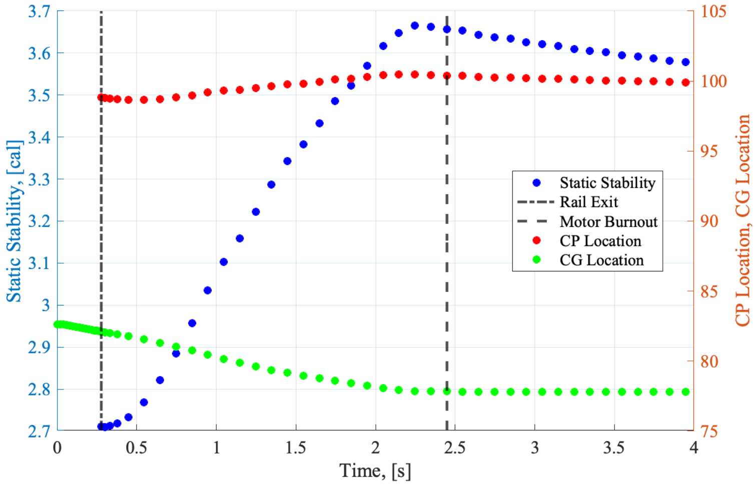


Figure 81: Plot of static stability, CP location, and CG location simulated in OpenRocket

Figure 82 shows the location of both the center of gravity and center of pressure on the launch vehicle. The center of gravity is shown with a blue dot at a distance of 82.25 in from the tip of the nose cone, while the center of pressure is shown with a red dot at a distance of 99.25 from the tip of the nose cone.

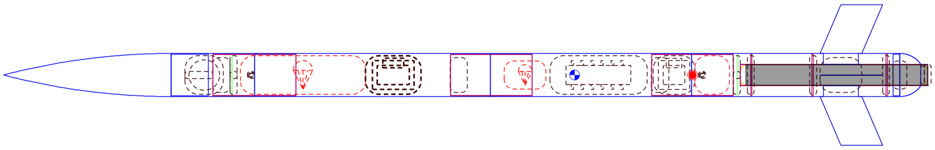


Figure 82: CG (blue) and CP (red) Locations on Vehicle

A summary of launch vehicle stability parameters can be found in Table 39.

Table 39: Summary of Important Stability Parameters

CG location (in.)	CP location (in.)	Static stability margin (cal.)	Off-rail stability (cal.)	Off-rail velocity (ft/s)
82.25	99.25	2.75	2.79	75.0

5.4 Ballast

The full scale demonstration flights were performed with a total ballast of 41.1 oz and 36.4 oz. This does not exceed 10% of the total unballasted weight of the launch vehicle (823 oz) (NASA 2.23.7). The launch competition flight will be flown to use any range of ballast less than 41.1 oz (NASA 2.19.1.6). The ballast was split between two different locations inside of the launch vehicle. The first location was on the eye bolt of the payload bulkhead, where 14.9 oz was added. The second location was on the SRM aft U-bolt, where 26.2 oz was added. Steel quick links were used as ballast and were not in the load path of recovery forces. The total ballast weight reduced the simulated apogee so that the target apogee will be within the operating range of ACS. The locations of the ballast were selected to ensure that the CG remained in a location that resulted in a static stability of 2.76.

5.5 Flight Descent

The vehicle descent is modeled using two different methods: OpenRocket simulations and a MATLAB script that performs basic flight descent calculations. The `SimpleDescent.m` MATLAB script estimates the following performance parameters for the vehicle:

- Kinetic energy
- Drift radius at landing
- Descent time
- Acceleration at main deployment

from the following input parameters:

- Streamer and parachute dimensions and drag coefficients
- Apogee (using the highest predicted from OpenRocket)
- Deployment altitude of main parachute
- Weight of each vehicle section
- Wind velocity (using 20 mph maximum)

Calculations by `SimpleDescent.m` are done under various assumptions that account for a higher prediction for descent time and drift than OpenRocket. The difference between these calculations is mainly due to assuming an instantaneous velocity change at main deployment in the `SimpleDescent.m` code and the turbulence model used by OpenRocket. Open Rocket simulations assume a 10 degree launch angle.

5.5.1 Kinetic Energy

Kinetic energy at landing is calculated using the descent rate following the main parachute deployment for both the OpenRocket and MATLAB simulations. The following equation was used in `SimpleDescent.m`:

$$KE = \frac{1}{2} m_{\text{section}} \left(v_{\text{main}}\right)^2$$

The simulated values for kinetic energy at landing for each section of the launch vehicle is given in Table 40, where the section masses are given in Table 41.

Table 40: Kinetic Energy at Landing of Vehicle Sections

Section	MATLAB K.E. [ft-lb]	OpenRocket K.E. [ft-lb]
Payload Bay	48.7155	44.6175
Recovery Bay	38.7554	37.8616
ACS Bay	57.8367	55.4263
Fin Can	74.8338	71.3501

Table 41: Vehicle Section Masses

Section	Weight (oz)
Nose Cone and Payload Bay	141.0
Recovery Bay	97.7
ACS Bay	167.4
Fin Can	216.6
Vehicle after Motor Burn	736.4

All of the hand calculations and OpenRocket simulation values are within 4 ft-lbs of each other. They are all within NASA's requirement of 75 ft-lbs (NASA 3.3).

5.5.2 Descent Time

Descent time is calculated in `SimpleDescent.m` using the following equations in MATLAB. It is assumed that there are wind speeds of up to 20 miles per hour (NASA 3.11).

$$\text{Main Descent}: \ T_{\text{main}} = h_{\text{main}} / v_{\text{main}} = 30.5401 \text{ s}$$

$$\text{Drogue Descent}: \ T_{\text{drogue}} = (h_{\text{apo}} - h_{\text{main}}) / v_{\text{drogue}} = 54.2901 \text{ s}$$

$$\text{Total}: T_{\text{tot}} = T_{\text{main}} + T_{\text{drogue}} = 84.8302 \text{ s}$$

where T is descent time and h is altitude at the drogue or main deployment.

The OpenRocket simulation calculated a descent time of 83.5 seconds with the assumption of no wind, which is within 1.58% of the calculation in MATLAB.

5.5.3 Drift

The estimated drift radius of the rocket from the point of launch is calculated in MATLAB using the following equations (NASA 3.10):

$$\text{Drift}_{\text{drogue}} = T_{\text{drogue}} v_{\text{drogue}}$$

$$\text{Drift}_{\text{main}} = T_{\text{main}} v_{\text{wind}}$$

$$\text{Drift}_{\text{tot}} = \text{Drift}_{\text{drogue}} + \text{Drift}_{\text{main}}$$

where T is descent time and v is velocity. The estimated drift radius as calculated by both the MATLAB and OpenRocket Simulations is shown in Table 42:

Table 42: Drift Radius

Wind Speed [mph]	MATLAB [ft]	OpenRocket [ft]
0	0	0
5	622.0882	368.9
10	1244.1764	932.86
15	1866.2646	1473.334
20	2488.3528	2092.38

There is a difference between OpenRocket and hand calculations since OpenRocket accounts for the lateral momentum from the thrust of the motor. Wind acts against this lateral momentum, accounting for a smaller drift radius estimate.

5.6 Structural Verification

The launch vehicle is subject to many different loading conditions during the flight. The following sections detail the worst-case maximum expected loading scenarios and the structural verification of all components subject to them.

5.6.1 Peak Thrust

The force transmitted to the vehicle is 700 lbf at maximum thrust. Finite Element Analysis was used during the CDR phase to examine the resultant stress from this loading on the vehicle components.

The thrust load is applied to the base of the motor motor mount tube. The epoxied centering rings then transfer the load to the airframe. The motor mount analysis was done with a fixed support at the location of each centering ring and the full thrust force applied to the bottom edge. The centering ring analysis was performed with a fixed support on the outer edge and the full thrust force acting on the inner edge. The unsupported sections of the recovery bay and the ACS bay were also analyzed each with a fixed support on top and the full thrust load on the bottom surface. Based on the available specifications, the compressive strength of the carbon fiber tubing is at least 175 ksi while the flexural strength of the G10 fiberglass centering rings is at least 60 ksi.

The resultant stresses were then used to determine the factor of safety for each component, shown in Table 43. Each of these factors of safety are greater than 2, satisfying NDRT LV.2.

Table 43: Body Tube and Bulkhead Structural Verification at Peak Thrust

Bulkhead	Applied Load (lbf)	Peak Resultant Stress (ksi)	Strength (ksi)	FOS
Motor Mount	700	2.76	175	63.4
Centering Rings	700	9.57	60	6.27
ACS Bay	700	1.89	175	92.6
Recovery Bay	700	0.52	175	336.5

5.6.2 Main Deployment

The deployment of the main parachute causes the vehicle to experience a large acceleration, which translates to forces on various components of the vehicle. Figure 83 shows the free body diagram of forces on the different vehicle components.

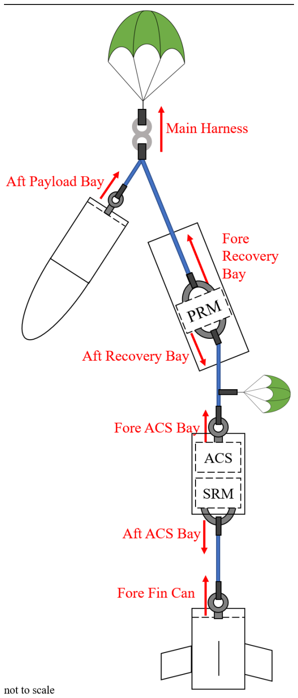


Figure 83: Main Deployment Free Body Diagram

The global vehicle acceleration is found by assuming instantaneous parachute deployment and summing the forces on the vehicle at the moment the parachute opens. The forces on each section were found using Newton's Second Law and are listed in Table 45. The section masses are located in Table 44.

Table 44: Vehicle Section Masses

Section	Weight (oz)
Nose Cone and Payload Bay	137.2
Recovery Bay	116.4
ACS Bay	170.4
Fin Can	219.4
Vehicle after Motor Burn	730.2

Table 45: Forces on Launch Vehicle Sections at Main Deployment

Location	Force [lbs]
Main Recovery Harness	920.5
Aft Payload Bay	208.4
Fore Recovery Bay	712.1
Aft Recovery Bay	567.7
Fore ACS Bay	567.7
Aft ACS Bay	320.2
Fore Fin Can	320.2

The main parachute quicklink and shock cord carry the greatest load during this event because they are supporting the mass of the entire launch vehicle. On either side of the harness, the quicklinks, u-bolts and eyebolts, bulkheads, and screws experience lower forces, proportionate to the amount of mass supported by them. The factors of safety of the attachment hardware at main deployment were calculated and are shown in Table 46.

Table 46: Attachment Hardware Factors of Safety at Main Deployment

Hardware	Location	Load (lbs)	Breaking Strength (lbs)	FOS
Drogue Harness	Drogue Harness	567.7	2520	4.44
3/8 in. Quicklink	Aft Recovery Tube	567.7	2200	3.88
3/8 in. Quicklink	Fore ACS Bay	567.7	2200	3.88
3/8 in. Quicklink	Drogue Chute	567.7	2200	3.88
U-bolt	Aft Recovery Tube	567.7	2000	3.52
3/8 in. Eye Bolt	Fore ACS Bay	567.7	3100	5.46
Main Harness	Main Harness	920.5	2520	2.74
3/8 in. Quicklink	Main Chute	920.5	2200	2.39
3/8 in. Quicklink	Pilot Chute	920.5	2200	2.39
3/16 in. Quicklink	Aft Payload Bay	208.4	500	2.39
3/8 in. Quicklink	Fore Recovery Tube	779.8	2200	2.82
1/4 in. Eye Bolt	Aft Payload Bay	208.4	500	2.39
U-bolt	Fore Recovery Tube	712.1	2000	2.81
Swivel	Main Chute	920.5	3000	3.26
Fin Can Harness	Fin Can Harness	320.2	2520	7.87
3/8 in. Quicklink	Aft ACS Bay	320.2	2200	6.87
3/8 in. Quicklink	Fore Fin Can	320.2	2200	6.87
5/16"-24 Eye Bolt	Fore Fin Can	320.2	2000	6.87

Each bulkhead will be secured to the airframe with 4 Alloy Steel screws with a 8-32 thread and a length of 1/2 in. These screws are the main load bearing pathway from the recovery modules to the airframe and the factor of safety for each screw was calculated using

$$FOS = \frac{\tau_{max}\frac{\pi}{4}D^2}{\frac{1}{n}F_{main}} = 4.17$$

where τ_{max} is the max shear screw of each screw, D is the screw's minor diameter, n is the number of screws used, and F_{main} is the force from main deployment. Each bulkhead was evaluated with a worst-case scenario assumption, using $n = 4$ for all bulkheads including the fore and aft of the PRM. The bulkheads are on the main load bearing pathway through the launch vehicle and transmit the load into the airframe. The strength of the bulkheads was evaluated using Finite Element Analysis performed with ANSYS Structural as described in the CDR document. The FEA was not performed again since the forces on the bulkhead have decreased since CDR. Table 47 shows the applied load, resultant stress, material strength, and FOS for each bulkhead loaded. The FOS of every component on the load path is greater than 2 even with the higher expected loads from CDR, verifying R.1, LV.2, and LVIS.2.

Table 47: Bulkhead Structural Verification at Main Deployment

Bulkhead	Applied Load (lbf)	Peak Resultant Stress (ksi)	Strength (ksi)	FOS
PRM Bulkheads	779.8	96.7	250	2.58
ACS Bulkhead	600.4	11.9	35	2.94
SRM Bulkhead	337.9	68.1	250	3.67
Payload/Fin Can Bulkhead	337.9	18.6	45	2.42

6 Technical Design and Testing: Launch Vehicle Identification System

6.1 Mission Statement and Success Criteria

The Launch Vehicle Identification System (LVIS) is the Notre Dame Rocketry Team's experimental payload for the 2022 NASA Student Launch Competition. The team will independently design, build, and test a system that will remain in the launch vehicle during flight to determine the exact landing position and grid value of the launch vehicle. The mission shall be successful if the payload is safely retained during launch, collects and filters data throughout the flight, and correctly calculates the exact landing position and grid value of the launch vehicle. All of this must be completed without causing damage to the launch vehicle, surroundings, or spectators.

The following criteria will be used to evaluate the success of the payload system: (4.1):

- 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.
- 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 correctly identifies and transmits the grid square in which the launch vehicle lands and depicts the launch rail in the gridded image.

6.2 Changes from CDR

The sensor fusion algorithm in the software used to determine the final landing location was changed from a Gaussian Newton Filter to an Extended Kalman Filter. This change was made due to the resources available for the filter since it is the industry standard for nonlinear state estimation. The 1S2P battery switched to a 2S1P battery to allow for more adequate power distribution to the electronics. Additionally, the battery now goes through a buck converter instead of a boost converter to power the 5V rail. The battery will now be mounted on a 3D printed stand on the top fiberglass bulkhead to allow for easy battery insertion and removal. This allows for more effective use of the vertical space in the nosecone. Lastly, the LVIS will only utilize three microcontrollers as opposed to four to save space on the bulkheads and conserve power.

6.3 Mechanical Design Features

The LVIS mechanical design features three bulkheads, two fiberglass and one wood, aluminum standoffs, and the retention system as well as incorporate the mounting of the sensors. The following sections detail the manufacturing, assembly, and integration of the bulkheads, the sensor mounts, and the retention blocks.

6.3.1 Manufacturing

Three bulkheads were needed to house the sensors, wiring, Raspberry Pi, battery, battery holder, and custom PCB. The top and bottom sections of the payload sled were made from fiberglass with retention blocks attached to interface with the tube of the vehicle. The middle bulkhead was constructed out of hardwood plywood to dampen vibrations and house the sensors associated with the payload mission. Each bulkhead had a diameter of 5.787 in. to account for the nosecone shoulder and tolerancing.

A sheet of hardwood plywood was purchased and cut into several squares of 6.5 in with a large dremel before the bulkhead was cut out to a diameter of 5.787 in. using the laser cutter. This process was iterated several times as some wooden bulkheads were scorched in the construction process, while others were too large. The bulkheads were refined using the belt sander.

Each sensor and the aluminum standoffs were placed on a sketch of the bulkhead and dots were drawn marking where holes needed to be drilled. This paper served as a drilling guide which was then taped onto the bulkhead. This process can be seen in Figure 84. The designated holes were then drilled on the drill press. Each sensor was mounted with M2 screws, washers, and nuts.

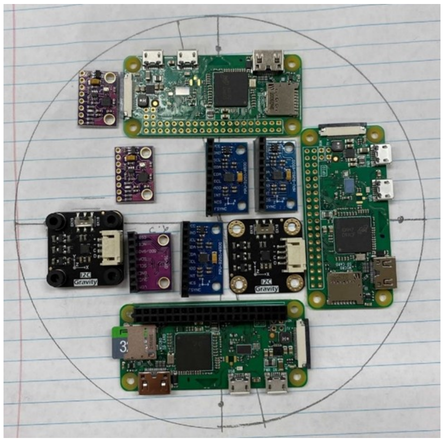


Figure 84

The fiberglass bulkheads were cut with the water jet on the same sheet as the vehicle's fins. The drill press created the holes for the standoffs, retention blocks, and the battery.

Lastly, a 3D printed battery holder was designed in Fusion360. This battery holder includes a slot to insert and remove the battery without obstruction of the nut and Airframe Interface Blocks (ABS). The power distribution and transmission board lies on the top of the 3D printed prism. A Stratasys F123 series printer was used to create the piece that can be seen in Fig. 85

6.3.2 Assembly and Integration

The LVIS was assembled from three bulkheads and eight aluminum standoffs. The fore bulkhead houses a battery in a battery casing for the transmission board. Then, the transmission board is attached to the battery casing through M3 screws. The middle bulkhead is connected to the fore bulkhead through male-female aluminum standoffs with the male end tightened with a locknut on the fore side of the fore bulkhead. The middle bulkhead has the three identical sensor suits of three sensors each, which are attached to the wooden bulkhead with M2 screws and nuts. Finally, the aft bulkhead is screwed into the middle bulkhead using the aluminum standoffs and screws into the female end. The aft bulkhead has the GPS altimeter and battery which are attached using screws. There are four Airframe Interface Blocks screwed onto the fore side of the fore and aft bulkheads.

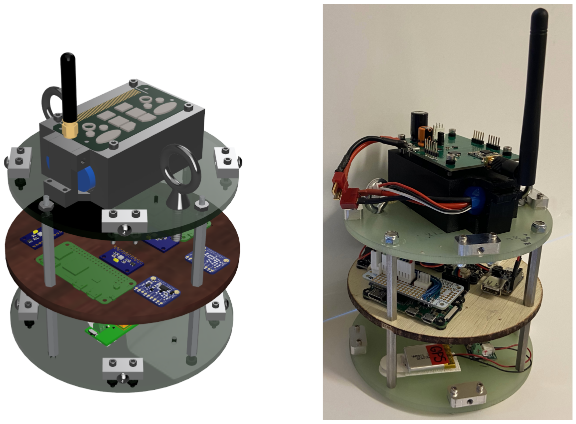


Figure 85: CAD model (left) and as constructed (right)

Early payload iterations had three five bulkheads, but the constructed one has three because all of the sensors were found to be able to fit onto one bulkhead. In addition, it has two eyebolts on the fore bulkhead in order to assist with removal from the payload bay.

Integration
There are four Airframe Interface Blocks screwed onto the fore side of the fore and aft bulkheads for integration into the launch vehicle.The LVIS is inserted into the payload bay, screws inserted into the bottom four AIBs, and then the nosecone is inserted and screws are used to secure the LVIS.

6.3.3 Retention

The team decided to use retention blocks, interfaced with the upper and lower payload bulkheads, and attached to the interior wall of the launch vehicle body to integrate the LVIS with the main launch vehicle. These bulkheads are made of fiberglass for added strength to secure and retain the LVIS. The retention blocks are made from aluminum for a durable and lightweight design. Each block consists of three holes for screws: two smaller 4-40 screws attach the block to the bulkhead and an 8-32 screw inserted into a threaded hole attaches to the launch vehicle tube. Figure 86 shows the bottom bulkhead mounted with the recovery GPS. This GPS will also serve to verify the grid location of the payload. Figure 87 shows the underside of the retention bulkhead with the washers and nuts fastening the 4-40 screws.

Four blocks are used on each bulkhead to retain the LVIS to the launch vehicle for redundancy and added safety.

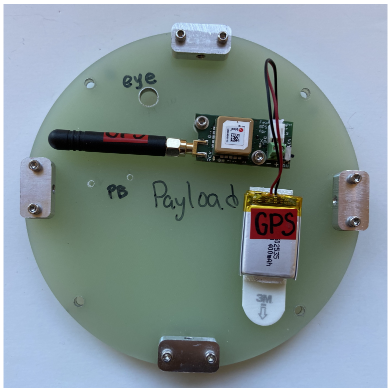


Figure 86: LVIS bottom bulkhead with the Recovery GPS

Figure 87: The underside of the LVIS bottom bulkhead.

The LVIS is located in the payload bay, overlapping with the 5.5in. shoulder of the nose cone to save space.

6.4 Electrical Design Features

The LVIS electrical design features three identical modular units powered by a central board that incorporates transmission. The modular units consist of a Raspberry Pi and a sensor suite of two IMUs and a HiG accelerometer. The following sections detail their selection, integration, and fabrication process where applicable such as the custom PCB.

6.4.1 Sensors

The three subunits of the LVIS consist of two Inertial Measurement Units (IMUs), a HiG accelerometer, and a microcontroller. Two different IMUs were selected, a 9-Axis Inertial Navigation Module and HiLetgo MPU9250, because of their sensitivity and sampling rates. They record the launch vehicle's motion and orientation during flight to determine the launch vehicle's final position. Using two IMUs gives the system redundancy and reduces the signal to noise ratio in the data. The magnetometers present will not be used during flight, only while the vehicle is on the launch pad to calibrate the sensors.

The HiG accelerometer is used to record acceleration accurately during the high force moments such as main parachute deployment. A DFRobot Gravity 12C was chosen for cost effectiveness, accuracy, and its widespread availability.

The microcontroller the team chose is a Raspberry Pi 0W, due to its processing capabilities, low power use, small size, and cost effectiveness. It is used as the microcontroller for the three subunits and the main unit. To save space and power, one of the three subunits will become the main unit. The subunits receive data from the sensor suite, filter the data, compute the displacement, and send it to the main unit. The main unit receives the displacements, averages them based on their uncertainties, converts them into a grid coordinate, and transmits the grid location to the ground station.

The sensors are mounted onto the wooden bulkhead in the configuration seen in Figure 84. Each sensor was fitted with rubber dampers to reduce vibration effects in the data and attached to the bulkhead with screws. The layout was determined by the wiring configuration, and all parts are removable for easy access.

6.4.2 Power Distribution and Transmission Board

The power distribution and transmission board integrates the task of powering the various electronics and transmitting the final landing location to the ground station. The schematic for supplying the power is shown in Fig. 88 and the schematic for the wireless transmission is shown in Fig. 89.

H

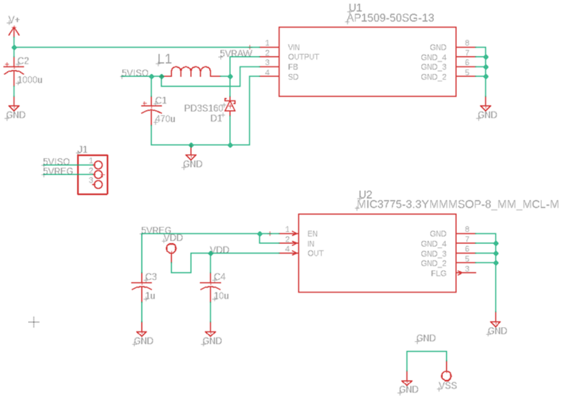


Figure 88: Power Supply

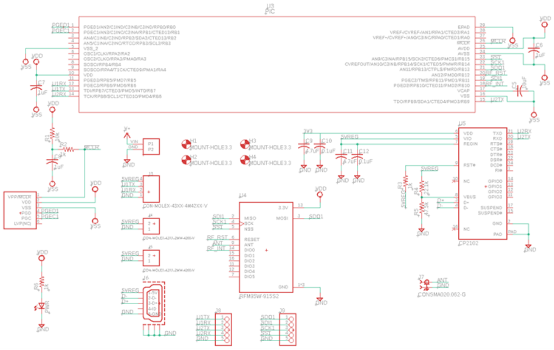


Figure 89: Wireless Transmission

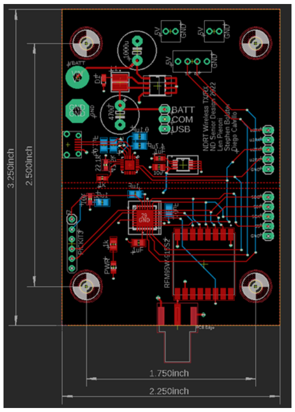


Figure 90: Board Design

Figure 91: Ground Station and LVIS Boards

Table 48: LVIS Major PCB Components

Part Name	Description
AP1509-50	5V fixed output buck converter
MIC3775-3.3	3.3V fixed output LDO
PIC32MX110F016B	32 bit microcontroller
RFM95W	LoRa wireless transceiver
CP2104	5 V boost regulator
CP2102N-A02	SUSB to UART bridge

Fig. 90 highlights the design of the board that incorporates the dual tasks. The major components for the board are listed in Table 48. Once designed, the printed circuit board was fabricated by PCBWay. Board components were purchased from Digikey. Solder paste was applied to the board using the solder mask provided by PCBWay. Surface mount components were placed on the board and baked in a reflow oven to solder them to the board. Through-hole and backside components were soldered to the board by hand. A battery connector was fastened to the board using screw terminals. Molex jumper cables were made to connect the power supply to the inertial navigation system's three Raspberry Pi's. Identical boards are used for both the LVIS and ground station as seen in Fig. 91.

The PIC32 microcontrollers used in the launch vehicle's wireless transmission module and the ground station are programmed using the C programming language and the MPLAB integrated development environment. The launch vehicle's wireless transmission module is able to edit the transceiver's settings and transmit a packet with predetermined contents using the LoRa (Long Range) protocol. The ground station's transmission module is able to receive that packet and send it to a computer connected via USB. The microcontrollers' software is planned to add the use of address filtering to protect the modules from interference caused by nearby use of the 915MHz range as well as the capability to transmit data received from a connected device using the Universal Asynchronous Receiver-Transmitter (UART) protocol.

6.5 Software Design Features

The software for the completion of the mission involves the procedures by which the data is collected from the various sensors and processed through the various filters into an accurate location output for the launch vehicle. The following sections outline the control flow for the procedures and the filters used.

6.5.1 Control Flow

The LVIS control flow is separated into three parts: the in-flight portion of collecting and filtering data in real time, the post-flight filtering of data between launch and landing, and the position calculation once sensor data has been filtered.

6.5.1.1 In-Flight The three separate sensor arrays each consist of Raspberry Pi Zero W connected to an IMU and an accelerometer. Each subunit takes measurements while the rocket is in flight. The data obtained from the sensors includes an acceleration vector denoting acceleration in the x, y, and z directions, a rotation vector denoting rotation in the x, y, and z directions, and a barometer measurement for altitude(y direction). Raw data from the sensors is loaded into a CSV file for further analysis during post-flight. During flight the acceleration data is first rotated per iteration using the rotation vector to properly orientate the direction of the rocket's acceleration in order to facilitate positional calculations The data is filtered for accuracy and smoothness by removing noise using a Kalman filter after rotation. Rotation and filtering occurs in real time during flight, and the rotation and filtering algorithms iterate through incoming data as new measurements are taken. Rotated and filtered data is then stored internally and used to check certain flight parameters including flight start and flight end. In-flight calculations are terminated once the conditions of the flight end parameters have been met, and the post-flight sequence begins. The control flow for the in-flight portion of the LVIS is shown in Figure 92.

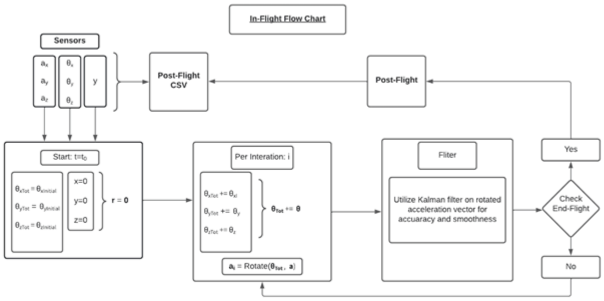


Figure 92: In-Flight Control Flow Schematic

6.5.1.2 Post-Flight The post-flight control flow will consist of a recalculation of overall position using an extended Kalman filter. This more complex filter will approximate a nonlinear system and more accurately determine displacement. The raw data collected from the accelerometer and gyroscope that was written to a CSV will be fed into the filter after landing is detected. The timestamps on the CSV determined during the in-flight Kalman filter will be used to only utilize data between launch and landing.

First, the starting orientation will be set and the filter will continuously rotate acceleration vectors based on the gyroscope data. After each iteration, the Euler angles will be adjusted using the change in orientation. This updated orientation will be used to rotate the acceleration for that timestamp. The acceleration is then integrated to get position using a matrix that multiplies acceleration by $\frac{1}{2}\Delta t$. Lastly, the position of each coordinate axis is summed until the extended Kalman filter has iterated through to landing. The final position along with the covariance matrix of each approximation will be sent to the main microcontroller. The post-flight control flow is shown in Figure 93.

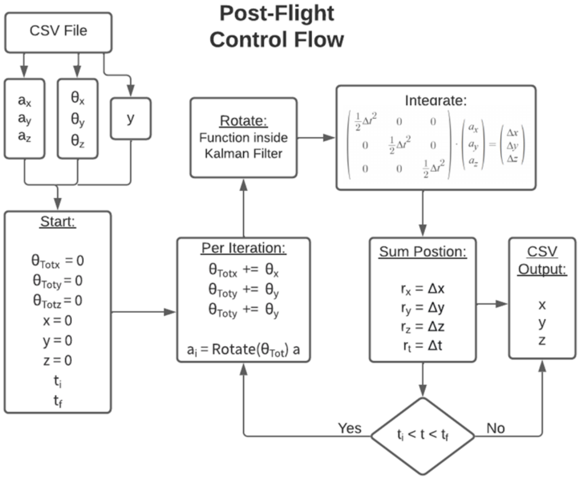


Figure 93: Post-Flight Control Flow Schematic

6.5.1.3 Position Calculation The LVIS's main unit receives 4 values from each subunit: the x and y position of the launch vehicle and the uncertainties of each, Δx and Δy. These are combined into vectors for each value. The uncertainty vectors are converted into probabilities through inversion and then normalized to sum to one. The dot product of the position vectors x and y with their respective probability vectors are then taken to incorporate the uncertainties in the sensor data. The dot product results dx and dy are the average coordinates of the launch vehicle's overall displacement. This process is detailed with matrices in Figures 94, 95, and 96. The coordinates dx and dy are run through a transformation function that outputs the grid location. The grid location is then transmitted to the ground station. This system will be verified by using sensor and GPS data from both the subscale and full-scale flights.

$$\begin{pmatrix} C_x & - & - \\ - & C_y & - \\ - & - & C_z \end{pmatrix} \rightarrow \begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix} \rightarrow \begin{pmatrix} 1-C_x \\ 1-C_y \\ 1-C_z \end{pmatrix} = \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix}$$

Figure 94: Calculating the probability from each IMU using the covariant matrix

$$\Delta x_n = \frac{\Delta x_n}{\sqrt{\left(\Delta x_1\right)^2 + \left(\Delta x_2\right)^2 + \left(\Delta x_3\right)^2}}$$

$$\Delta y_n = \frac{\Delta y_n}{\sqrt{\left(\Delta y_1\right)^2 + \left(\Delta y_2\right)^2 + \left(\Delta y_3\right)^2}}$$

$$\Delta z_n = \frac{\Delta z_n}{\sqrt{\left(\Delta z_1\right)^2 + \left(\Delta z_2\right)^2 + \left(\Delta z_3\right)^2}}$$

Figure 95: Normalizing the probabilities for each coordinate

$$\begin{pmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = x \quad \begin{pmatrix} \Delta y_1 \\ \Delta y_2 \\ \Delta y_3 \end{pmatrix} \cdot \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = y \quad \begin{pmatrix} \Delta z_1 \\ \Delta z_2 \\ \Delta z_3 \end{pmatrix} \cdot \begin{pmatrix} z_1 \\ z_2 \\ z_3 \end{pmatrix} = z$$

Figure 96: Dot product of probabilities with coordinate from each IMU to obtain final position.

6.5.2 Filters

The data collected by the sensor suites of LVIS will be passed through data filters both in real time during the flight and after the vehicle has landed. The purpose of this is to filter out process and measurement noise in the data in order to have a more accurate estimate of the vehicle's state at a given time. For mid-flight filtering, the linear Kalman filter will be utilized, and for post-flight filtering, the Extended Kalman Filter will be utilized, which is an industry standard for nonlinear state estimation.

For mid-flight filtering, the linear Kalman filter is an effective option due to its computational and memory efficiency, ease of implementation, and relative accuracy. Only the previous state of the vehicle and measurements corresponding to the current state of the vehicle are needed to perform data filtering and to estimate the current state of the vehicle.

A multi-dimensional Kalman filter works as the following: given an n^{th} stage where the state of the system is $\hat{\mathbf{x}}_{n,n}$, the filter will extrapolate an $n+1^{th}$ stage where that state of the system is $\hat{\mathbf{x}}_{n+1,n}$. This extrapolation is calculated according to the State Extrapolation equation, which is

$$\hat{\mathbf{x}}_{n+1,n} = \mathbf{F}\hat{\mathbf{x}}_{n,n} \tag{1}$$

where $\mathbf{F}$ is the state transition matrix, which in this application translates the previous position, velocity, and acceleration into the current position, velocity, and acceleration using the kinematic equations. Alongside extrapolating the state, the system also extrapolates an uncertainty $\mathbf{P}_{n+1,n}$ associated with its calculated expected state using the following equation

$$\mathbf{P}_{n+1,n} = \mathbf{F}\mathbf{P}_{n,n}\mathbf{F}^{\boldsymbol{T}} + \mathbf{Q} \tag{2}$$

After doing these extrapolations, the Kalman filter will compare these extrapolations with the values of the measurements. Setting $\hat{\mathbf{x}}_{n,n-1} = \hat{\mathbf{x}}_{n+1,n}$ and $\mathbf{P}_{n,n-1} = \mathbf{P}_{n+1,n}$, first the Kalman gain $\mathbf{K}_n$ is computed

$$\mathbf{K}_n = \mathbf{P}_{n,n-1}\mathbf{H}^{\boldsymbol{T}}(\mathbf{H}\mathbf{P}_{n,n-1}\mathbf{H}^{\boldsymbol{T}} + \mathbf{R}_n)^{-1} \tag{3}$$

where $\mathbf{H}$ is the observation matrix such that $\mathbf{z}_n = \mathbf{H}\mathbf{x}_n$, where $\mathbf{z}_n$ is the measurement and $\mathbf{x}_n$ is the true state of the system. The Kalman gain is then used to update the estimate using the measurement vector $\mathbf{z}_n$

$$\hat{\mathbf{x}}_{n,n} = \hat{\mathbf{x}}_{n,n-1} + \mathbf{K}_n(\mathbf{z}_n - \mathbf{H}\hat{\mathbf{x}}_{n,n-1}) \tag{4}$$

Along with the state estimate, its associated estimate uncertainty is also

$$\mathbf{P}_{n,n} = (\mathbf{I} - \mathbf{K}_n\mathbf{H})\mathbf{P}_{n,n-1}(\mathbf{I} - \mathbf{K}_n\mathbf{H})^{(}T) + \mathbf{K}_n\mathbf{R}_n\mathbf{K}_n^T \tag{5}$$

where $\mathbf{I}$ is the identity matrix. This process is repeated for every iteration, i.e. for every measurement, until the end of the flight is reached. It is initialized by inputting an initial state estimate $\hat{\mathbf{x}}_{0,0}$ and an associated uncertainty $\mathbf{P}_{0,0}$.

For post-flight, the Extended Kalman filter will be utilized for more accurate estimates as the trajectory of the launch vehicle will be inherently nonlinear. The state extrapolation and measurement equations in this application are

$$\hat{\mathbf{x}}_{n+1,n} = \mathbf{f}(\hat{\mathbf{x}}_{n,n})\mathbf{z}_n \qquad\qquad = \mathbf{h}(\mathbf{x}_n)$$

where $\mathbf{f}$ is a nonlinear state transition function and $\mathbf{h}$ is a nonlinear measurement function of the state of the system. This more computationally demanding model will provide more accurate state estimations during post-flight analysis in order to complete the mission of accurately determining the final location of the vehicle.

6.6 Vehicle Demonstration Flight

The payload was included in a modified state for both vehicle demonstration flights occurring on February 24th and March 1st. The modified configuration for the payload did not include the power distribution and transmission board, the battery, and battery mount in this launch.These elements will be included for the payload demonstration flight. For these flights, the payload was active with one branch of the three part redundancy system collecting data. During the vehicle demonstration flight, the retention system performed successfully with the 8-32 screws holding the payload in place despite high landing velocity. This can be seen in Fig.97. The screws holding the sensors to the wooden bulkhead and the standoffs did not break, and the wooden bulkhead did not crack. The temporary battery became loose, but did not disconnect. A ballast of 11.7 ounces was used to replace the weight of the excluded elements. The launch vehicle drifted 1796 ft, well within the 2500 ft meaning that the payload can perform tests of its filters post-flight in-house.

Figure 97: Nosecone and payload bay after VDF 2

6.7 Payload Demonstration Flight

March 16th and March 19th are two possible dates for the Payload Demonstration flight to occur pending weather conditions. In order for the mission to be deemed successful, the LVIS has to correctly identify and transmit the grid in which the launch vehicle has landed. Moreover, the LVIS has to be successfully retained as a system and all of its components. The team does not anticipate any issues with the second success criteria as the payload has demonstrated successful retention during both vehicle demonstration flights as discussed in the previous section. Moreover, the payload will fly in its final configuration with all of the designed elements such as the power distribution and transmission board. The data collected from the vehicle demonstration flights will serve to make the inertial navigation system more accurate.

7 Technical Design and Testing: Apogee Control System

7.1 Mission Statement and Success Criteria

The Apogee Control System (ACS) aims to induce controlled drag to bring the launch vehicle to the team's target apogee, 4,800 ft. Mechanically, the ACS is primarily driven by a lead screw and four drag tabs that extend outward from the body tube of the launch vehicle via hinges attached to the main system. The extension of such tabs is driven by a code that constantly analyzes the launch vehicle's position, velocity, and acceleration. The code utilizes an accelerometer, IMU, and power relay to determine the necessary extension of the drag tabs. The motor then turns the lead screw the necessary amount which rotates the lead screw and thus the drag tabs. When the target apogee is reached or the launch vehicle begins to descend (whichever occurs first), the drag tabs will retract inward and remain in that position for the remainder of the flight.

The following criteria In order for the ACS to be determined successful, it must meet the following criteria:

- The induced drag will cause the launch vehicle to reach the target apogee with a margin of error of ±25 ft.
- Reach the target apogee without jeopardizing the stability or safety of the launch vehicle or its flight.
- Extend and retract the tabs appropriately based on the position, velocity, and acceleration of the launch vehicle.
- The ACS shall not interfere with the other critical systems of the launch vehicle.
- The ACS shall only function after motor burnout.
- Data shall be saved for post-flight analysis.

7.2 Changes Since CDR

The design of the ACS mechanism was slightly altered to improve the safety and structural integrity of the system, but the overall concept of using rotational motion from the lead screw to generate linear motion in the pusher arms will remain unchanged. The thickness of the lead screw was increased from 0.315 in. to 0.5 in. Increasing the thickness of the lead screw increased the safety factor to 2. This change caused the design of the central hub to be slightly altered in order to interface with the new lead screw nut. The pressure isolation was removed based on evidence from the vehicle demonstration flight that it was not necessary in order to provide smooth altitude data. The material of the top bulkhead was changed from fiberglass to carbon fiber because carbon fiber is both lighter and stronger than fiberglass. This change in material increased the structural integrity of the system. Finally, the pusher arms were shortened from 6.25 in. to 5.25 in. to increase the speed at which the mechanism operates.

7.3 Mechanical Design

7.3.1 Mechanical Design and Fabrication

The mechanical design of the ACS contains four drags flaps which are integral to the body tube of the launch vehicle and actuated by a lead screw. To acuate the drag flaps, a HSR-M9382TH continuous servo motor rotates the leadscrew, which vertically translates a central hub that causes the drag flaps to hinge out via pusher arms. Flap support arms are connected to the backs of each drag flap so that the drag flaps themselves do not need to bear the mechanism loads during flight.

7.3.2 Drag Flaps

The drag flaps are the component of the ACS that induces controlled drag on the launch vehicle. The drag flaps are screwed into the flap support arms, which bear the mechanism loads. The flaps were made from the cutout sections of the body tube, and thus are made out of carbon fiber and match the curvature of the launch vehicle's exterior. Screw holes were cut in each flap using a drill press and their edges sanded with a belt sander to ensure smooth fitting with the body tube. The CAD model compared to a constructed drag flap is given in Figure 98.

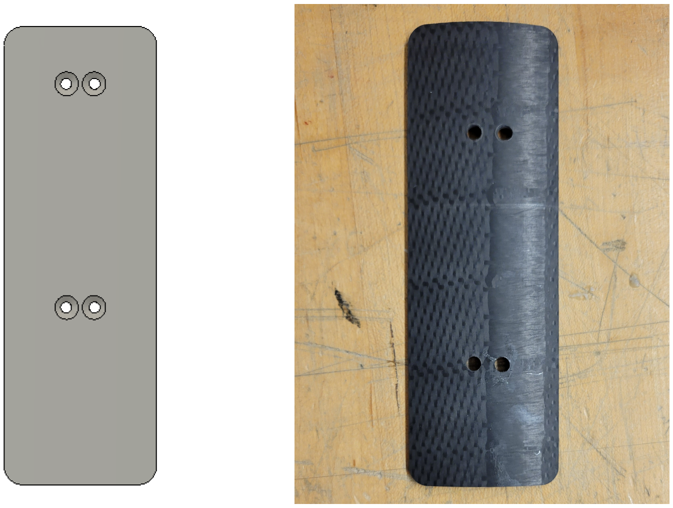


Figure 98: CAD model (left) and as constructed (right) Drag Flap

7.3.3 Flap Support Arms

The flap support arms hinge on the pusher arms and bulkhead hinges, providing structural support such that the load path does not primarily flow through the drag flaps. The flap supports were manufactured out of aluminum bar stock using a CNC mill to cut out the profile and a band saw and belt sander to make final adjustments. Additionally, holes were drilled and tapped to allow the flap supports to interface with the drag flaps. The CAD model compared to a constructed flap support arm is given in Figure 99.

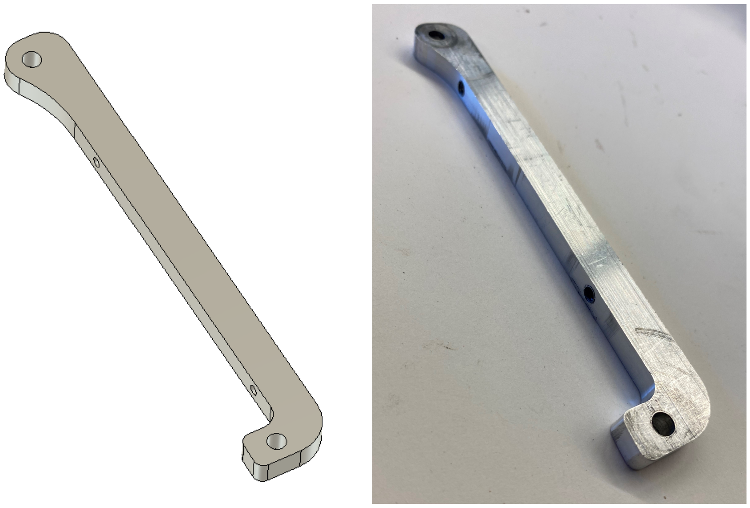


Figure 99: CAD model (left) and as constructed (right) Flap Support Arm

7.3.4 Bulkhead Hinges

The bulkhead hinges are fixed to the underside of the top bulkhead with nuts and bolts and interface with the flap support arms, allowing them to freely rotate. The hinges are load bearing components, and thus were machined out of aluminum bar stock. A CNC mill was used to first machine the hole along the hinge extrusion. Then, the stock was rotated and the CNC mill cut the hinge profile. A band saw and belt sander were used to remove tabs, and a drill press was used the drill the holes that interface with the fore ACS bulkhead. The CAD model compared to a constructed bulkhead hinge is given in Figure 100.

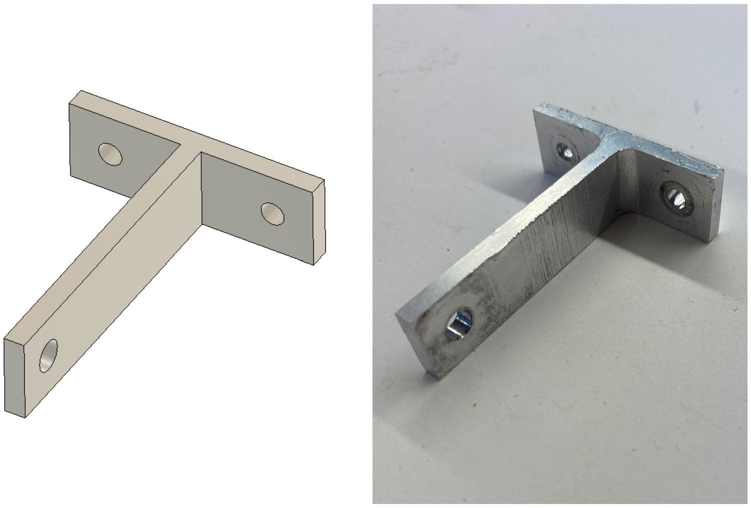


Figure 100: CAD model (left) and as constructed (right) Bulkhead Hinge

7.3.5 Pusher Arms

The pusher arms connect the central hub to each flap support arm, causing the flap supports to rotate about the bulkhead hinges as the central hub translates vertically. The pusher arms are load bearing and were manufactured out of aluminum bar stock. They were machined using a CNC mill, with finishing operations on the saw and belt sander to remove excess material. The CAD model compared to a constructed pusher arm is given in Figure 101.

Figure 101: CAD model (left) and as constructed (right) Pusher Arm

7.3.6 Lead Screw

The lead screw attaches to the motor and runs through the central hub. It must be capable of withstanding all possible loads on the mechanism, so the lead screw was sized based on the worst case scenario expected load of 308 lbs. The team selected a Thomson linear lead screw and lead screw collar assembly with a load capacity of 620 lbs, giving it a factory of safety above the required value of 2. The ends of the lead screw were machined on a manual lathe to better interface with the motor and bushing. Additionally, a set screw was added to better secure the lead screw to the motor. The physical lead screw is given in Figure 102.

Figure 102: As constructed lead screw

7.3.7 Central Hub

The central hub transforms the rotational motion of the lead screw into translational motion that moves the pusher arms and actuates the drag tabs in and out. The central hub was machined out of 6061 aluminum in a multi-operation process. First, the four through holes were machined by placing the stock in the mill on its side. Then, the top-down profile, hole, and counter bore were machined with a CNC mill, Finally, a 15/16"-16 tap was used to cut threads in the center hole, giving the central hub the ability to interface with the lead screw which runs through its center. The CAD model compared to the manufactured central hub is given in Figure 103.

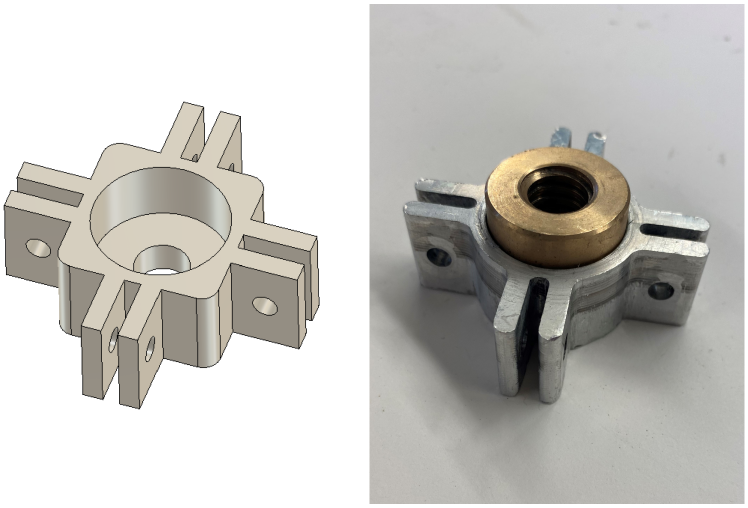


Figure 103: CAD model (left) and as constructed (right) Central Hub

7.3.8 Bulkheads

There are three bulkheads in the ACS, two to bookend the ACS structure and one additional bulkhead to house the servo motor. The top bulkhead is made out of carbon fiber because its high strength allows it to bear the loads experienced during drogue parachute deployment. The middle and bottom bulkhead were manufactured using fiberglass due its strength, light weight, and the team's experience working with the material in the past. Each bulkhead was sized using FEA calculations according to the maximum worst case scenario loads with a factory of safety of 2. The holes the bulkheads were cut out using a laser-cut piece of wood to locate each hole and a drill press to drill the appropriately sized holes. Aluminum airframe interfacing blocks will be fixed the the top and bottom bulkheads to position and fix the ACS in place within the launch vehicle.

7.3.9 Mechanical Design Assembly and Integration

Mechanical assembly began by attaching the arms together using a shoulder screw and the corresponding nut. Each arm has three main separate pieces, the flap supports that attach to the top bulkhead and the flaps and the push arm that fits between the flap supports and attaches to the central hub with the same size shoulder screw. The two pieces that are attached to the top bulkhead are secured in place by the hinge brackets which are also screwed into the top bulkhead.

Each flap is attached to two arm supports with two screws on the top half of the flap and two screws on the bottom half of the flap; each arm support has two points of contact with the flap.

The PCB is screwed into the electronics board at four different positions and attached to the motor and batteries through wire connections. The black electronics board is attached to the top and middle bulkheads with eight "L" brackets, two at each connection point (four connected to each bulkhead).

The fully assembled ACS system fits into the body tube with cutouts. While the flaps are attached to the push arms, the flaps are able to extend outside of the body tube as expected.

The top bulkhead interfaces with the electronics board via four L-brackets on the bottom side of the bulkhead. Two L-brackets face each on each side in order to sandwich the electronics board. Each L-bracket is held in place by one screw so that it can be rotated into the correct orientation. The standoffs also sit on the bottom of the bulkhead which are screwed in through the top. Four airframe interfacing blocks sit on the top of the bulkhead which are screwed in by two screws each facing downward. Lastly, each arm interfaces with the bottom of the bulkhead via two downward-facing screws. Lastly, the hook sits in the center of the top bulkhead and is screwed in from the top as well.

The middle bulkhead sits at the bottom of the electronics board. It holds the electronics board in place with four standoffs facing each other on each side. The standoffs which hold up the top bulkhead also mirror how they are held in place by the top bulkhead. Additionally, four standoffs are screwed in from the top which holds up this bulkhead. Lastly, the motor sits on the bottom side of this bulkhead and faces downward.

The bottom bulkhead holds up the middle bulkhead with the aforementioned standoffs. The bottom of the central hub also rests in the center of the top of this bulkhead when the arms are fully down.

The central hub holds the bottom of the arms with a shoulder screw for each arm which allows the arms to rotate as the central hub moves up the leadscrew. The leadscrew nut fits into the center of the central hub and screws into the lead screw. The top of the lead screw then interfaces with the rotor of the motor.

Four standoffs each sit in the gaps between the bulkheads and hold them up. The ones holding up the top bulkhead create a rectangle with the longer sides perpendicular to the length of the electronics board. The lower standoffs create a square. This way, the two sets of standoffs do not rest directly on top of one another which allows them to screw in. An image of the integrated system compared to the CAD model is shown in Figure 104.

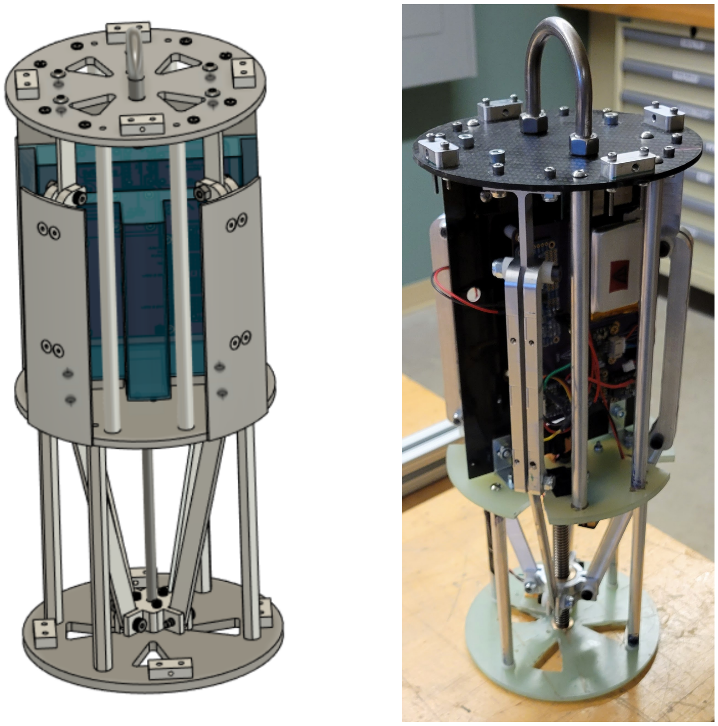


Figure 104: CAD model (left) and as constructed (right) Integrated ACS

7.4 Electrical Design

The following sections detail the electronic design and testing for the ACS.

7.4.1 Electrical Component Integration and Testing

The ACS is comprised of a series of sensors which are connected to a Raspberry Pi 4 microcontroller using a custom PCB which is detailed in Section 7.4.2. These sensors include a DFRobot Gravity I2C H3LIS200DL Triple Axis Accelerometer, Adafruit BMP390 Altimeter, and an ICM-20948 9DoF inertial measurement unit. The Raspberry Pi 4 constantly monitors data pertaining to the state of the rocket and operating the servo accordingly to induce drag on the launch vehicle. Section 7.5.2 explains this algorithm in more detail. The entire system is powered by two 3.7 V 2800 mAh LiPo batteries connected to the Raspberry Pi 4 via an Adafruit PowerBoost 500C to step up the voltage to the 5 V. An additional identical battery and powerboost is used to supply the servo through a Adafruit PCA9685 16-Channel 12-bit PWM/Servo Driver compatible with the I2C interface, which has the additional function of allowing us to control the servo more precisely and avoid jittering/uncertain movements. Finally, the servo is encased in copper tape shielding to prevent the relatively high current from interfering with the sensors by inducing magnetic fields.

Two tests were performed to ensure rigorous and effective design and integration of the electrical component of the ACS. The first consisted of powering on the system for 3 hours in sub-freezing temperatures and ensuring all functionality had been maintained over this duration. The entire system was able to properly read data and respond to signals for the entire time. The second test employed specially developed software to simulate the conditions of an actual flight. Using data collected from real subscale test flights in addition to data from computer models, the microcontroller was supplied with mock sensor data in the form of a csv file, the same sort of file that is generated during an actual flight. The microcontroller successfully read through the data in real time and deployed the drag flaps at burnout in addition to retracting them at overshoot and apogee.

7.4.2 PCB Design

The team designed a 2-layer purple Printed Circuit Board (PCB) in KiCAD and printed it using OSHPark's fabrication service, so that all components of the system are mounted securely. Using a PCB mostly eliminates the need for external wiring and provides a more reliable way of keeping all the components electrically connected. It also reduces the space taken up by electronics on the sensor sled when compared to using a perfboard with manually wired connections.

The PCB was designed with the following dimensions: 124.0 x 98.0 x 1.6 mm. It was designed for the THT (Through Hole Technology) mounting of electronics, which involved soldering header pins onto each component. These components were then soldered onto the appropriate placeholders of the PCB, which were marked out and labeled using the front silkscreen and/or the back silkscreen layer when designing the PCB. The silkscreen also includes the names of a component's pins that must be soldered to ensure connectivity with other components. The bonds created between THT components and the board are far stronger than SMT (surface mount technology) bonds, making THT ideal for components that will undergo significant mechanical stress (such as during vehicle launch and recovery). A 2D rendering of the PCB as seen from the top is shown in Figure 105.

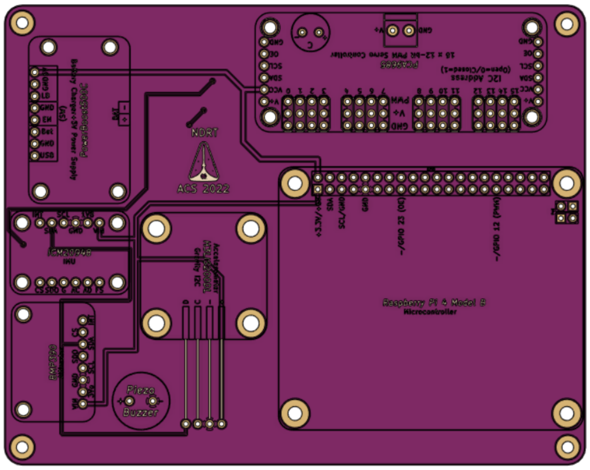


Figure 105: Top view of ACS PCB

7.5 Control Flow Design

The overall control flow design of the system is described by Figure 106.

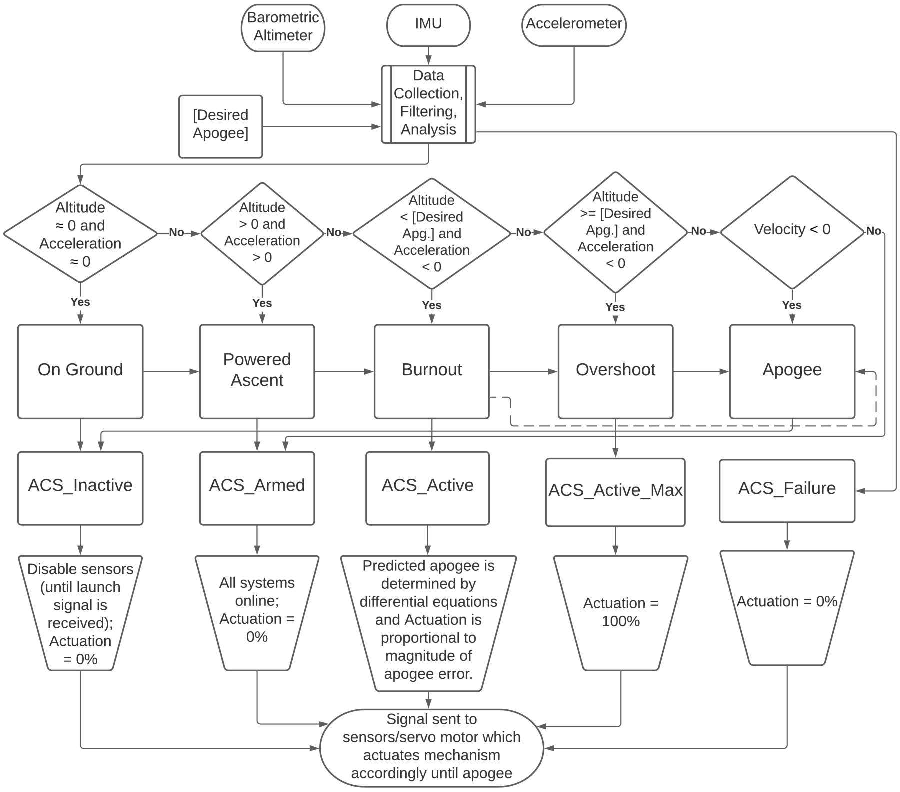


Figure 106: ACS overall control code flow chart

There are three main sensors that collect data: Barometric altimeter, Internal measurement unit, and Acceleration sensor. The raw data from these sensors is collected, filtered, and analysed along with desired apogee. An error within this process will lead to a start of the ACS_Failure function, causing zero percent actuation, meaning that the sensors will be sent to repair. The determination of the next step depends on the values of altitude and acceleration in all other cases. If both of the values are equal to zero, it means that the measurements are made on ground. In this case, ACS_Inactive function is started, meaning that actuation is equal to zero percent and sensors are disabled until the launch signal is received. If both altimeter and accelerometer values are positive, then the rocket is in its powered ascent phase. In this case, ACS_Armed function is started, so all systems are online, but actuation is still equal to zero percent. If the altitude value is less than a desired apogee and acceleration value is below zero, then the rocket is in its burnout phase. This starts the ACS_Active function, so the predicted apogee is determined by differential equations, while the actuation is proportional to the magnitude of the apogee error. If the altitude is greater than or equal to the desired apogee and acceleration value is negative, then the rocket is in its overshoot phase. Thus, ACS_Active_Max function is started, meaning that the actuation is equal to a hundred percent. In all other cases, if velocity value is below zero, then the rocketry is in its apogee phase, leading to the start of the ACS_Inactive function, in which, the sensors are temporarily disabled and actuation is equal to zero percent. However, if velocity value is positive, then the ACS_Armed function is started, meaning that all systems are online, but actuation is equal to zero percent. Each outcome sends a signal to the sensors monitor that actuates mechanism accordingly until the apogee, regardless of the function used. The successful implementation of this control flow represents a successful verification of ACS.1.

7.5.1 Kalman Filter

The purpose of the ACS control system is to dynamically adjust the extension of the drag surfaces during flight to ensure that the launch vehicle attains the target apogee. The system must first know the current position, velocity, and acceleration of the vehicle to determine the optimal action at any given time. However, the system cannot use these sensor values directly, since they contain sensor noise and lack an estimate of velocity.

A Kalman filter can be used to address these issues. The purpose of the Kalman filter is to combine information from different data streams with a physical model of how the system will evolve over time to determine a single, denoised estimate of the current height, velocity, and acceleration of the launch vehicle. The Kalman filter was chosen for its task due to its relative accuracy, efficiency, and ease of implementation. However, the greatest advantage to the Kalman filter over other similar data filters is that it is memory-less. At any given time, the only next output from the filter is solely dependent on the current previous output and the current input to the filter.

The Kalman filter must carry out two stages of calculations at each time step. First, the filter uses a kinematic model of the system to determine how the launch vehicle will likely move in the prediction stage. Next, the update step allows the system to update the filter with current sensor data and correct the extrapolations used to produce the estimate from the prediction step. The input to the prediction step is the vector $\hat{x}_{k(-)} = \langle y, v_y, a_y \rangle$, which contains the current estimate of the state of the rocket, which consists of the height y, the vertical velocity v_y, and the vertical acceleration a_y. A matrix Φ_k is used to translate from estimates of the current state $\hat{x}_k$ to an estimate of the next state, $\hat{x}_{k+1}$ at some time step k. This matrix is derived from basic kinematics equations, and is defined in Equation 6.

$$\Phi_k = \begin{pmatrix} 1 & \Delta & \frac{1}{2}\Delta^2 \\ 0 & 1 & \Delta \\ 0 & 0 & 1 \end{pmatrix} \tag{6}$$

Δ denotes the change in time between the current iteration of the algorithm and the previous iteration of the algorithm. Combining this definition with $\hat{x}_k$ gives the relation seen in Equation 7

$$\hat{x}_{k(-)} = \Phi_{k-1}\hat{x}_{k-1(+)} \tag{7}$$

Here, $\hat{x}_{k(-)}$ is the model's cursory estimate of the current state of the launch vehicle based solely on the previous state and the kinematic equations encapsulated by Φ_k. Once this estimate is obtained, it is combined with the vector z, which contains the current set of readings from the accelerometer, altimeter, and IMU. The matrix H is used to convert some state vector $\hat{x}$ into some estimate of what the sensor readings would be given that state, which is denoted as z. This conversion, along with the Kalman gain K, is used to create a more refined estimate of the current state of the launch vehicle, as seen in Equation 8.

$$\hat{x}_{k(+)} = \hat{x}_{k(-)} + K_k(z_k - H_k\hat{x}_{k(-)}) \tag{8}$$

The quantity $\hat{x}_{k(+)}$ is a refined estimate of state which can be outputted to the rest of the system to ensure that the other components can operate under the best possible estimate of the current state. The Kalman filter then performs a few extra computations to ensure that the model is prepared for the next iteration. The matrices Q_k and R_k store the estimates of the covariances of the states and measurements respectively. These matrices are tuned by hand based on analysis of sensor readings. Additionally, the Kalman gain matrix P_k gives an estimate of the covariance of the current $\hat{x}_k$. In order to update the Kalman gain matrix, the Equations 9 - 11 are used. Note that here, I represents the identity matrix.

$$P_{k(-)} = \Phi_{k-1} P_{k-1(+)} \Phi_{k-1}^T + Q_{k-1} \tag{9}$$

$$P_{k(+)} = [I - K_k H_k] P_{k(-)} \tag{10}$$

$$K_k = P_{k(+)} H_k^T [H_k P_{k(+)} H_k^T + R_k]^{-1} \tag{11}$$

This filter is based on a linear, kinematic model of the launch vehicle which assumes no drag. However, it is still effective at providing a noise-free estimate of the state of the launch vehicle at any given time. The team will explore some alternative data filtering algorithms which could provide a more sophisticated model of the flight. However, the Kalman filter has proven to be reliable and relatively straightforward during previous years.

7.5.2 Proportional Control Algorithm Design

Actuation of the drag tabs will be actively controlled after burnout is detected with a PID algorithm until apogee is detected. The servo motor will function as the actuator, as its angle will adjust the extension of the tabs as previously described. The algorithm will incorporate model predictive features; from the current state of the rocket, a fourth order Runge-Kutta integration will be performed to predict the final apogee of the rocket. This predicted value will be compared to the target apogee of 5300 ft, and the tabs will be extended according to the PID control law given in Equation 12.

$$\Phi(s) = K_P E(s) + K_D s E(s) + K_I \frac{E(s)}{s} \tag{12}$$

Here, $E(s)$ is the error in the frequency domain, Φ is the angle of servo rotation, and K_P, K_D, and K_I are the proportional, derivative, and integral gains respectively. The integral of the error will be computed using a trapezoidal method of numerical integration, and the derivative of the error will be calculated using a first order backward finite difference method. The algorithm includes an error threshold such that the servo does not try to extend the tabs further than they are able. Gain scheduling will be employed because the drag varies so significantly between burnout and apogee. Sets of gains will be selected for three regimes based on the airspeed of the rocket, which will allow finer adjustment and help prevent undershooting. The flights will be simulated using a Matlab script based on OpenRocket modeling that will generate adaptive flight data in order to select the gains for each airspeed regime and test the effectiveness of the tabs.

7.6 Testing and Demonstration Flights

All ACS system tests and demonstrations either passed or were completed. This gives the team confidence that the ACS will function as expected while in flight. The success of the Battery Duration Test (ACST.6) gave the team confidence that the ACS would be able to survive the worst-case scenario weather conditions on launch day. The Static Loading Test (ACST.8) and Loaded Flap Actuation Demonstration (ACST.5) gave the team confidence that ACS would be capable of withstanding the substantial loads during launch and be able to respond appropriately to flight data. The team was also given confidence in the system's capabilities during the Limit Switch Detection Test (ACST.7), where it was shown that drag tabs actuate up to when the pusher arm makes contact with the limit switch, rather than stopping because the motor stalled. The success of these four tests allows the team to be prepared for the system's use and functionality while in flight.

A complete Vehicle Demonstration Flight with Active Apogee Control System was completed on March 1. Further discussion of the expected and actual behavior of the system, as well as the data collected is given in Section 8.4.2.

8 Demonstration Flights

This next section details the team's two vehicle demonstration flights and the analysis of the data collected.

8.1 Demonstration Flight Overview

The team attempted two vehicle demonstration flights in Three Oaks, Michigan. The first demonstration flight occurred on February 24, 2022. A second vehicle demonstration flight was deemed necessary after an error in the recovery sequence, and an ACS malfunction that caused it to be inactivate in flight. A second flight was conducted on March 1, 2022. The flight summary for the two flights is shown in Table 49.

Table 49: Vehicle Demonstration Flight Information

Variable	Summary	Summary
Flight Type	Demonstration Flight 1	Demonstration Flight 2
Date	2/24/22	3/01/22
Location	Three Oaks, MI	Three Oaks, MI
Wind (mph)	13	7
Atmospheric Pressure (inHg)	30.15	30
Air Temperature (°F)	27	43
Motor (NASA 2.19.1.5)	Aerotech L2200G-P	Aerotech L2200G-P
Ballast (oz) (NASA 2.19.1.6, NASA 2.23.7)	41.1	36.4
Final Payload (Y/N)	N	N
Apogee Control System Status	Inactive	Active
Official Target Altitude (ft)	4800	4800
OpenRocket Trajectory Altitude (ft)	5119	5237
RockSim Trajectory Altitude (ft)	5808	5759
Measured Altitude (ft)	5815	5397

8.2 Flight Profile

The flight profiles taken from the PRM altimeters from both attempted demonstration flights are shown plotted in Figure 107. (NASA 2.19.1.8).

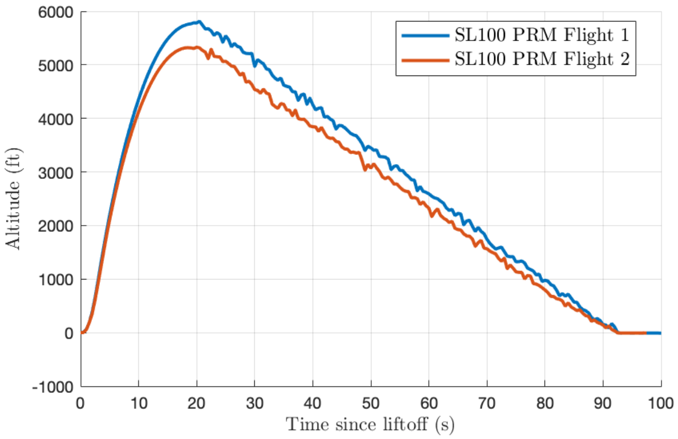


Figure 107: Flight Profiles for Each Attempted Flight

8.3 Vehicle and Recovery System Verification

During Flight 1, the majority of the launch vehicle components performed as intended. The launch vehicle exited the launch rail in stable flight. On-board footage showed that very little rotation occurred during ascent, suggesting the fins were well-aligned and the vehicle's stability was very close to the target static stability of 2.75. At apogee, the first separation event was successful and resulted in the separation of the recovery and payload body tubes and the successful deployment of the drogue parachute. At the second separation event approximately 500 ft AGL, the fin can and ACS body tubes separated successfully. However, the pilot parachute did not successfully pull the main parachute out of its deployment bag at this separation point. With the main parachute not functioning properly, the launch vehicle continued to descend rapidly and contacted the ground at a high kinetic energy. This impact resulted in damage to several vehicle components. The full extent of the damage and repairs to the launch vehicle are detailed in Table 50.

Table 50: Damage and Repairs to Launch Vehicle from Flight 1

Vehicle Component	Damage	Repairs
Fins	Two fins dislodged from their respective slots in the fin can	Old epoxy from fins was removed and fins were re-epoxied into the fin can.
Fin Can Body Tube	Minor cracks less than 1 inch in length originating from the fin slots	The cracks were sanded an cleaned before epoxy was applied to the cracks and sanded once the epoxy was set.
ACS Coupler	Major crack in the longitudinal direction of the coupler	Several sheets of carbon fiber were applied and epoxied to the inside wall of the coupler. Epoxy was added to the outside cracks of the coupler which were subsequently sanded.
Payload Coupler	Minor crack in fiberglass coupler	Several fiberglass sheets were epoxied to the inside of the coupler walls.
Nose Cone	Two cracks near the tip of the nose cone	Fiber glass sheets epoxied to the nose cone and sanded to maintain the orignal shape of the nose cone.

During the second attempt, the recovery system performed as expected until the deployment of the main parachute. Rather than inflating, the main parachute remained closed and the vehicle descended as if it were under a streamer. This resulted in the vehicle landing with higher kinetic energy than intended.

8.4 Payload System Verification

The following sections detail the criteria needed to verify the LVIS and ACS.

8.4.1 Launch Vehicle Identification System

Since the final payload configuration was not flown, the team could not verify all of the requirements. However, the retention system of the payload was in its final design iteration and proved successful. The following success criteria were completed and verified after the two vehicle demonstration flights.

- 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. Moreover, satisfies (NDRT Req. LVIS.2)

8.4.2 Apogee Control System

The functionality of the ACS was based on the completion of the following success criteria.

- System correctly identifies the state of the launch vehicle throughout the flight (NDRT Req. ACS.1)
- System actuates and retracts drag tabs in the burnout to apogee stage of flight, also known as the active ACS state
- System collects reasonable altitude, acceleration, and orientation data, and sensor readings agree with one another and with readings taken from the Recovery system (NDRT Req. ACS.2)
- Apogee of the launch vehicle with active ACS is lower than predicted apogee from simulations (NDRT Req. ACS.4)

These criteria were met during this demonstration flight. The Apogee Control System deployed as expected, decreasing the apogee of the launch vehicle from the predicted 5705 ft to 5463 ft, or a delta of 242 ft. Through tuning of the PID control algorithm, the system is fully expected to decrease apogee to the target apogee of 4800 ft. The finalized algorithm will be demonstrated at the payload demonstration flight.

The sensor suite, including acceleration, altitude, and orientation data, performed as expected. A plot of the Kalman filtered altitude data vs time is given in Figure 108

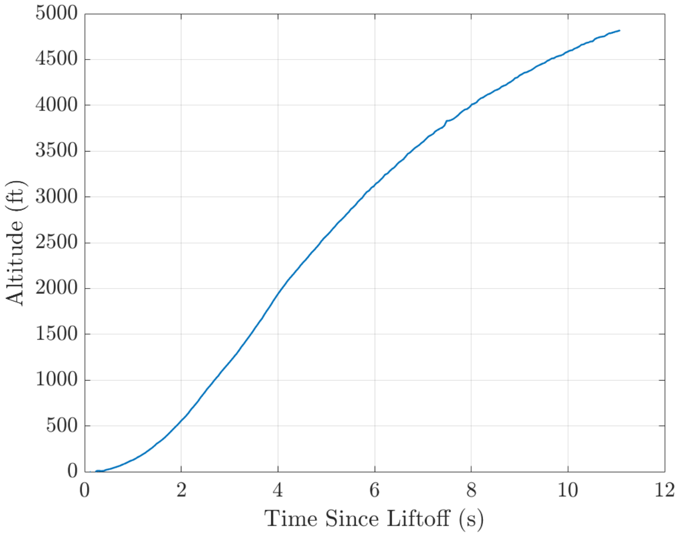


Figure 108: Kalman filtered altitude data in ft versus time in seconds since launch

The filtered altitude data has minimal noise despite having an active ACS, as shown in Figure 108. This suggests that no further isolation of the pressure sensor is necessary in order to provide satisfactory altitude data for the control algorithm.

8.5 Vehicle Demonstration Flight Analysis

OpenRocket and RockSim were used to simulate the vehicle flight under the same conditions as each demonstration flight, including the wind speed, turbulence intensity, temperature, pressure, and launch rail length. The simulated apogees for the first flight in Open Rocket and RockSim respectively were 5119 and 5808. The simulated apogees for the second flight in Open Rocket and RockSim respectively were 5237 and 5759. Figures 109 and 110 shows a comparison between the altitude data simulated by OpenRocket and RockSim and the data collected by the recovery altimeter. One important note in analyzing these plots is that the ACS system was active in the second flight but not the first. Therefore, the actual measured apogee in the first flight should line up with simulations while the measured data from the second flight should be substantially less than the simulations due to the added drag. Based on the results from both flights, RockSim appears to be more accurately predicting the performance of the full scale vehicle while OpenRocket had been more accurate at subscale. All of the components in both simulations were simulated as being coated with a smooth paint.

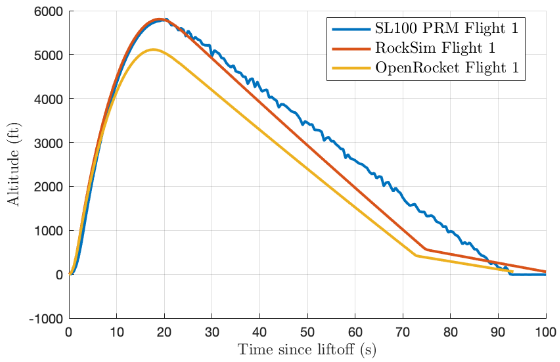


Figure 109: Flight 1 Data Compared to Simulation Data

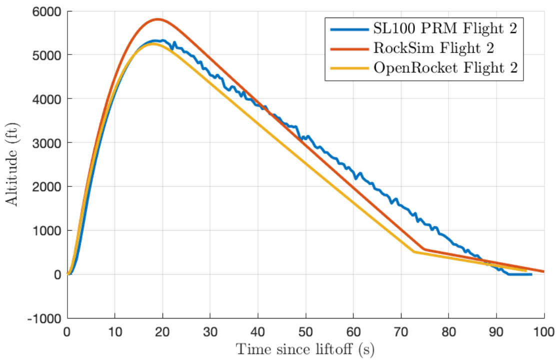


Figure 110: Flight 2 Data Compared to Simulation Data

The drag coefficient, C_d, of the launch vehicle was found using the recovery altimeter data from burnout to apogee. This data was passed through a Kalman filter in order to smooth the data. A 5th-order polynomial fit was then applied to the data. Figures 111 and 112 below shows the recovery altimeter data form burnout to apogee along with the fitted curve.

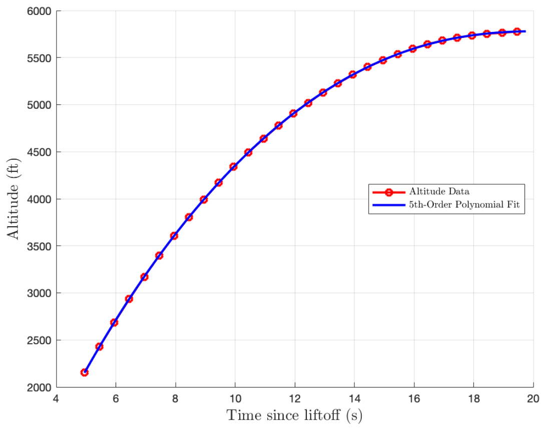


Figure 111: Flight 1 Polynomial Fit Check

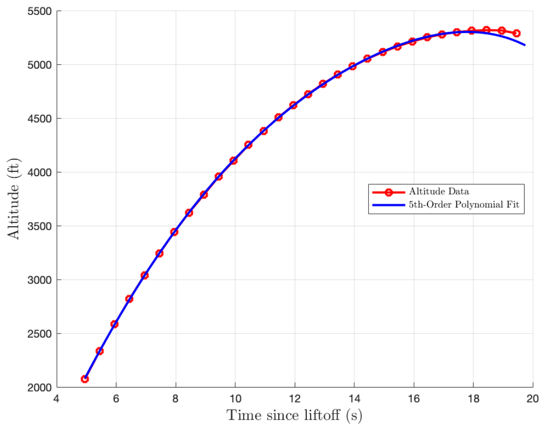


Figure 112: Flight 2 Polynomial Fit Check

The equation for the fitted curve was differentiated with respect to time in order to determine the velocity and acceleration of the launch vehicle. Equation 13 was used to calculate the acceleration of the launch vehicle at every point from burnout to apogee. During this period, the only significant forces acting on the vehicle were the force due to gravity and the drag force. Due to this, the drag force could be calculated using Equation 13.

$$F_d = ma - mg \tag{13}$$

The drag coefficient of the vehicle demonstration flight could then be calculated using Equation 14 below.

$$C_d = \frac{2F_d}{\rho A v^2} \tag{14}$$

Figure 113 shows a graph of the drag coefficient over the period from burnout to apogee using the described method for both demonstration flights.

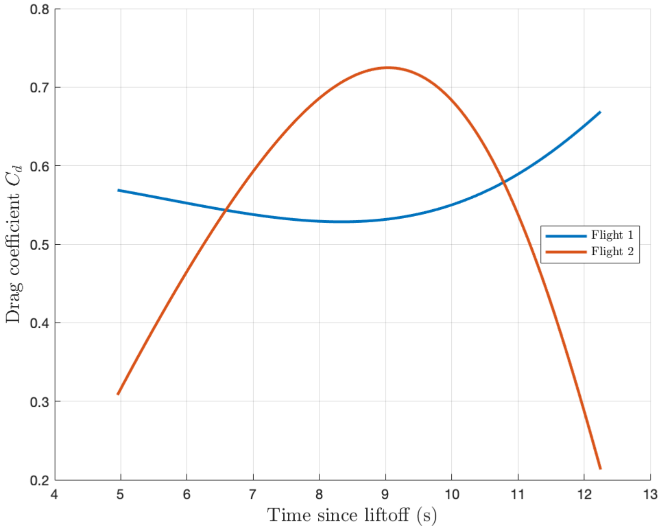


Figure 113: Demonstration Flight Attempts Approximated Drag Curves

The drag shown in Figure 113 represents the full scale vehicle without ACS because the first flight did not have an active ACS deployment. The average value of the drag coefficient was found to be near 0.55. This was close to the simulated drag coefficient of 0.48. However, the drag for the second flight is seen to be far higher as the the ACS deploys drag tabs. RockSim was used to perform the simulation again using this value. Because the calculation does not factor in the angle relative to vertical that the vehicle is travelling at, these drag values are based on the vertical ascent of the vehicle. This likely leads to drag values that appear to be higher than the actual due to not taking the horizontal travel into account. Further analysis will be conducted on the data from subsequent vehicle demonstration and payload demonstration flights.

8.6 Comparison to Subscale

A 50% subscale flight was completed in order to gain an understanding of the construction and flight parameters of the full scale rocket. A comparison of full-scale and subscale dimensions can be found in Table 52. There were two major implications for the full-scale launch based on the subscale. First, the subscale launch vehicle experienced a wobble immediately after exiting the launch rail. This was attributed to low off-rail stability under higher wind conditions. For full scale, the team reviewed stability data from the simulations as well as wind speed data before launching in order to assure that the minimum off-rail stability was met. The stability data for both subscale and full-scale can be seen in Table 51. Second, due to the drag force produced by the ACS flaps on subscale, care was taken to appropriately size the shear pins to prevent a premature separation event on the full-scale launch vehicle. Details on shear pin calculations can be found in section 4.3.2. Additionally, while the subscale results lined up closely with the OpenRocket simulation, the full scale results, so far, line up better with the RockSim results. However, the predicted drag coefficient for full scale was 0.55 while that of subscale was 0.56 showing close similarity.

Table 51: Comparison of Full-Scale to Subscale Stability Parameters

Parameter	Full-Scale	Subscale
CG location (in.)	82.2	82.2
CP location (in.)	99.2	99.1
Static stability margin (cal)	2.76	2.75
Off-rail stability (cal)	2.75	2.79
Off-rail velocity (ft/s)	75.2	89.9

Table 52: Dimensions of Full-Scale and Subscale Vehicle

Component	Full-Scale (in.)	Subscale (in.)	Scaling Error
Nose cose exposed length	24	10	-16.67%
Body tube total length	105	56.5	7.62%
Body tube diameter	6.17	3.125	1.30%
Tail cone length	3	1.5	0.00%
Fin root chord	6	3	0.00%
Fin height	7	3	-14.29%

8.7 Post-Flight Structural Integrity

The following details the results of on vehicle's structural components after the demonstration flights.

8.7.1 Launch Vehicle

The launch vehicle was put through two vehicle demonstration flight attempts. Throughout ascent and section separation, all vehicle components remained intact and undamaged proving to be able to reliably handle all standard in-flight loads. Due to issues with the main parachute, the vehicle landed excessively hard on both flight attempts. Fin and coupler damage was sustained during each landing, but this damage is not thought to be representative of possible damage during a nominal descent.

8.7.2 Recovery

The structural components of both recovery modules remained undamaged and secure during both demonstration flights.

8.7.3 LVIS

The LVIS did not sustain any structural damage for either vehicle demonstration flights. The overall structure remained secure through the AIBs and retention screws.

8.7.4 ACS

The ACS remained structurally intact throughout both demonstration flight attempts. The system was successfully retained within the ACS bay using the airframe interfacing blocks and 8-32 screws.

8.8 Payload Mission Sequence

The final, active payload was not flown, so the team cannot evaluate the entirety of the payload systems. However, the retention system was complete and was tested as outlined in the 6.6. For the final, active payload, the following mission sequence for the payload demonstration flight will be followed.

1. Inspect the LVIS retention and electrical elements for secure attachment, secure fastening, and structural rigidity.
2. Measure the battery to verify full charge.
3. Ensure that the required programs and SD cards have been uploaded and inserted.
4. Insert LVIS into payload body tube and align retention blocks with the body tube holes.
5. Secure LVIS with the 8-32 screws.
6. Once the launch vehicle is on the launch pad, power on LVIS electronics through the use of a pull-pin switch.
7. After landing, the LVIS will transmit the grid number and will be ready for retrieval.
8. After retrieving the nosecone and payload bay, the LVIS will be removed by unscrewing the retention screws and powered off.
9. Verify reported grid with the recovery GPS mounted on the LVIS.

8.9 Timeline Verification and Future Flights

NDRT has already scheduled upcoming flights, and backup dates, with the Michiana Rocketry Club in Three Oaks, MI, for the Vehicle Demonstration Re-Flight and Payload Demonstration Flight. Four potential dates have been scheduled for further demonstration flights, due to the large quantity of weather-induced cancellations when planning vehicle demonstration flights. Additionally, the competition, and respective backup location in Three Oaks, MI, have also been scheduled. All dates of launch opportunities can be viewed in Table 53.

Table 53: Future Flights

Date	Flight Type	Objectives
March 19/20, 2022	Vehicle Demonstration Re-Flight + Payload Demonstration Flight	Fulfill Req 2.19, 4.3
March 26/27, 2022	Vehicle Demonstration Re-Flight + Payload Demonstration Flight (Backup)	Fulfill Req 2.19, 4.3
April 23, 2022	Competition Flight	Fulfill Req 6.2
April 9, 2022	Competition Flight (Backup at Three Oaks, MI)	Fulfill Req 6.2

9 Safety

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 and FAA rules and regulations (NASA 4.3.2).
- Ensure team compliance with **all** NASA Student Launch rules and regulations.
- Ensure team compliance with **all** University of Notre Dame rules and regulations.
- Ensure safe practices at **all** NDRT STEM Engagement Activities.

These responsibilities result from the team's paramount goal of ensuring the safety of all individuals 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 of and implement risk mitigation strategies for specific components of the launch vehicle's airframe, recovery system, payload, and Apogee Control System.

9.1 Launch Concerns and Operation Procedures

LAUNCH OPERATING PROCEDURES

Revision Number	Date	Change Description
1.0	12/21/2021	Initial
1.1	2/3/2022	First Updated Version
1.2	2/27/2022	Second Updated Version

9.1.1 Introduction

Full scale launches are the culmination of a year's worth of hard work, dedication, and passion. Full scale launches also consist of costly and dangerous components that, if handled improperly, can result in launch vehicle damages, human injuries, or worse. Because of these risks, launch procedures have been written to provide a step-by-step guide on the necessary procedure for a successful launch.

Note: All actions must follow NAR/TRA and FAA rules and regulations. Further information on NAR/TRA and FAA rules can be explained by the Safety Officer, Michael Bonaminio, or they can be found in Safety Handbook Section 10. For all launch activities, the Range Safety Officer (RSO) has the final say.

Required Personnel:

NAR/TRA Level 3 Certified Team Mentor: Dave Brunsting

Safety Officer: Michael Bonaminio

Project Manager: Jacob Shapiro

Systems Lead: John McBride

Vehicles Lead: Tyler MacKnight

ACS Lead: Nandini Sadagopan

Recovery Lead: Katherine Fink

Payload Lead: Jackie Lomeli

If necessary, a qualified team member may assume the responsibilities of a required personnel, besides the Team Mentor, upon the approval of both the Safety Officer, Project Manager, and the applicable required individual.

Important: All equipment must be handled with intense care before, during, and after the launch. Do not handle any equipment without proper understanding of its operation, and only handle components when necessary.

9.1.2 Launch Rehearsal

The day before the launch, full scale launch attendees must attend a launch rehearsal event where the launch vehicle is constructed by following the Launch Procedures, including all steps from sections 9.1.3 through 9.1.9. However, any energetics which may only be handled by Team Mentor Dave Brunsting will ***not*** be included in the launch rehearsal. This event is beneficial for all team members to understand the step-by-step procedures for launch. The launch rehearsal allows the team to update launch procedures to include unexpected complications so these issues can be easily resolved in the future. At the end of the launch rehearsal, the Project Manager and Safety Officer must announce launch day weather conditions to attendees to ensure all team members are dressed appropriately for the launch.

9.1.3 Launch Checklist

Before departure from the workshop for the launch, the following checklists must be accounted for. All required personnel must sign off that all checklist equipment is packaged and ready for launch. Once the equipment is accounted for and stored for transportation, no one may handle it until arrival at the launch site.

Note: Lithium-polymer batteries are a potential fire hazard and must be inspected for imperfections, such as swelling or punctures, before departure from the workshop. Additionally, store all batteries not in use in the fire proof battery case, and turn OFF all electronics until it is necessary for the mission for them to be turned ON. If launch conditions are frigid, place all electronics in the warmth of a transportation vehicle until it is necessary for the electronics to be used, as specified in the launch procedures.

Troubleshooting: What if batteries are found to be damaged?

1. Team members tasked with handling the batteries are REQUIRED to wear heat resistant gloves and safety glasses.
2. Approach the batteries with caution; they are to be handled as an explosive hazard.

3. Hold batteries away from your face and body.
4. Place batteries in a fire resistant battery bag.
5. Bring battery bag to qualified and authorized disposal site. (See Safety Handbook Section 9)

How to test lithium polymer batteries:

1. Use a multimeter.
2. The nominal voltage of a lithium polymer battery is 3.7 V or 7.4 V, depending on the type of battery being tested for launch vehicle components.
3. If the batteries are not fully charged, charge them and ensure they are fully charged before packing for launch.

PERSONAL PROTECTIVE EQUIPMENT

- ☐ Nitrile gloves (1 box)
- ☐ Cut resistant gloves (1 pair)
- ☐ Heat resistant gloves (1 pair)
- ☐ Leather gloves (1 pair)
- ☐ Fully-stocked first aid kit (See Safety Handbook Section 2.1)
- ☐ Dust masks (1 box)
- ☐ Safety glasses (3 minimum)
- ☐ Fire resistant battery bags (5 minimum)

TOOLS

- ☐ Fully charged portable hand drill
- ☐ Screwdriver set
- ☐ Scissors
- ☐ Butane soldering iron (SOP 1.1.4)
- ☐ Butane gas canister
- ☐ Digital multimeter
- ☐ Standard drill bit case
- ☐ Exacto knives
- ☐ Metal files
- ☐ Wire cutters (SOP 1.1.5)
- ☐ Wire strippers (SOP 1.1.5)
- ☐ Bluntnose pillars
- ☐ Standard wrenches
- ☐ Standard Allen wrenches
- ☐ Needle Nose pliers
- ☐ Dial calipers
- ☐ Tape measure
- ☐ Clamps

GENERAL EQUIPMENT

- ☐ Electrical tape (1)
- ☐ Duct tape (1)
- ☐ Masking tape (1)
- ☐ Folding tables (2)
- ☐ Scale (1)
- ☐ Tarp (1)
- ☐ Sandpaper (1 roll)
- ☐ Wooden vehicle support stand (1)
- ☐ PVC vehicle support stands (2 minimum)
- ☐ JB Weld 5 Minute Epoxy (1)
- ☐ Garbage bags (5 minimum)
- ☐ Pens/pencils (5 minimum)
- ☐ Assorted screws, bolts, and nuts (4-40 and 8-32)
- ☐ Electric Drill
- ☐ Epoxy applicators (3 minimum)
- ☐ Extra wire spool
- ☐ Digital Camera
- ☐ Soldering Iron
- ☐ Soldering Material

VEHICLE EQUIPMENT

- ☐ Payload Bay and nose cone assembly
- ☐ Recovery Bay
- ☐ ACS Bay
- ☐ Fin Can
- ☐ Motor retainer cap
- ☐ Airframe mounting screws
- ☐ Ballast material

ACS EQUIPMENT

- ☐ Assembled ACS system without flaps
- ☐ ACS drag flaps (4)
- ☐ Fully charged battery

RECOVERY EQUIPMENT

- ☐ Assembled PRM
- ☐ Assembled SRM
- ☐ Fully charged altimeter batteries (6)
- ☐ Key for key switches
- ☐ Main parachute
- ☐ Pilot parachute
- ☐ Drogue parachute
- ☐ Main recovery quicklinks (4)
- ☐ Main recovery swivel
- ☐ Main recovery shock cord
- ☐ Drogue recovery quicklinks (2)
- ☐ Drogue recovery shock cord
- ☐ Fin can separation quicklinks (2)
- ☐ Fin can separation shock cord
- ☐ GPS
- ☐ Cell phone for GPS connection
- ☐ Sewing needle
- ☐ Kevlar thread
- ☐ Lighter
- ☐ Nylon fabric

LVIS EQUIPMENT

- ☐ Assembled LVIS system
- ☐ Ground station-laptop system
- ☐ Car-converter power supply
- ☐ Fully charged battery
- ☐ Raspberry Pi connection cords

TEAM MENTOR HANDLED EQUIPMENT

- ☐ Black powder (120g)
- ☐ Aerotech L2200G-P Motor (3)
- ☐ E-matches
- ☐ Cellulose insulation

Confirmation: I hereby attest that the packing list above has been completed and confirmed by all necessary team individuals, and the next stage of the launch procedures can commence. If batteries require disposal, I assure that team members will wear the proper PPE.

Safety Officer Signature: ____________________________________

Team Mentor Signature: ____________________________________

Recovery Lead Signature: ____________________________________

ACS Lead Signature: ____________________________________

Payload Lead Signature: ____________________________________

Vehicles Lead Signature: ____________________________________

9.1.4 Transportation

Failure to properly conduct the pre-flight checklist may result in the following failure modes: PR.8, L.11, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

The following measures must be taken to ensure a safe and timely arrival to the launch field. It is the duty of the Safety Officer and Project Manager to ensure that the following measures are followed and understood by all team members:

- ☐ Departure to the launch field shall be planned an hour earlier than ideal in order to provide a buffer time for delays such as traffic.
- ☐ All team members must arrive in the workshop a half hour before departure from the workshop in order to provide a buffer time if any team member arrives late.
- ☐ Weather conditions of the road and launch field must be announced to the team. Any off-nominal weather conditions must be understood before travel commences to prepare drivers for such conditions. If weather may conflict with the ability to launch, contact the Team Mentor prior to launch.
- ☐ Only team members with updated driver licenses are eligible to transport team members and equipment to the launch field. Team members driver licenses must be checked before departure.
- ☐ Only team members with safe, legal vehicles are eligible to transport team members and equipment to the launch field. Transportation vehicles are to be checked before departure. If the transportation vehicle is deemed unsafe for travel, the vehicle will not be used for launch transportation.

- ☐ The location of the launch field must be communicated to all members attending the launch via Slack, the team messaging board, before departure. No team member driving any vehicle may use their mobile device to access the launch location while driving; it is the responsibility of the passengers in their vehicle to guide the driver.
- ☐ Launch vehicle components must be transported in padded containers or against soft materials to provide protection from potential damage.
- ☐ Carefully place launch vehicle components into transportation vehicles. Do NOT throw components into transportation vehicles; this may cause unwanted damages
- ☐ ***ONLY*** individuals with a NAR/TRA Level 2 Certification may transport energetics to the launch field. This includes the motor and black powder.

Confirmation: I hereby attest that the transportation measures listed above have been followed and understood by all necessary team individuals before travel to the launch field commences.

Safety Officer Signature:____________________________________

Project Manager Signature:____________________________________

9.1.5 Upon Arrival at Launch Field

Required Personnel: Vehicles Lead, Safety Officer, Systems Lead

Required PPE: None required

The following measures must occur upon arrival at the launch field. These steps outline critical actions; if any step fails to pass a quality check, the launch may need to be cancelled.

Failure to properly conduct the pre-flight checklist may result in the following failure modes: ACS.2, VFM.1 - VFM.6, VS.1 - VS.5, VS.7, VS.8, VE.1, VE.5, VE.6, VE.10, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

- ☐ Confirm with the RSO and LCO that launch preparations may safely commence. Weather conditions are the main factor in the safeness of a launch. If the RSO and LCO determine that the launch is unable to occur, gather all team equipment and return to the workshop.
- ☐ Thoroughly inspect the nose cone, payload body tube, recovery body tube, fin can, and tail cone assemblies for deformations and/or cracks. If damages are found and not able to be fixed within the launch time frame, gather all team equipment and return to the workshop.
- ☐ Lightly pull on all U-bolts and eye bolts to check the adhesive strength at each connection. If any adhesive strength test fails, there is not enough time to re-epoxy the bulkheads within the launch time frame; pack up all team equipment and return to the workshop. This procedure will be checked again in Section 9.1.5 due to the importance of bulkhead strength.
- ☐ Visually inspect the fins for any cracks or deformations. If a fin is deemed unsuitable for launch, there is not enough time to fix the fins within the launch time frame; pack up all team equipment and return to the workshop.

Confirmation: I hereby attest that the inspection measures listed above have been performed and pass all quality standards before all other recovery procedures commence.

Vehicles Lead Signature: ____________________________________

Systems Lead Signature: ____________________________________

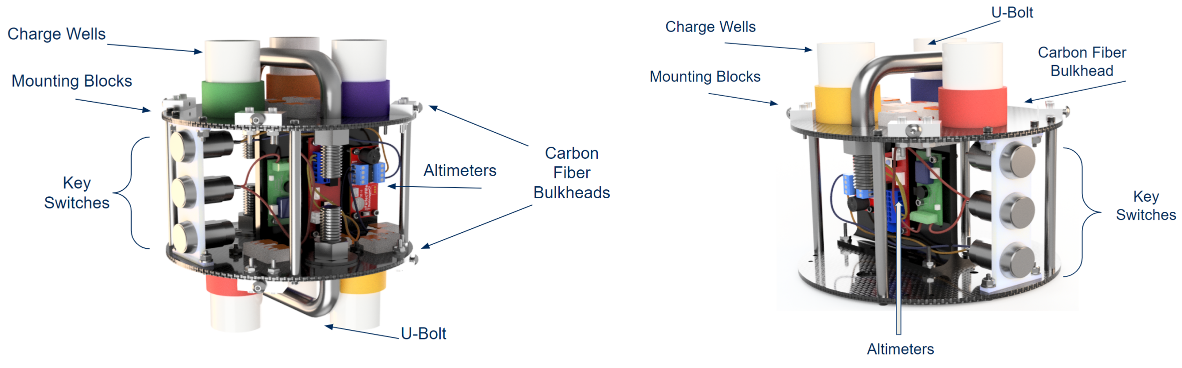
Safety Officer Signature: ____________________________________

9.1.6 Recovery Preparation

Required Personnel: Recovery Lead, 8. Safety Officer, Project Manager, Team Mentor, Systems Lead

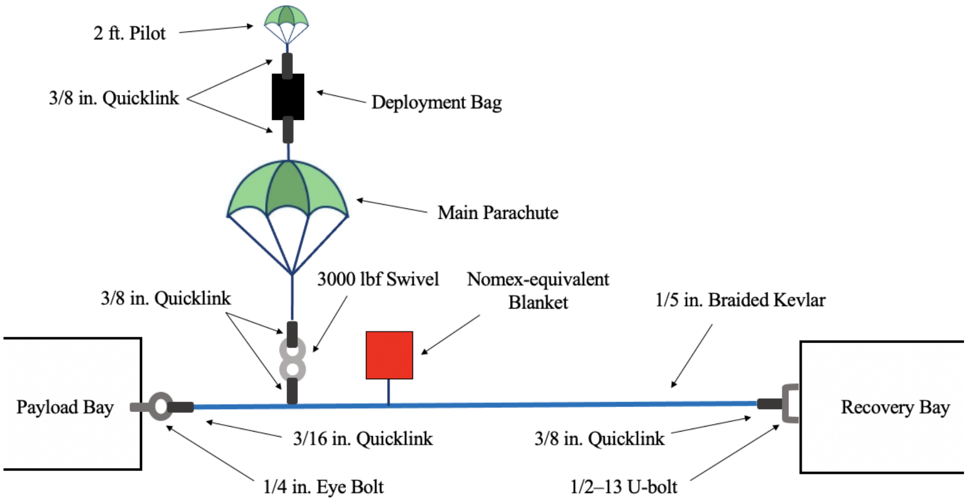
Required PPE: Nitrile gloves, Safety goggles

9.1.6.1 Inspection Checklist :

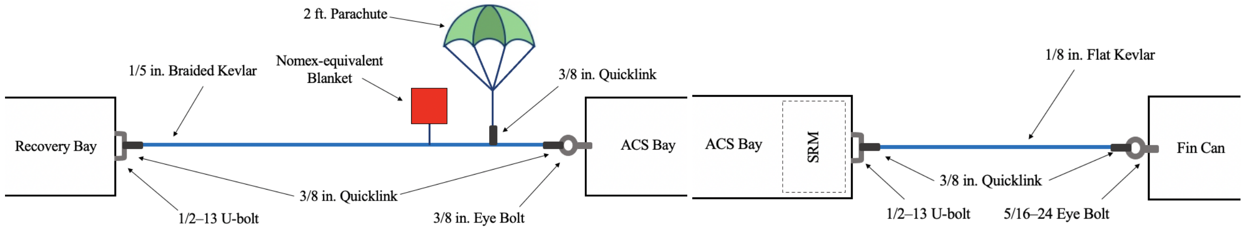


(a) PRM (b) SRM

Figure 114: Recovery Module Assemblies



(a) Main Deployment



(b) Drogue Deployment (c) Fin Can Deployment

Figure 115: Recovery System Deployments

Failure to properly conduct an inspection may result the following failure modes: R.1- R.10, VS.3, ACS.2, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

Note: Lithium-polymer batteries are a potential fire hazard and must be inspected for imperfections, such as swelling or punctures, before insertion into the recovery system. Additionally, store all batteries not in use in the fire proof battery case, and turn OFF all electronics until it is necessary for the mission for them to be turned ON; launch procedures will clearly specify when electronics need to be turned on. If launch conditions are frigid, place all electronics in the warmth of a transportation vehicle until it is necessary for the electronics to be used, as specified in the launch procedures.

- ☐ Inspect bulkheads and U-bolts on PRM. Give the U-bolts a light tug to ensure they are secured. If they are loose, tighten the nuts.
- ☐ Inspect bulkhead and U-bolt on SRM. Give the U-bolts a light tug to ensure they are secured. If they are loose, tighten the nuts.
- ☐ Inspect bulkheads and eye bolt on LVIS retention bulkhead. Give the eye bolts a light tug to ensure they are secured. If they are loose, tighten the nuts.
- ☐ Inspect bulkheads and eye bolt on ACS bulkhead.Give the eye bolts a light tug to ensure they are secured. If they are loose, tighten the nuts.
- ☐ Ensure that the ends of all three shock cords have loops to connect with quick links. If loops are not present, create them before moving onto the next step.
- ☐ Investigate shock cords for holes or general wear. A simple tug on the shock cord should also be performed. Use a backup shock cord if any damages are noticed.
- ☐ Investigate the main and drogue parachutes for holes or general wear. Repair parachute(s) if any damages are noticed with nylon fabric.
- ☐ Check that all lithium polymer batteries are fully charged with the use of a multimeter. 1S LiPo batteries should be at 4.1V fully charged, and 2S LiPo batteries should be at 8.2V fully charged. If the batteries are not fully charged, charge them and ensure they are fully charged before moving forward.
- ☐ Ensure Recovery Lead has the power switch key for both the PRM and SRM. Additional backup keys for the PRM and SRM are also present in the event one key is lost.

Troubleshooting: What if the loops in the shock chord are not present?

- ☐ Locate the sewing needle, Kevlar thread, and lighter. **Warning: remove all flammable substances around the lighter before use.**
- ☐ Sew a Kevlar thread into the shock chord
- ☐ Use the lighter to melt the Kevlar thread onto the shock chord. Let the new loop cool off before moving onto the next step

Confirmation: I hereby attest that the inspection measures listed above have been performed and pass all quality standards before all other recovery procedures commence.

Recovery Lead Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.6.2 Recovery Pre-Flight Checklist :

Failure to properly conduct the pre-flight checklist may result in the following failure modes: R.1 - R.10, VS.3, ACS.2, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

9.1.6.2.1 Main Parachute Folding :

NOTE: At least three team personnel are required to fold the main parachute, including the Recovery Lead.

- ☐ Raise the parachute in the air, ensuring all 4 shroud lines are straight.
- ☐ Shake the parachute lightly to untangle the cords.
- ☐ Attach a quicklink to the open loop at the end connection of all shroud lines. Hold this quicklink to keep main parachute from flying away.
- ☐ Line up all four shroud lines so they are of equal lengths.
- ☐ Use masking tape to z-fold the shroud lines in parallel at the same length to make parachute folding easier.
- ☐ **Tape MUST be removed prior to launch or the main parachute will not open (failure mode R.5)**.

For future steps, reference Figure 116 for additional help.

- ☐ **Step 1:** Fold the parachute in half so the shroud lines meet at the edges.

☐ **Step 2:** Fold the parachute in half again so that all four shroud lines meet in the same location in the middle.
☐ **Step 3:** Fold both sides of the parachute into the middle.
☐ Adjust the fold based on the diameter of the launch vehicle.
☐ **Step 4:** Fold the parachute in half the opposite direction.
☐ **Remove tape from the shroud lines**.
☐ Zig-zag shroud lines carefully in the middle of the parachute to avoid tangling. Tangled shroud lines may result in failure mode R.5.
☐ **Step 5:** Fold the parachute in thirds, top to bottom, such that the parachute covers up the shroud lines twice.
☐ Screw parachute quicklink to recovery shock cord harness.
☐ Ensure quicklink is attached to the recovery shock cord to avoid failure mode R.10.
☐ Roll up the parachute so it is accessible for the next step
☐ **Steps 6 - 8:** Slide the parachute into the deployment bag, and then fold the flap over the bag.

Main parachute is now ready to be installed into the launch vehicle (Launch Procedure Step 9.1.9.3).

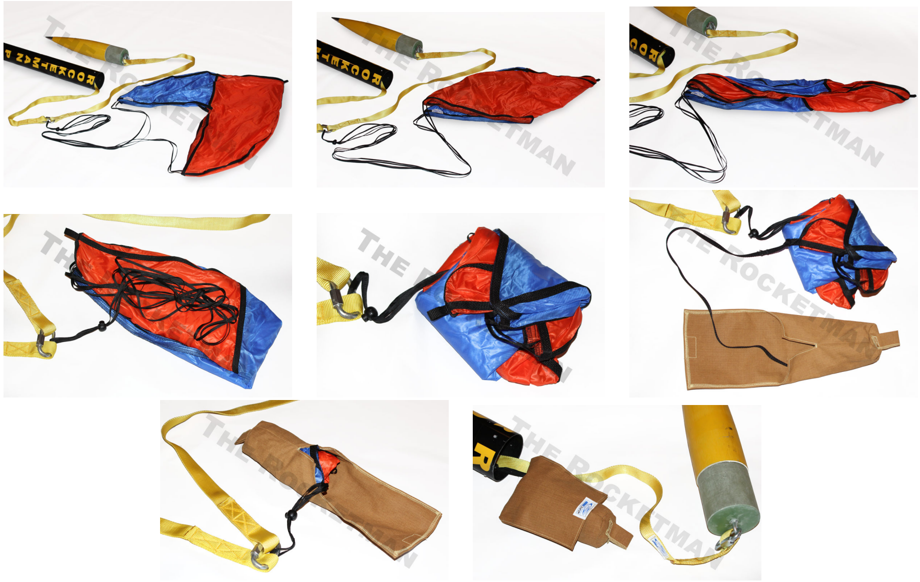


Figure 116: Main Parachute Visual Folding Guide

Confirmation: I hereby attest that the main parachute folding measures listed above have been performed and pass all quality standards before further recovery procedures commence.

Recovery Lead Signature: ______________________________

9.1.6.2.2 Drogue and Pilot Parachute Folding :

Unlike the main parachute, the drogue and pilot parachutes do not require four team members to fold.
☐ Raise the parachute in the air, making sure all 8 shroud lines are straight.
☐ Untangle all cords, if needed.
☐ Shake the parachute lightly to untangle the cords.
☐ Attach a quicklink to the open loop at the end connection of all shroud lines.
☐ Ensure all drogue parachute connections are securely attached, including quicklinks.

For future steps, reference Figure 117 for additional help.
☐ **Step 1:** Lay the parachute on the ground flat.
☐ **Step 2:** Fold the parachute in half so all shroud lines meet in the same location in the middle.
☐ **Step 3:** Fold the parachute in the opposite direction to decrease parachute width.
☐ **Steps 4-5:** “Zig-zag” fold the parachute to make the parachute three times as thick but a third of the length.
☐ If not already done, attach a quicklink to drogue recovery shock chord. Ensure the quicklink is attached with a simple tug

to avoid failure mode R.10.

☐ **Step 6:** Gently pull on the shroud lines to straighten them out. Tangled shroud lines could result in failure mode R.6.

☐ **Step 7:** Place the shroud lines in the center of the folded parachute, and fold the parachute again to cover the shroud lines.

☐ **Steps 8-9:** Roll all the shroud lines around the drogue parachute while keeping all shroud lines together and avoiding tangling.

☐ Place the parachute in the center of nomex blanket and fold the blanket around the parachute to easily fit in the launch vehicle body tube.

☐ Repeat steps for the other parachute folding

Drogue and pilot parachutes is now ready to be installed into the launch vehicle (Launch Procedure Step 9.1.9.3).

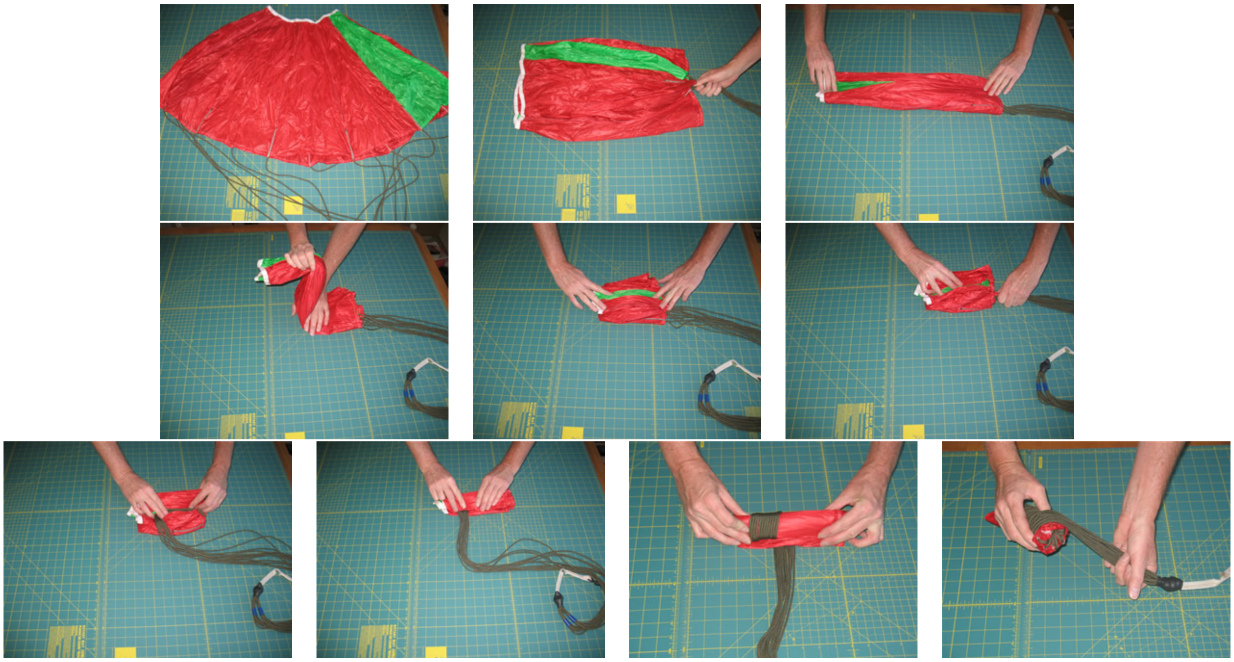


Figure 117: Drogue Parachute Visual Folding Guide

Confirmation: I hereby attest that the drogue parachute folding measures listed above have been performed and pass all quality standards before further recovery procedures commence.

Recovery Lead Signature: ________________________________

9.1.6.2.3 Primary Recovery Module (PRM) Pre-Flight Assembly :

Reminder: Lithium-polymer batteries are a potential fire hazard and must be inspected for imperfections, such as swelling or punctures, before insertion into the recovery system. Additionally, store all batteries not in use in the fire proof battery case, and turn OFF all electronics until it is necessary for the mission for them to be turned ON; launch procedures will clearly specify when electronics need to be turned on. If launch conditions are frigid, place all electronics in the warmth of a transportation vehicle until it is necessary for the electronics to be used, as specified in the launch procedures.

☐ Ensure the PRM is completely assembled, excluding the batteries and black powder.

☐ Ensure all PRM wiring connections are secured. Do NOT pull on the wires to ensure this; just observe.

☐ Ensure that two wires are securely connected to each key power switch.

☐ Ensure that wires are securely connected to each charge well.

☐ Ensure that the altimeters are labeled with colors.

☐ Make sure the batteries are still fully charged (Step 9.1.6.1).

☐ Insert a fully charged altimeter battery into each battery slot. Plug batteries into the JST port on the perfboard, if applicable.

Confirmation: I hereby attest that the PRM pre-flight assembly measures listed above have been performed and pass all quality standards before further recovery procedures commence.

Recovery Lead Signature: ______________________________

9.1.6.2.4 Secondary Recovery Module (SRM) Pre-Flight Assembly :

Reminder: Lithium-polymer batteries are a potential fire hazard and must be inspected for imperfections, such as swelling or punctures, before insertion into the recovery system. Additionally, store all batteries not in use in the fire proof battery case, and turn OFF all electronics until it is necessary for the mission to turn them ON; launch procedures will clearly specify when electronics need to be turned on. If launch conditions are frigid, place all electronics in the warmth of a transportation vehicle until it is necessary for the electronics to be used, as specified in the launch procedures.

- ☐ Ensure that the SRM is completely assembled, excluding the batteries and black powder.
- ☐ Ensure that all SRM wiring connections are secured. Do NOT pull on the wires to ensure this; just observe.
- ☐ Ensure that two wires are securely connected to each key power switch.
- ☐ Ensure that wires are securely connected to each charge well.
- ☐ Ensure that the altimeters are labeled with colors.
- ☐ Make sure the batteries are still fully charged (Step 9.1.6.1).
- ☐ Insert a fully charged altimeter battery into each battery slot. Plug batteries into the JST port on the perfboard, if applicable.

Confirmation: I hereby attest that the SRM pre-flight assembly measures listed above have been performed and pass all quality standards before further recovery procedures commence.

Recovery Lead Signature: ______________________________

9.1.6.2.5 Black Powder Separation Charges :

Note: ***<u>ONLY</u>*** the Team Mentor Dave Brunsting can perform this task due to his NAR/TRA Level 3 Certification. Nitrile gloves and safety glasses are REQUIRED to perform this task, as enforced by the Safety Officer.

The Team Mentor must create nine total ejection charges: six charges for the PRM and three charges for the SRM. The ejection charges consist of e-matches and black powder.

Note: Before handling the black powder, ensure the e-matches are shunted together to avoid accidental ignition.

Fill the charges with the corresponding amount of black powder.

- ☐ PRM main parachute charge 1: 4.5g
- ☐ PRM main parachute charge 2: 5 g
- ☐ PRM main parachute charge 3: 5 g
- ☐ PRM drogue parachute charge 1: 5 g
- ☐ PRM drogue parachute charge 2: 5.5 g
- ☐ PRM drogue parachute charge 3: 5.5 g
- ☐ SRM fin can ejection charge 1: 2 g
- ☐ SRM fin can ejection charge 2: 2.5 g
- ☐ SRM fin can ejection charge 3: 2.5 g

Note: Before continuing, ensure the PRM and SRM power switches are OFF to avoid accidental ignition of charges.

- ☐ Connect the e-matches to the corresponding black powder charge.
- ☐ Insert all nine ejection charges into their corresponding charge wells in the PRM and SRM.
- ☐ Once inserted, cover the charge wells with masking tape to ensure the charges remain stationary during flight and as a safety precaution to check if ejection charges have ignited before handling upon landing.
- ☐ Connect the wires from the e-match to WAGO connectors

Note: When taping the top of the charge well, leave a slight opening in the charge well to facilitate air flow.

Confirmation: I hereby attest that the black powder separation charge measures listed above have been performed and pass all quality standards before further recovery procedures commence.

Team Mentor Signature: ______________________________

Confirmation: I hereby attest that the Team Mentor Dave Brunsting performed the above tasks with the use of all necessary PPE, and that all black powder separation charge measures listed above have been performed and passed all quality standards before further recovery procedures commence.

Safety Officer Signature: ______________________________

9.1.6.2.6 Parachute Integration :

Note: Remove the masking tape from the shroud lines from Steps 9.1.6.2.1 and 9.1.6.2.2, or failure modes R.5 and/or R.6 may occur.

- ☐ Ensure the nomex blanket is connected to the shock cords and the shock cords to the respective parachutes.
- ☐ Enclose the main and drogue parachutes in their respective nomex blankets.
- ☐ Zig-zag fold the shock cord. Once folded, tape each separate fold with masking tape.
- ☐ See "Recovery Integration" (Section 9.1.9.3) for recovery system integration into launch vehicle, the next step for recovery.

Confirmation: I hereby attest that the parachute integration measures listed above have been performed and pass all quality standards before further recovery procedures commence.

Recovery Lead Signature: ______________________________

Overall Recovery Confirmation: I hereby attest that the recovery preparation checklist in Section 9.1.6 listed above have been performed and passed all quality standards before integration into the launch vehicle.

Recovery Lead Signature: ______________________________

Systems Lead Signature: ______________________________

Safety Officer Signature: ______________________________

Project Manager Signature: ______________________________

9.1.7 Launch Vehicle Identification System (LVIS) Preparation

Required Personnel: Payload Lead, Safety Officer, Project Manager, Systems Lead

Required PPE: None for LVIS preparation

9.1.7.1 Inspection Checklist :

Failure to properly conduct an inspection may result in the following failure modes: LVIS.1- LVIS.6, LI.1 - LI.3, EV.11, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

Note: Lithium-polymer batteries are a potential fire hazard and must be inspected for imperfections, such as swelling or punctures, before insertion into the LVIS. Additionally, store all batteries not in use in the fire proof battery case, and turn OFF all electronics until it is necessary for the mission to turn them ON; launch procedures will clearly specify when electronics need to be turned on. If launch conditions are frigid, place all electronics in the warmth of a transportation vehicle until it is necessary for the electronics to be used, as specified in the launch procedures.

- ☐ Inspect LVIS retention bulkhead and eye bolt to ensure structural strength, achieved by pulling on eye bolt.
- ☐ Inspect LVIS to ensure all electrical components are securely fastened without any visible damage to the system.
- ☐ Check that the 2S lithium-polymer battery is fully charged with the use of a multimeter. The nominal voltage of a the 2S lithium polymer battery is 7.4 V. If the battery are not fully charged, charge them and ensure they are fully charged before moving onto the next step.
- ☐ Confirm the correct code has been implemented into the LVIS's Raspberry Pi.

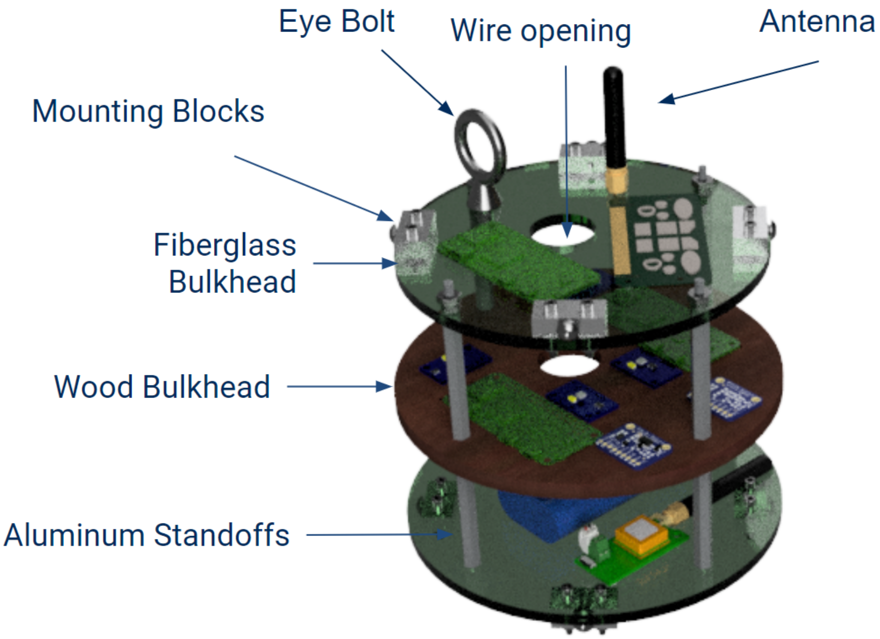


Figure 118: Launch Vehicle Identification System (LVIS)

Confirmation: I hereby attest that the LVIS inspection checklist listed above has been performed and passed all quality standards before further payload procedures commence.

Payload Lead Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.7.2 LVIS Pre-Flight Checklist :

Failure to properly conduct the pre-flight checklist may result in the following failure modes: LVIS.1 - LVIS.6, LI.1 - LI.3, EV.11, or an unidentified mode. The occurrence of any failure mode may result in a launch failure.

☐ Ensure all LVIS wiring connections are secured. Do NOT pull on the wires or electronics; just observe.
☐ Ensure all batteries are still fully charged (Step 9.1.7.1).
☐ Install the 7.4 V batteries into the appropriate slot.
☐ Ensure the correct SD cards has been inserted into their respective Raspberry Pis.

Additional reminder: All electronics for LVIS should be OFF. Launch procedures will specify when electronics should be turned ON.

☐ Check the SD cards to ensure all sensors are working and the Raspberry Pi is collecting the sensors' data.

See "LVIS Integration" (Section 9.1.9.2) for LVIS integration into launch vehicle, the next step for LVIS.

Confirmation: I hereby attest that the LVIS pre-flight checklist listed above has been performed and passed all quality standards before further payload procedures commence.

Payload Lead Signature: ______________________________

Overall LVIS Confirmation: I hereby attest that the LVIS preparation checklist listed above has been performed and passed all quality standards before integration into the launch vehicle.

Payload Lead Signature: ______________________________

Systems Lead Signature: ________________________________

Safety Officer Signature: ________________________________

Project Manager Signature: ________________________________

9.1.8 Apogee Control System (ACS) Preparation

Required Personnel: ACS Lead, Safety Officer, Project Manager, Systems Lead

Required PPE: None for ACS preparation

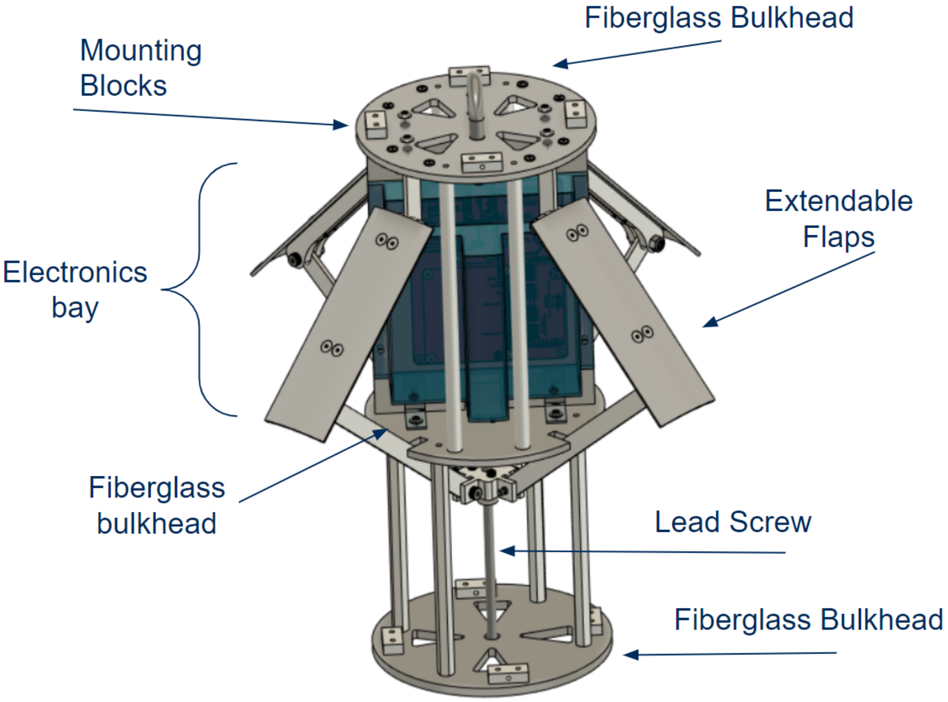


Figure 119: Apogee Control System (ACS)

9.1.8.1 Inspection Checklist :

Failure to properly conduct an inspection may result in the following failure modes: ACS.1- ACS.9, VE.5, VE.8, EV.11, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

Note: Lithium-polymer batteries are a potential fire hazard and must be inspected for imperfections, such as swelling or punctures, before insertion into the ACS. Additionally, store all batteries not in use in the fire proof battery case, and turn OFF all electronics until it is necessary for the mission for them to be turned ON; launch procedures will clearly specify when electronics need to be turned on. If launch conditions are frigid, place all electronics in the warmth of a transportation vehicle until it is necessary for the electronics to be used, as specified in the launch procedures.

☐ Inspect ACS to ensure all electrical components are securely fastened without any damage observed.
☐ Check that all lithium-polymer batteries are fully charged with a multimeter. The nominal voltage of a lithium-polymer battery is 3.7 V or 7.4 V, varying based on ACS battery. If the batteries are not fully charged, charge them and ensure they are fully charged before continuing.
☐ Confirm the correct code has been implemented into the ACS's Raspberry Pi.
☐ Confirm the data collection of the sensors data is reasonable through the use of previous flight data

Confirmation: I hereby attest that the ACS inspection checklist listed above has been performed and passed all quality standards before all other ACS procedures commence.

ACS Lead Signature: ______________________________________

Safety Officer Signature: ______________________________________

9.1.8.2 ACS Pre-Flight Checklist :

Failure to properly conduct the pre-flight checklist may result in the following failure modes: ACS.1- ACS.9, VE.5, VE.8, EV.11, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

Reminder: Lithium-polymer batteries are a potential fire hazard and must be inspected for imperfections, such as swelling or punctures, before insertion into the recovery system. Additionally, store all batteries not in use in the fire proof battery case, and turn OFF all electronics until it is necessary for the mission to turn them ON; launch procedures will clearly specify when electronics must be turned on. If launch conditions are frigid, place all electronics in the warmth of a transportation vehicle until it is necessary for the electronics to be used, as specified in the launch procedures.

9.1.8.2.1 Ballast Integration :

Recall: Per NASA Requirement 2.23.7, the ballast added to the system may not surpass 10% of the total non-ballast launch vehicle weight. Additionally, per NASA Requirement 2.19.1.6, the ballast flown during the full-scale launch must be the max ballast weight possible for the competition launch.

☐ The following are methods of ballasting the system: additional quicklinks onto bolt hardware, cement bags.
☐ Weigh ballast before adding it to the system.
☐ Insert ballast into the system per ACS and apogee calculations performed prior to arrival at launch field.
☐ Ensure ballast is secured to the system.

Confirmation: I hereby attest that the ACS ballast integration checklist listed above has been performed and passed all quality standards before further payload procedures commence.

ACS Lead Signature: ______________________________________

9.1.8.2.2 Battery Integration :

☐ Ensure all ACS wiring connections are secured. Do NOT pull on the wires; simply observe.
☐ Ensure all batteries are still fully charged (Step 9.1.8.1).
☐ Install the 3.7 V batteries into the appropriate slot.
☐ Once the 3.7 V batteries are inserted, install the 7.4 V batteries into the appropriate slot.
☐ Ensure the correct SD card has been inserted into the Raspberry Pi.

☐ Additional reminder: all electronics for ACS should be OFF. Launch procedures will specify when any electronics should be turned ON.
☐ Check the status LEDs on SD cards to ensure all sensors are working and the Raspberry Pi is collecting the sensors' data. The status LEDs should be ON for this step if things are working accordingly.
☐ Turn ON the arming switch.

See "ACS Integration" (Section 9.1.9.1) for ACS integration into launch vehicle, the next step for ACS.

Confirmation: I hereby attest that the ACS battery integration checklist listed above has been performed and passed all quality standards before further payload procedures commence.

ACS Lead Signature: ______________________________

Overall Confirmation: I hereby attest that the ACS preparation checklist listed above have been performed and passed all quality standards before integration into the launch vehicle.

ACS Lead Signature: ______________________________

Systems Lead Signature: ______________________________

Safety Officer Signature: ______________________________

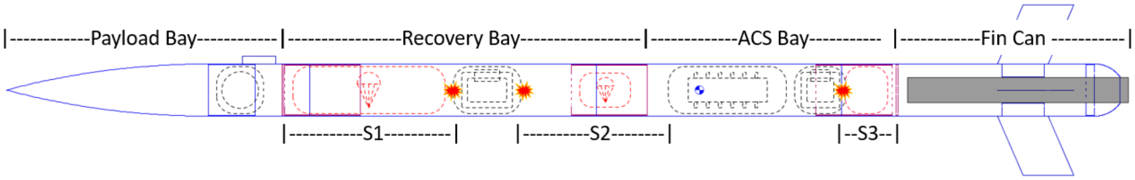
Project Manager Signature: ______________________________

9.1.9 Launch Vehicle Preparation

Required Personnel: ACS Lead, Recovery Lead, Payload Lead, Vehicles Lead, Systems Lead, Safety Officer, Project Manager, Team Mentor

Required PPE: Nitrile gloves, Safety glasses

(a) Launch Vehicle, Unlabeled



(b) Launch Vehicle, Labeled

Figure 120: Full Launch Vehicle

Note: Team members should surround the construction table on all sides to ensure no launch vehicle component falls off the table, resulting in potential damages.

9.1.9.1 ACS Integration :

Failure to properly conduct the ACS integration may result in the following failure modes: ACS.1 - ACS.9, R.4, R.7, R.9, VE.5, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

☐ Ensure ACS preparation has been completed before ACS integration.
☐ Insert ACS into the fin can so the flaps extend fore-ward. Secure to ACS body tube using mounting blocks. Due to symmetry, there is no specific orientation inside the body tube as long as the flaps can be attached.
☐ Ensure the mounting blocks have secured the ACS to the body tube.

☐ Attach the flaps to the ACS from the outside.
☐ Ensure the flaps are secured to the ACS.
☐ Run the ACS flaps to full extension and back to ensure full movement. If this fails, repeat all 9.1.9.1 steps.
☐ Ensure the system is still not in the launched state.
☐ Review all 9.1.9.1 Steps once again to ensure the system is fully ready for launch.

The ACS is now ready for launch. Do NOT handle the ACS until it is time to combine all body tubes and launch.

Troubleshooting: What happens if the ACS is in the launched state?

1. Remove the ACS from the ACS body tube.
2. Turn off all electronics.
3. Repeat ACS steps from 9.1.8 until premature launched state error goes away.

Confirmation: I hereby attest that the ACS integration checklist listed above has been performed and passed all quality standards before launch.

ACS Lead Signature: ______________________________________

Systems Lead Signature: ______________________________________

9.1.9.2 LVIS Integration :

Failure to properly conduct LVIS integration may result in the following failure modes: LI.1, LI.3, LVIS.2, LVIS.5, R.4, VE.5, or an unidentified mode. The occurrence of any failure mode may result in a launch failure.

☐ Ensure LVIS preparation has been completed before LVIS integration.
☐ Power ON the LVIS.
☐ Connect LVIS transmitter with ground station.
☐ Ensure transmission is working by taking LVIS at least 500 ft away and ensuring that a connection can be made from the team's computer and LVIS.
☐ Insert LVIS into payload body tube by aligning the retention blocks and the body tube holes.
☐ Secure LVIS into place through the retention blocks.
☐ Ensure LVIS is secure in the body tube before proceeding.
☐ Review all 9.1.9.2 Steps once again to ensure the system is fully ready for launch.

LVIS is now ready for launch. Do NOT handle the LVIS until it is time to combine all body tubes and launch.

Confirmation: I hereby attest that the LVIS integration checklist listed above has been performed and passed all quality standards before launch.

Payload Lead Signature: ______________________________________

Systems Lead Signature: ______________________________________

Safety Officer Signature: ______________________________________

9.1.9.3 Recovery Integration :

Failure to properly conduct the recovery integration may result in the following failure modes: R.1 - R.10, VE.2, VE.5, VE.10, LVIS.2, LVIS.5, VS.7, or an unidentified mode. The occurrence of any failure mode may result in a launch failure.

☐ Ensure Recovery Preparation has been completed before recovery integration.

9.1.9.3.1 PRM Integration :

☐ Ensure PRM Pre-Flight Assembly, LVIS Integration, and ACS Integration are complete before PRM integration.
☐ Ensure both main and drogue parachute shock cords are secured to the PRM U-bolts with the use of quicklinks.
☐ Ensure the main parachute is located at the fore of the PRM.
☐ Ensure the drogue parachute is located at the aft of the PRM.
☐ Insert PRM into the recovery body tube, aligning the eight retention blocks with the eight holes in the body tube.

☐ Secure the PRM to the recovery body tube using eight screws.
☐ One end of each shock cord attached to the PRM should be unattached to anything. As a reminder, there should be two different shock cords attached to the PRM.
☐ **Ensure all tape securing the parachutes in the folded position are removed before insertion. Failure to do this will result in Failure Modes R.5, R.6**
☐ **Insert the folded main parachute and pilot parachute in the fore section of the PRM. When inserting the parachutes, ensure the nomex blanket surrounds the main parachute. Ensure it is easily removable from the body tube as well**.
☐ **Insert the folded drogue parachute in the aft section of the PRM. When inserting the parachute, ensure the nomex blanket surrounds the parachute. Ensure it is easily removable from the body tube as well**.
☐ Ensure the eye bolt on the LVIS bulkhead is secure.
☐ Attach the main parachute's free end shock cord to the eye bolt of the LVIS with the use of a quicklink.
☐ Ensure the quicklink and shock cord are secured.
☐ Slide recovery and payload body tubes together.
☐ Ensure the eye bolt on the fore ACS bulkhead is secure.
☐ Attach the drogue parachute's free end shock cord to the fore eye bolt of the ACS with the use of a quicklink.
☐ Ensure the quicklink and shock cord are secured.
☐ Slide recovery and ACS body tubes together. Ensure the nomex blanet still surrounds the parachute when inserting the body tubes together.

Troubleshooting: What happens if the main and/or drogue parachute is unable to easily fit inside the recovery body tube?

1. Unfold the parachute and repeat 9.1.6.2.1 Main Parachute Folding or 9.1.6.2.2 Drogue Parachute Folding depending on the situation.
2. This time, ensure the folds are more crisp, and make sure not to compress or scrunch the parachute.
3. Perform 9.1.9.3.1 PRM integration again.
4. If the parachute is still unable to fit easily inside the recovery body tube, repeat steps one and two again and apply talcum powder to folded parachute before sliding it in.

Confirmation: I hereby attest that the PRM integration checklist listed above has been performed and passed all quality standards before launch.

Recovery Lead Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.9.3.2 SRM Integration :

☐ Ensure SRM Pre-Flight Assembly and ACS Integration has been completed before SRM integration.
☐ Ensure shock cord is attached to the SRM with the use of a quicklink.
☐ Insert SRM into the fin can, making sure to align the four retention blocks with the four holes in the fin can.
☐ Secure the SRM to the fin can using four screws.
☐ At this point, one end of the shock cord attached to the SRM should be free: unattached to anything.
☐ Ensure the eye bolt on the ACS aft bulkhead is secure.
☐ Attach the SRM's free end shock cord to the aft eye bolt of the ACS aft with the use of a quicklink.
☐ Ensure the quicklink and shock cord are secured.
☐ Slide fin can and ACS body tubes together.

Confirmation: I hereby attest that the SRM integration checklist listed above has been performed and passed all quality standards before launch.

Recovery Lead Signature: ______________________________

Safety Officer Signature: ______________________________

Overall Recovery Confirmation: I hereby attest that the recovery integration checklist listed above have been performed and passed all quality standards before launch.

Recovery Lead Signature: ______________________________

Systems Lead Signature: ______________________________

Safety Officer Signature: ______________________________

Project Manager Signature: ______________________________

9.1.9.4 Flight Camera Integration :

☐ Insert MicroSD card into the back of the camera.
☐ Turn on the camera by holding down the power button. A yellow light will appear to confirm the camera is on.
☐ Press the recording button, indicated by a camera icon. The yellow light will start to flash, confirming it is recording.
☐ Insert the camera into the camera shroud with the camera lens facing the aft of the launch vehicle.
☐ Once the camera is inserted, slide the plastic plate over the end of the shroud to lock the camera into place.
☐ Ensure the camera is secured into the camera shroud by gently pulling on the camera shroud.

Confirmation: I hereby attest that the flight camera integration checklist listed above have been performed and passed all quality standards before launch.

Vehicles Lead Signature: ______________________________

9.1.9.5 Shake Test :

Failure to properly conduct the shake test may result in the following failure modes: VE.5, VS.1 - VS.4, ACS.1 - ACS.4, L.2 - L.5, LVIS.5, LI.1 - LI.3, R.1, VFM.1, VE.12, or an unidentified mode. The occurrence of any failure mode may result in a launch failure.

This test is to ensure that there are no loose components inside the launch vehicle. At least four team members are required to complete this task.

☐ Acquire at least four team members.
☐ Perform a shake test; Testing Procedure Section 10.1 outlines all necessary steps for performing a shake test.
☐ If moving components are heard, then the whole launch vehicle must be disassembled, and launch procedures must restart from Launch Procedure 9.1.6.
☐ If a component is found damaged from the shake test, locate a replacement component in team toolboxes; reference Launch Procedure 9.1.3 for a compiled list of all items brought to the launch field. Failure to replace any damaged component will result in an aborted launch.

Confirmation: I hereby attest that the shake test listed above has been performed and the launch vehicle has passed before continuing launch procedures.

Vehicles Lead Signature: ______________________________

Systems Officer Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.9.6 Motor Preparation :

Failure to properly conduct the preparation checklist may result in the following failure modes: VS.1, VS.4, VS.6, L.1, VFM.1, VFM.7, PR.5, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

9.1.9.6.1 Motor Inspection :

☐ Carefully remove motor from packaging.
☐ Ensure that the motor was assembled correctly, according to the manufacturer's instructions.
☐ Inspect the motor for any defects. If defects are detected, do NOT use the motor.
☐ Confirm the findings with the Team Mentor.

Confirmation: I hereby attest that the motor inspection checklist listed above has been performed and the motor passed all quality standards before integration.

Team Mentor Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.9.6.2 Motor Integration :

Note: ***ONLY*** the Team Mentor Dave Brunsting can perform this task due to his NAR/TRA Level 3 Certification. Nitrile gloves and safety glasses are required to perform this task.

☐ Ensure two spacers are already preceding the motor.
☐ Insert the motor into the motor mount tube.
☐ Screw on the rear closure of the mount tube.
☐ Ensure the rear closure is securely attached.
☐ Insert the motor into the motor mount tube, with the release of the propellant.
☐ pointing away from the launch vehicle.
☐ Attach the motor retainer ring.
☐ Ensure the motor retainer ring is securely attached.
☐ Ensure the motor is securely attached to the system.

Confirmation: I hereby attest that the motor integration checklist listed above has been performed and passed all quality standards before launch.

Team Mentor Signature: ______________________________

Safety Officer Signature: ______________________________

Overall Motor Confirmation: I hereby attest that the motor preparation checklist listed above has been performed and passed all quality standards before launch.

Team Mentor Signature: ______________________________

Systems Lead Signature: ______________________________

Safety Officer Signature: ______________________________

Project Manager Signature: ______________________________

9.1.9.7 Stability Test :

Failure to properly conduct the stability may result in the following failure modes: VFM.2, VFM.3, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

This test is to locate the center of gravity (CG) on the launch vehicle, and, given the location of the center of pressure (CP), the stability location can be found. The stability location is critical for mission performance. At least four team members are required to complete this task.

☐ Ensure Recovery Integration, LVIS Integration, ACS Integration, and Motor Preparation have been completed before the stability test is performed.
☐ Acquire at least four team members.
☐ Position the fully assembled launch vehicle onto a thin wooden stand until the launch vehicle is perfectly balanced (horizontal) on each side; this is the location of the Center of Gravity (CG).
☐ Mark the location of the actual CG, as just found.
☐ Mark the location of the the calculated CG and CP values.
☐ Calculate the stability of the system based on the actual CG and calculate the CP. The stability of the launch vehicle should be greater than two calipers, per NASA Requirement 2.14.
☐ Ensure the calculated stability corresponds to predicted stability value. The stability margin of the launch vehicle should be within 10% of the predicted value.

☐ If the actual stability margin is greater than two calipers and not within 10% of our predicted value, then the launch vehicle has passed the stability test.

Troubleshooting: What if the stability margin is less than two calipers nor within 10% of the predicted margin?

1. If there is room for additional ballast, ballast may be added to shift the location of the center of gravity towards a more ideal location.
2. If there is no room or additional ballast, determine if weight can be removed from the launch vehicle to shift the location of the center of gravity towards a more ideal location.
3. If there neither of the other scenarios can occur, then the launch is unsafe to occur and there is a failure to launch.

Confirmation: I hereby attest that the stability test listed above have been performed and the launch vehicle has passed before moving on with launch procedures.

Vehicles Lead Signature: ______________________________

Systems Officer Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.9.8 Shear Pin Integration :

Failure to properly conduct the integration checklist may result in the following failure modes: R.2 - R.4, R.7, R.9, VE.5, or an unidentified failure mode.The occurrence of any failure mode may result in a launch failure.

☐ Input shear pins into all holes in the launch vehicle.
☐ Ensure all holes intended for shear pins are filled.

Confirmation: I hereby attest that the shear pins have been integrated into the launch vehicle before continuing launch procedures.

Vehicles Lead Signature: ______________________________

Safety Officer Signature: ______________________________

Overall Launch Vehicle Preparation Confirmation: I hereby attest that the launch vehicle preparation checklist listed above has been performed and passed all quality standards before launch. This launch vehicle should be able to be prepared under two hours; this conformation attests that it was completed in under two hours (NASA 2.6).

Team Mentor Signature: ______________________________

Systems Lead Signature: ______________________________

Recovery Lead Signature: ______________________________

ACS Lead Signature: ______________________________

Payload Lead Signature: ______________________________

Vehicles Lead Signature: ______________________________

Safety Officer Signature: ______________________________

Project Manager Signature: ______________________________

9.1.10 Setup on Launch Pad

Required Personnel: ACS Lead, Recovery Lead, Payload Lead, Vehicles Lead, Systems Lead, Safety Officer, Project Manager, Team Mentor, Range Safety Officer (RSO), Launch Control Officer (LCO)

Required PPE: Nitrile gloves, Safety glasses

9.1.10.1 Launch Pad Inspection :

Failure to properly conduct the inspection may result in the following failure modes: VFM.4, VFM.5, VFM.8, LE.1 - LE.4, L.4, EV.6, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

- ☐ Clean the launch rail of anything that may inhibit the launch vehicle's takeoff.
- ☐ Ensure there is no damage on the launch vehicle's rail buttons.
- ☐ Inspect the screws and knobs on the launch rail to ensure they are adjustable, secure, and NOT loose. If loose, alert the RSO immediately.
- ☐ Confirm with the RSO that the team's launch controller is satisfactory for launch.

Confirmation: I hereby attest that the launch pad inspection has been performed and passed all quality standards before launch pad construction.

Project Manager Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.10.2 Launch Site Evaluation :

Failure to properly conduct the inspection may result in the following failure modes: VFM.4, VFM.5, VFM.8, LE.1 - LE.4, L.4, EV.1 - EV.7, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

- ☐ Walk on the ground adjacent to where the launch pad will be located to ensure the ground is suitable for a launch rail: hard and flat. If the ground is soft or muddle, move the launch pad location upon approval from the RSO.
- ☐ Reconfirm with the RSO and LCO that the launch is safe to occur. Weather conditions, such as precipitation, low cloud cover, high winds over 20 mph, temperature below 0 degrees Fahrenheit, and tornado warning will delay or cancel a launch. If the RSO and LCO determine that the launch is unable to occur, pack up all team equipment and return to the workshop. If the RSO and LCO determine that the launch is able to occur, continue launch procedures.
- ☐ Consult RSO, LCO, and Team Mentor to ensure no wildlife will be affected by the launch.

Confirmation: I hereby attest that the launch site evaluation has been performed and passed all quality standards before launch pad construction.

Project Manager Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.10.3 Launch Equipment Setup :

Failure to properly conduct the inspection may result in the following failure modes: VFM.4, VFM.5, VFM.8, LE.1 - LE.4, L.4, EV.6, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

- ☐ Ensure that there is no external ground equipment other than provided equipment (NASA 2.9).
- ☐ Register your team and launch rail with the LCO and RSO.
- ☐ Set up the launch pad on the hard, flat ground found in step 9.1.10.2.
- ☐ Set up the launch pad with the Team Mentor's instructions. Note: NEVER construct the launch pad without the approval and guidance of the Team Mentor.
- ☐ Ensure the launch pad is level with a protractor. The launch pad should be between zero and one degree from the horizontal.
- ☐ Position the launch block so the launch vehicle is able to launch without damaging the motor. A typical launch block is wooden.
- ☐ Ensure the rail buttons will not be obstructed during launch rail departure.

Confirmation: I hereby attest that the launch equipment setup has been performed and passed all quality standards before launch.

Team Mentor Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.10.4 Launch Rail Checklist :

Failure to properly conduct the inspection may result in the following failure modes: VFM.4, VFM.5, VFM.7, VFM.8, LE.1 - LE.4, L.4, EV.6, VE.8, R.1, ACS.1, LVIS.2, LI.1, LI.3, or an unidentified mode. The occurrence of any failure mode can result in a failed launch.

☐ Gain the approval of the RSO to bring the launch vehicle to the launch pad.

☐ At least four team members are required to transport the launch vehicle to the launch pad and assist in all launch rail checklist procedures. Additional personnel are required to bring a ladder and the recovery electronics' key and ensure the path to the launch rail is clear.

☐ Team members must hold onto the launch vehicle until specified to let go. Failure to comply to this will result in potential vehicle and personnel damage.

9.1.10.4.1 Place Launch Vehicle on Launch Pad :

☐ Lower the launch rail so the rail is parallel with the ground.

☐ Align the rail buttons of the launch vehicle with the launch rail.

☐ Gently slide the launch vehicle onto the launch rail, fin can side first.

☐ Once the entire launch vehicle is on the launch rail, slowly lift up the launch rail.

☐ Before the launch rail is in the vertical direction, place the launch block at the bottom of the launch rail.

☐ Continue to raise the launch rail to the vertical position.

☐ Secure the launch rail.

☐ Ensure the launch rail is secure with confirmation from the Team Mentor, Once secure, the personnel may let go of the launch vehicle.

Confirmation: I hereby attest that the launch vehicle setup on the launch rail has been performed and passed all quality standards before launch.

Team Mentor Signature: ______________________________________

Safety Officer Signature: ______________________________________

9.1.10.4.2 Activate Recovery Electronics :

☐ Use the ladder to reach the recovery payload while the launch vehicle remains upright on the launch rail.

☐ Acquire the recovery electronics key. The same key will be used on the PRM and SRM regardless of copies available.

☐ Climb the ladder and turn the key in the PRM for each of the three battery box switches.

☐ Turn the key in the SRM for each of the two battery box switches.

Troubleshooting: What happens if the key switches do not turn?

1. Turn off all battery box switches with the use of the key. Failure to turn off all battery box switches may result in unintentional black powder ignition, which may result in vehicle and/or personnel damage.
2. Take the launch vehicle off the launch rail by reversing the steps in section. 9.1.10.4.1.
3. Remove the shear pins with the use of scissors or pliers.
4. Separate the body tubes.
5. Remove the parachutes attached to the PRM.
6. Unscrew the PRM from the body tube.
7. Again, ensure that the PRM is OFF.
8. Remove the PRM from the body tubes.
9. Remove all black powder charges from the PRM.
10. Unbolt and remove the PRM's upper bulkhead.
11. Remove the core of the PRM and examine the altimeters, wiring, and switches to find the problem.
12. If no problems are found, plug the altimeters into a computer to run diagnostics and carefully inspect the switch mechanics. When in doubt, consult the user's manual for additional information.
13. Steps 1-12 can also be done for the SRM in the same exact manner.

Confirmation: I hereby attest that the recovery electronics have been activated and passed all quality standards before launch.

Recovery Lead Signature: ______________________________________

Safety Officer Signature: ______________________________

9.1.10.4.3 Verify ACS Power

☐ Climb the ladder to look closely at the ACS.

☐ Ensure that the ACS is NOT in the launched state; if it is in the launched state, a LED will glow.

☐ Ensure that the ACS is powered and ready for launch. The piezo system should be making an audible buzzing noise if it is powered and ready.

Troubleshooting: What happens if the ACS is in the launched state or not powered on?

1. Remove launch vehicle from launch rail.
2. Turn OFF ALL electronics in the launch vehicle.
3. Ensure all electronics have been turned off.
4. Remove the ACS from the ACS body tube.
5. Repeat all steps from 9.1.8 onward until premature launched state error goes away.

Confirmation: I hereby attest that the ACS is powered up and not in the launched state before launch while on the launch rail.

ACS Lead Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.10.4.4 Verify LVIS Power :

☐ Climb the ladder to look closely at the LVIS.

☐ Ensure that the LVIS is powered up and ready for launch.

Troubleshooting: What happens if the LVIS is not powered up?

1. Remove launch vehicle from launch rail.
2. Turn OFF all electronics in the launch vehicle.
3. Ensure all electronics have been turned off.
4. Remove the LVIS from the payload body tube.
5. Repeat all steps from 9.1.7 onward until the LVIS is powered on at the launch rail.

Confirmation: I hereby attest that the LVIS is powered before launch while on the launch rail.

Payload Lead Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.10.4.5 Finalize the Launch Rail Position :

☐ Ensure that the ACS, LVIS, and recovery systems are powered on and in their intended state of readiness.

☐ Have all team members nearby the launch rail hold onto the launch vehicle again.

☐ Unsecure the launch vehicle by loosening the launch rail clamp.

☐ Use a level protractor to re-orient the launch rail angle between five and ten degrees from the vertical, per NASA Requirement 1.12.

☐ When the launch rail is in the intended position, secure the launch vehicle by clamping the launch rail.

☐ Ensure the launch rail is secure. Once secure, team members can let go of the launch vehicle.

☐ Ensure the launch pad is level with a protractor. The launch pad should be between zero and one degree from the horizontal. If the launch pad is not level, remove the launch vehicle and repeat steps from 9.1.10 onward.

Confirmation: I hereby attest that the launch vehicle is in its intended position on the launch rail.

Vehicles Lead Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.10.4.6 Igniter Installation :

Note: *ONLY* the Team Mentor Dave Brunsting can perform this task due to his NAR/TRA Level 3 Certification. Nitrile gloves and safety glasses are required to perform this task.

☐ All personnel, besides the Team Mentor, must return to the RSO-designated observation location.
☐ Ensure that the ignition wires, which are connected to the launch control system, do not have any voltage flowing through them. This can be achieved by touching two wires together AWAY from the launch vehicle. If sparks are created, then the wires are live. In this case, analyze the launch control system and turn off the connection. If no sparks are created, then the wires are not live.
☐ Remove the igniter clips from the igniter.
☐ Ensure the igniter ends are at least 3 in. long and properly exposed.
☐ Insert the igniter into the motor.
☐ Attach the launch control system clips into the igniter.
☐ Ensure sufficient contact with the clips and the igniter.
☐ Return to the RSO-designated observation location.
☐ Notify the RSO that the igniter is live and the launch vehicle ready for launch.

Confirmation: I hereby attest that the igniter installation setup has been performed and passed all quality standards before launch.

Team Mentor Signature: ______________________________

Safety Officer Signature: ______________________________

Overall Launch Vehicle Preparation Confirmation: I hereby attest that the launch vehicle preparation checklist listed above have been performed and passed all quality standards before launch.

Team Mentor Signature: ______________________________

Systems Lead Signature: ______________________________

Recovery Lead Signature: ______________________________

ACS Lead Signature: ______________________________

Payload Lead Signature: ______________________________

Vehicles Lead Signature: ______________________________

Safety Officer Signature: ______________________________

Project Manager Signature: ______________________________

9.1.11 Launch Flight Procedures

Required Personnel: Safety Officer, Project Manager, Team Mentor, Range Safety Officer (RSO), Launch Control Officer (LCO)

Required PPE: Nitrile gloves, Safety glasses

Failure to properly conduct the inspection may result in the following failure modes: L.6, LE.1 - LE.4, EV.1 - EV.7, VE.11, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

Ensure the following procedures have been completed:
☐ 9.1.5 Upon Arrival at Launch Field
☐ 9.1.6 Recovery Preparation
☐ 9.1.7 LVIS Preparation
☐ 9.1.8 ACS Preparation
☐ 9.1.9 Launch Vehicle Preparation
☐ 9.1.10 Launch Rail Checklist
☐ Once again, confirm with the RSO and LCO that the launch controller being utilized is safe and effective for the intended launch.
☐ Team Mentor needs to confirm with the LCO that all launch preparations have been completed to the necessary standards.
☐ LCO will announce the launch is about to commence, giving all members present at the launch field adequate time to

prepare. The launch will not occur until all members at the launch field are at a safe distance away from the launch.

☐ LCO will countdown the launch.
☐ One member on the team will press the launch button when the LCO's countdown reaches one.
☐ During the launch, all team members must point to the direction of the launch vehicle in order to ensure all members know the location of the launch vehicle at all times.
☐ All personnel must remain in RSO-designated observation location until both the LCO and RSO allow team members to go into launch field.

Troubleshooting: What if the motor fails to ignite?

1. Attempt to ignite the motor again by pushing the launch control button. If the motor still fails to ignite, then the following steps can ONLY be performed by the Team Mentor or LCO while wearing safety glasses and nitrile gloves.
2. Carefully remove the igniter from the motor.
3. Install another igniter into the motor, following all procedures from Launch Procedures Section 9.1.10.4.5.
4. Attempt to launch the vehicle again, repeating all procedures from 9.1.11.
5. If the motor fails to ignite again, the Team Mentor shall remove the launch vehicle from the launch rail and inspect the motor for imperfections.
6. If the motor is in good condition, the LCO shall ensure the launch controller and launch systems are in good condition.
7. Attempt another ignition. If this one fails, then consult the LCO, RSO, and Team Mentor for further details.

Confirmation: I hereby attest that the launch vehicle has been launched according to the launch flight procedures.

Team Mentor Signature: ______________________________

Safety Officer Signature: ______________________________

9.1.12 Post Launch Procedures

Required Personnel: ACS Lead, Recovery Lead, Payload Lead, Vehicles Lead, Systems Lead, Safety Officer, Project Manager, Team Mentor, Range Safety Officer (RSO), Launch Control Officer (LCO)

Required PPE: Heat resistant gloves, Safety glasses, Nitrile gloves

Failure to properly conduct the inspection may result in the following failure modes: L.6, or an unidentified failure mode. The occurrence of any failure mode may result in a launch failure.

9.1.12.1 Retrieving the Launch Vehicle :

Note: The motor is still hot upon landing. No team member should touch anywhere near the fin can for minutes after touchdown.

Note: Black powder charges may still be active after touchdown. No team member should EVER put any body part, especially their extremities or face near the body tube holes until it is confirmed that all black powder charges have gone off.

☐ Ensure both the LCO and RSO have given the team approval to enter to launch area.
☐ Upon arriving to the launch vehicle, team members are to take as many photos of the launch vehicle as possible to document the landing, being careful not to go near the launch vehicle.
☐ The Team Mentor must confirm that all nine recovery black powder charges have all been ignited. To do this, the Team Mentor can observe the tape on the charge wells; if the tape is removed, then the charge was ignited. If the charges are not all ignited, then the Team Mentor will have to remove the black powder charges before the procedures can continue.
☐ Once all nine black powder charges are ignited or removed, the team can come as close as possible to the launch vehicle.
☐ Locate the location of the launch vehicle via GPS. This is important for confirming the LVIS's estimated location.
☐ Remove the quicklinks from the parachutes.
☐ Remove the nomex blankets and parachute bags.
☐ Allocate who will carry which components back to the launch location. Whoever is carrying the fin can is required to wear heat resistant gloves.
☐ Ensure everything is being carried back to the launch location.

Troubleshooting: What if a black powder charge failed to ignite and is still live after touchdown?

1. Turn OFF all altimeters by flipping the power switch to avoid accidental ignition.
2. Ensure the altimeters have been turned off.
3. The following steps can ***ONLY*** be performed by the Team Mentor while wearing safety glasses and nitrile gloves.
4. If the PRM still has active charges, separate the recovery tube, payload tube, and ACS tube.
5. If the SRM still has active charges, separate the ACS tube and fin can.
6. Unscrew either the PRM, SRM or both, depending on the situation.
7. Remove either the PRM, SRM or both, depending on the situation.
8. Ensure that the PRM and SRM are both OFF before proceeding.
9. Unhook the black powder charges from the wired connections.
10. Remove the black powder charges from the charge wells.
11. Dispose of the charges through University Hazardous Waste procedures. (See Safety Handbook Section 9)

Confirmation: I hereby attest that the launch vehicle has been retrieved according to the launch retrieving procedures.

Safety Officer Signature: ______________________________________

Team Mentor Signature: ______________________________________

Project Manager Signature: ______________________________________

9.1.12.1.1 Post Launch Analysis :

Once all items have been returned to the launch location, another launch may occur if the necessary resources are available. In this case repeat all launch procedures, starting from 9.1.5.

Even if another launch is not going to occur, the following measures must take place:

- ☐ After ten minutes, ***ONLY*** the Team Mentor can remove the motor casting from the fin can with the use of safety glasses and heat resistant gloves.
- ☐ The payload lead must confirm that the LVIS received data of the launch trajectory.
- ☐ The ACS lead must download the flight data from the microcontroller to compare among expected data.
- ☐ The ACS lead must verify that the ACS flaps extended during launch to reduce the apogee.
- ☐ The recovery lead must input the three PRM and three SRM altimeters into a computer to ensure access to the flight data and to record the apogee of each flight.
- ☐ The recovery lead must find the average apogee of the six altimeters for the flight and compare that number with the target apogee of 4800 ft.
- ☐ A team member must remove the camera from the camera shroud and download the micro SD card information into a laptop. The footage can confirm that the ACS flaps extended during flight.
- ☐ Communicate with the RSO of all changes to the launch vehicle if another launch is to occur.

If another launch is not going to occur, then the following measures will take place:

- ☐ Pack up all equipment, making sure to recount everything.
- ☐ Disassemble all components, making sure to recount everything.
- ☐ Disconnect batteries and return them to fire-proof battery bags.
- ☐ Perform a sweep of the launch area with the entire team to ensure all trash and parts are taken back to the team workshop in trash bags. Nothing can be left behind at the launch field.
- ☐ Upon return to the workshop, return all tools to components to their proper locations.
- ☐ Upon return to the workshop, dispose of all trash and recycling appropriately.

Confirmation: I hereby attest that the post launch analysis procedures have been performed.

Safety Officer Signature: ______________________________________

Project Manager Signature: ______________________________________

Overall Post Launch Confirmation: I hereby attest that the post launch procedures checklist listed above have been performed.

Team Mentor Signature: ______________________________________

Systems Lead Signature: ______________________________________

Recovery Lead Signature: ______________________________________

ACS Lead Signature: ______________________________________

Payload Lead Signature: ______________________________________

Vehicles Lead Signature: ______________________________________

Safety Officer Signature: ______________________________________

Project Manager Signature: ______________________________________

9.2 Failure Modes and Effects Analysis

9.2.1 Vehicle Flight Mechanics Failure Modes and Effects Analysis

Table 54: 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, personnel and/or structures	3	3	9	1. Construction procedures outline necessary steps for fin construction 2. Computer simulations and calculations verify the stability margin is at least 2.0 at rail exit (NASA Vehicle Requirement 2.14) 3. The material of the fins have been chosen with strength, weight, and system stability in mind 4. Fin can drop testing procedures have been performed to evaluate the strength of the fins 5. Launch Procedures outline the necessary steps for inspecting fin quality before launch	1. Fin construction procedures are found in Section 3.3.7 2. Calculations and simulations for the fins and stability margin are found in Section 5.2, and are approved by the Systems and Safety officers 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. All Testing Procedures can be found in Section 10.1, and all tests have been passed 5. Fin inspection procedures are found in Section 9.1.5 6. Material selection for the fins is found in Section 3.2.5	2	2	4
VFM.2	Launch vehicle is unstable during flight	1. Design fails to place the CP below the CM 2. Improper installation of the fins and/or motor results in failure to place the CP below the CM	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 outline the necessary steps for fin construction 2. Computer simulations and calculations ensure the stability margin is at least 2.0 at rail exit (NASA Vehicle Requirement 2.14) 3. The material of the fins has been chosen with strength, weight, and system stability in mind 4. The motors will be purchased from a reputable vendor and installed using proper techniques 5. Launch Procedures outline the necessary steps for determining the actual stability of the launch vehicle, which will be calculated at the launch field	1. Fin construction procedures are found in Section 3.3.7 2. Calculations and simulations for the fins, motor, and stability margin is found in Section 5.2, and were approved by the Safety and Systems officers 3. Stability testing procedures are found in Section 9.1.9.7 4. Team members ordering the motor and fins consulted the team's trusted vendor list and past motor data before purchase 5. Testing Procedures are found in Section 10.1 6. Launch procedures outline that only our Team Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is able to handle motor installation and will do so according to all NAR/TRA 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 have been written, and they outline the necessary steps for fin construction and instillation 2. Computer simulations and calculations have been performed to evaluate the location of the center of pressure and center of mass 3. Computer simulations and calculations have been performed to ensure the stability margin is at least 2.0 at rail exit (NASA Vehicle Requirement 2.14) 4. The center of mass will be calculated at the launch field to ensure accurate stability calculation 5. The material of the fins has been chosen with strength, weight, and system stability in mind 6. The motors will be purchased from a reputable vendor and installed using proper techniques 7. Launch Procedures have been written, and they outline the necessary steps for determining the actual stability of the launch vehicle	1. Construction procedures for the fins can be found in Section 3.3.7 2. Calculations and simulations for the fins, motor, and stability margin can be found in Section 5.2, and they were approved by both the Safety Officer and the Systems Officer 3. Launch procedures for stability testing can be found in Section 9.1.9.7 4. Team members ordering the motor and fins consulted the team's trusted vendor list and past motor data before making any motor purchase 5. All Testing Procedures can be found in Section 10.1, and all tests have been passed 6. Launch procedures have been written and made accessible to all members, and they 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. Construction procedures have been written, and they outline the necessary steps for rail button, fin, and motor mount construction and instillation 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. Computer simulations and calculations have been performed to ensure the stability margin is at least 2.0 at rail exit (NASA Vehicle Requirement 2.14) 4. Launch Procedures have been written, and they outline the necessary steps for a safe motor transportation to the launch site 5. Launch procedures have been written, and they will outline the necessary steps for motor inspection and instillation 6. Launch Procedures have been written, and they will outline the necessary steps for installing the launch equipment while following all NAR standards	1. Team members ordering the motor consulted the team's trusted vendor list and past motor data before making any motor purchase 2. Construction procedures for the rail buttons, fins, and motor mount can be found in Sections, 3.3.8, 3.3.7, 3.3.6, respectively. 3. Launch procedures have been written by FRR and made accessible to all members, and they 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. Calculations and simulations can be found in Section 5, and they were approved by both the Safety Officer and the Systems Officer 5. Launch Procedures for motor transportation can be found in Section 9.1.4 6. Launch Procedures for motor inspection and integration can be found in Section 9.1.9.6 7. Launch Procedures for launch pad setup can be found in Section 9.1.10 8. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 9.1.10.4	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 have been performed prior to motor selection to ensure an exit velocity of at least 52 feet per second (NASA Vehicle Requirement 2.17) 2. The motor has been purchased from a reputable vendor and installed using proper techniques 3. The systems squad will allocate and enforce weight limits to each system 4. Rail buttons were purchased from reputable vendors and installed using proper techniques 5. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for aligning both the launch rail and launch pad 6. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for installing the launch vehicle on the launch rail 7. Launch Procedures have been written, and they outline the necessary steps for motor inspection and integration	1. Calculations and simulations can be found in Section 5, and they were approved by both the Safety Officer and the Systems Officer 2. Team members ordering the motor and rail buttons consulted the team's trusted vendor list and past motor data before making any motor purchase 3. All information on weight allocation can be found in Section 3.4.2 4. Launch procedures have been written by FRR and made accessible to all members, and they 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 for launch pad setup can be found in Section 9.1.10 6. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 9.1.4 7. Launch Procedures for motor inspection and integration can be found in Section 9.1.9.6 8. Construction procedures for the rail buttons, fins, and motor mount can be found in Sections, 3.3.8, 3.3.7, 3.3.6, respectively.	1	3	3
VFM.6	Excessive and/or un-balanced drag	1. Imperfections with exterior of launch vehicle 2. Excessive exterior coatings and/or attach-ments 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 have be written, and they will help ensure proper methods are used to mitigate imperfections 2. Wind tunnel testing procedures have been written and performed, and they will help highlight possible drag issues with our design. 3. Paint layers to the exterior of our launch vehicle will be as minimal as possible to reduce any potential drag induced by it 4. All drag calculations and simulations have been performed and approved by our team graduate student and team University professor 5. Launch Procedures have been written, and they outline the necessary steps for identifying any imperfection with launch vehicle exterior prior to launch	1. Construction procedures for the rail buttons, fins, and motor mount can be found in Sections, 3.3.8, 3.3.7, 3.3.6, respectively. 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed 3. Our team graduate student and University professor has greater experience with drag calculations and simulations 4. Launch Procedures for identifying imperfections can be found in Section 9.1.5	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 was purchased from a reputable vendor and installed using proper techniques 2. Backup motors will be brought to every launch in the event of a defective motor 3. Launch Procedures have been written, and they outline the necessary steps for a safe motor transportation to the launch site 4. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment 5. Launch Procedures have been written, and they outline the necessary steps for motor inspection and integration	1. Team members ordering the motor consulted the team's trusted vendor list and past motor data before making any motor purchase 2. Launch procedures have been written and made accessible to all members, and they 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 3. Launch Procedures for motor transportation can be found in Section 9.1.4 4. Launch Procedures for operating launch equipment can be found in Section 9.1.10 5. Launch Procedures for motor inspection and integration can be found in Section 9.1.9.6	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 have been performed prior to motor selection to ensure an exit velocty of at least 52 feet per second (NASA Vehicle Requirement 2.17) 2. The motors were purchased from a reputable vendor and installed using proper techniques 3. The systems squad allocated and enforced weight limits to each system throughout the project 4. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for aligning both the launch rail and launch pad 5. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for installing the launch vehicle on the launch rail	1. Calculations and simulations can be found in Section 5, and they were approved by both the Safety Officer and the Systems Officer 2. Team members ordering the motor consulted the team's trusted vendor list and past motor data before making any motor purchase 3. All information on weight allocation can be found in Section 3.4.2 4. Launch procedures have been written by FRR and made accessible to all members, and they 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 for launch pad setup can be found in Section 9.1.10 6. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 9.1.10.4	1	3	3

9.2.2 Vehicle Structures Failure Modes and Effects Analysis

Table 55: 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 were chosen based on research and calculations 2. Centering ring materials were purchased from reputable vendors 3. Construction procedures were written prior to any construction and made accessible to all members, and they outline the necessary steps for centering ring construction.	1. Team members ordering the centering ring material consulted the team's trusted vendor list 2. Construction procedures for the motor mount tube can be found in Section 3.3.4 3. Centering ring information can be found in Section 3.2.2	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 were chosen based on research and calculations 2. Couplers were purchased from reputable vendors 3. Construction procedures were written and made accessible to all members, and they outline the necessary steps for centering ring construction and integration	1. Team members ordering the couplers consulted the team's trusted vendor list 2. Construction procedures for the couplers can be found in Section 3.3.4 3. Coupler information can be found in Section 3.2.2	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 were chosen with strength and weight in mind 2. Bulkhead material and U-bolts were purchased from reputable vendors 3. Construction procedures were written and made accessible to all members, and they outline the necessary steps for constructing and integrating the bulkheads and U-bolts 4. Bulkhead strength testing procedures have been written and performed, and they will evaluate the amount of weight the U-bolt and bulkhead can withstand to simulate the launch loads and parachute forces. 5. Launch Procedures have been written, and they outline the necessary steps for ensuring bulkhead, U-bolt, and eye-bolt strength on launch day	1. Team members ordering the bulkhead material and U-bolts consulted the team's trusted vendor list 2. Construction procedures for bulkheads can be found in Section 3.3.5 3. All Testing Procedures can be found in Section 10.1, and all tests have been passed 4. Launch Procedures for bulkhead, U-bolt, and eye-bolt strength testing can be found in Sections 9.1.5 and 9.1.6.1	1	3	3

VS.4	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 and design of the fins were chosen with strength and weight in mind 2. Wind tunnel testing procedures have been written and performed to evaluate the forces of the wind on the fins. 3. Fin can drop testing procedures have been written and performed to evaluate the ability of the fin can to withstand touchdown forces. 4. Simulations and calculations have been performed prior to launch to evaluate the strength of the fins 5. Launch Procedures have been written and made accessible to all members, and they outline the necessary steps for evaluating the fins on the day of the launch 6. Construction Procedures have been written, and they outline the necessary steps for the proper fin construction and instillation	1. All information on fins can be found in Section 3.2.5 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed 3. Calculations and simulations for the fins and stability margin can be found in Section 5.2, and they were approved by both the Safety Officer and the Systems Officer 4. Launch procedures for evaluating fin on launch day can be found in Section 9.1.5 5. Construction procedures for the fins can be found in Section 3.3.7	1	2	2
VS.5	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 has been chosen with strength and weight in mind 2. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for the launch vehicle shake test to ensure no components will come unattached during launch 3. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for motor retainer integration	1. All information of the motor retainer can be found in Section 3.3.6 2. Launch Procedures for the shake test can be found in Section 9.1.9.5 3. Launch procedures have been written and made accessible to all members, and they 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 motors were purchased from a reputable vendor and installed using proper techniques 2. Launch Procedures have been written, and they outline the necessary steps for a safe motor transportation to the launch site 3. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment 4. Launch Procedures have been written, and they outline the necessary steps for motor inspection and integration 5. Construction procedures were written, and they outline the necessary steps for motor mount construction.	1. Team members ordering the motor consulted the team's trusted vendor list and past motor data before making any motor purchase 2. Launch procedures have been written and made accessible to all members, and they 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 3. Launch Procedures for motor transportation can be found in Section 9.1.4 4. Launch Procedures for operating launch equipment can be found in Section 9.1.10 5. Launch Procedures for motor inspection and integration can be found in Section 9.1.9.6 6. Construction procedures for the motor mount can be found in Section 3.3.6	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 were chosen with strength, weight, and data transmissibility in mind 2. Nose cone drop testing procedures have been written and performed to evaluate the ability of the nose cone to withstand touchdown forces. 3. Fin can drop testing procedures have been written and performed to evaluate the ability of the fin can to withstand touchdown forces. 4. Launch Procedures have been written and made accessible to all team members, and they outline the necessary steps for performing a launch vehicle shake test to ensure no components will become unsecured during launch. 5. CAD models and drawings have been created to accurately fabricate the vehicle structure 6. Construction procedures have been written to ensure safe and consistent results	1. The material of the vehicle structure can be found in Section 3.2 2. All Testing Procedures can be found in Section 10.1 3. CAD models and/or drawings for the vehicle design can be found in Section 3 4. Construction procedures can be found in Section 3.3 5. Launch procedures for the shake test can be found in Section 9.1.9.5	2	2	4

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 have been written, and they 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 have been written, and they outline the necessary steps for maintaining the launch vehicle components on the tables.	1. Launch Procedures for launch vehicle transportation to the launch rail can be found in Section 9.1.10.4 2. Launch Procedures for maintaining launch vehicle components can be found in Section 9.1.9	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 was chosen with strength, weight, and data transmissibility in mind 2. Long-distance testing procedures have been written and performed in order to ensure the system's data can be transmitted long distances. 3. Transmitting frequencies of all electronic devices have been chosen to avoid potential interference 4. System interference testing procedures have been written and performed, and it will ensure all components don't interfere with data transmissibility. 5. Launch Procedures have been written, and they outline the necessary steps for ensuring the transmissibility of LVIS prior to launch 6. Launch Procedures have been written, and they outline the necessary steps for ensuring the recovery system is working properly prior to integration and launch. 7. Launch Procedures have been written and made accessible to all team members, and they outline the necessary steps for performing a launch vehicle shake test to ensure no components will become unsecured during launch.	1. The material of the vehicle structure can be found in Section 3.2 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed 3. Launch procedures for the shake test can be found in Section 9.1.9.5 4. Launch Procedures for ensuring LVIS transmissibility can be found in Section 9.1.9.2 5. Launch Procedures for ensuring recovery system is working properly can be found in Sections 9.1.6 and 9.1.9.3 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

9.2.3 Apogee Control System Failure Modes and Effects Analysis

Table 56: 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 testing procedures have been written and performed, and they were 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. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries. 5. Launch Procedures have been written, and they outline the PPE required and the procedure for checking battery quality. 6. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle	1. Launch Procedures Section 9.1.3 highlight the importance of storing all batteries in fire resistant bags when not in use 2. Launch Procedures for checking battery voltage can be found in Section 9.1.3 and in every other section that involves battery instillation 3. Launch Procedures for transporting ACS electronics can be found in Section 9.1.4 4. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 5. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1 6. All Testing Procedures can be found in Section 10.1, and all tests have been passed	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 containment mechanism materials and design were carefully selected to withstand the forces exerted on the system during flight and keep the ACS secured up to apogee 2. CAD models and drawings have been created prior to construction to accurately fabricate the ACS containment mechanism 3. The University of Notre Dame Engineering Innovation Hub Manager approved of all construction methods prior to part machining 4. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 3. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1	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 was tested with simulated flight data in order to evaluate the system's accuracy with testing procedures, which have already been written. 2. ACS battery duration testing procedures have been written and performed under multiple situations in order to evaluate the quality of the system's batteries. 3. Redundancy was be implemented into the system 4. ACS sensors were purchased from reputable vendors and installed using proper methods 5. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 3. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1 4. All ACS electronics information can be found in Section 7.4	3	2	6

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. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle 2. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle 3. Wind tunnel testing procedures have been written, and they were performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps mechanism.	1. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 2. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1 3. Launch Procedures for shake test can be found in Section 9.1.9.5 4. All Testing Procedures can be found in Section 10.1, and all tests have been passed	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 and flap deployment mechanics was tested with simulated flight data in order to evaluate the system's ability to filter data with testing procedures, which have already been written and performed. 2. ACS battery duration testing procedures have been written and performed under multiple situations in order to evaluate the quality of the system's batteries. 3. Redundancy was implemented into the system 4. ACS micro-controller was purchased from reputable vendors and installed using proper methods 5. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle	1. All Testing Procedures can be found in Section 9.1 2. ACS electronics information can be found in Section 7.4 3. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 4. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1	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 NASA 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 have been 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 have been created prior to construction to accurately fabricate the flap deployment mechanism 3. The University of Notre Dame Engineering Innovation Hub Manager approved of all construction methods prior to part machining 4. ACS wind tunnel testing procedures have been written and performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps mechanism. 5. ACS flap mechanism torque testing procedures have been written and performed in order to evaluate the system's ability to withstand the highest expected load with a safety factor of 1.25. 6. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle 7. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. All CAD models for the ACS design can be found in Section 7.3 3. Calculations for flap extensions can be found in Section 7.7, and it was approved by both the Safety Officer and the Systems Officer 4. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 5. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1	3	2	6

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 testing procedures have been written and 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. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle 5. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle 6. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries. 7. Launch Procedures have been written, and they outline the PPE required and the procedure for checking battery quality.	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Launch Procedures Section 9.1.3 highlight the importance of storing all batteries in fire resistant bags when not in use 3. Launch Procedures for checking battery voltage can be found in Section 9.1.3 and in every other section that involves battery instillation 4. Launch Procedures for transporting ACS electronics can be found in Section 9.1.4 5. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 6. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1 7. Launch Procedures for shake test can be found in Section 9.1.9.5	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. The Kalman filtration system has be chosen based on the criteria of speed and memory 2. ACS was tested with simulated flight data in order to evaluate the system's accuracy and speed with testing procedures, which have already been written.	1. ACS data filtration system information can be found in Section 7.5 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed	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 was 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 approved of all construction methods prior to part machining 3. ACS wind tunnel testing procedures have been written and performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps. 4. ACS drop test procedures have been written and performed in order to evaluate the ability to of the system to withstand launch touchdown. 5. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. All CAD models for the ACS design can be found in Section 7.3 3. Calculations for flap extensions can be found in Section 7.7, and it was approved by both the Safety Officer and the Systems Officer 4. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 5. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1	1	2	2

9.2.4 Recovery Failure Modes and Effects Analysis

Table 57: 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 testing procedures have been written and performed for 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. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries. 5. Launch Procedures have been written, and they outline the PPE required and the procedure for checking battery quality. 6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle	1. Launch Procedures Section 9.1.3 highlight the importance of storing all batteries in fire resistant bags when not in use 2. Launch Procedures for checking battery voltage can be found in Section 9.1.3 and in every other section that involves battery instillation 3. Launch Procedures for transporting recovery electronics can be found in Section 9.1.3 4. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 5. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3	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 was implemented in black powder charges 2. Separate recovery systems with individual avionics and black powder charges will be integrated into body tube 3. Altimeters are properly shielded from interference 4. Altimeters, system interference, redundancy, and more have been tested with testing procedures, which have also been written. 5. Black powder and altimeters were supplied from reputable sources and installed using proper methods 6. Launch Procedures have been written, and they outline the necessary steps for inserting black powder charges. 7. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Launch Procedures for black powder instillation can be found in Section 9.1.6.2.5 3. 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. This includes black powder 4. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 5. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3 6. Ejection charge sizing can be found in Section 4.3	1	4	4

R.3	Premature body tube 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 4. ACS flaps extend during motor burnout,and the shear pins are unable to withstand the intense drag induced by the flaps	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 have been carefully selected to withstand the forces exerted on the system during flight 2. Shear pins have been purchased from reputable vendors and installed using proper methods 3. Altimeters have been purchased from reputable vendors and installed using proper methods 4. Altimeters, system interference, redundancy, shear pins, and more have been tested with testing procedures, which have already been written. 5. Launch Procedures have been written, and they outline the necessary steps for inserting shear pins 6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle 7. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle	1. Safety factor calculations for shear pins can be found in Section 4.3, and all safety factor calculations were approved by both the Safety Officer and Systems Officer 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed 3. 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 4. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 5. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3 6. Launch Procedures for shear pin insertion can be found in Section 9.1.9.8 7. Calculations for flap extensions can be found in Section 7.7, and it was approved by both the Safety Officer and the Systems Officer 8. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 9. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1	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 have been purchased from reputable vendors and installed using proper methods 2. Shock cords have been carefully selected to withstand the forces exerted on the system during flight 3. Recovery system structural materials have been chosen based on their ability to withstand the forces exerted on the system during flight 4. Recovery system ground separation testing procedures have been written and performed in order to evaluate the structural integrity of the system during black powder ignition. 5. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle	1. Safety factor calculations for shock cords can be found in Section 4.3, and all safety factor calculations were approved by both the Safety Officer and Systems Officer 2. Safety factor calculations for recovery structural components can be found in Section 4.3, and the safety factor calculations were approved by both the Safety Officer and Systems Officer 3. All Testing Procedures can be found in Section 10.1, and all tests have been passed 4. 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 5. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 6. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3	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 was 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 have all been purchased from reputable vendors and installed using proper methods 3. Main parachute deployment testing procedures have been written and performed in order to evaluate the parachute's ability to fully deploy over a short period of time. 4. Altimeters, system interference, redundancy, and more have been tested with testing procedures, which have been written. 5. Main parachute will be properly protected from black powder charges with the use of a nomex blanket 6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle	1. Main parachute information can be found in Section 4.4.1 2. All calculations and simulations for the main parachute can be found in Section 5.3, and they were approved by both the Safety Officer and the Systems Officer 3. All Testing Procedures can be found in Section 10.1, and all tests have been passed 4. 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 5. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 6. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3	2	4	8

R.6	Drogue parachute fails to reduce descent velocity to acceptable levels after apogee	1. Drogue parachute not sized correctly to reduce the vehicle descent velocity 2. Recovery systems deploy drogue parachute at an incorrect time 3. Shock cords and/or shroud lines become tangled prohibiting full deployment of drogue parachute 4. Drogue parachute 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 was carefully selected to withstand the forces exerted on the system during flight while also adequately reducing the descnt velocty of the launch vehicle 2. Black powder, altimeters, and the drogue parachute were all purchased from reputable vendors and installed using proper methods 3. Drogue parachute deployment testing procedures have been written and performed in order to evaluate the parachute's ability to fully deploy over a short period of time. 4. Altimeters, system interference, redundancy, and more have been tested with testing procedures, which have been written. 5. Drogue parachute will be properly protected from black powder charges with the use of a nomex blanket 6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle	1. Drogue parachute information can be found in Section 4.4.2 2. All calculations and simulations for the drogue parachute can be found in Section 5.3, and they were approved by both the Safety Officer and the Systems Officer 3. All Testing Procedures can be found in Section 10.1, and all tests have been passed 4. 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 5. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 6. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3	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 have been carefully selected to withstand the forces exerted on the system during flight 2. Shear pins have been purchased from reputable vendors and installed using proper methods 3. Altimeters have been purchased from reputable vendors and installed using proper methods 4. Altimeters, system interference, redundancy, shear pins, and more have been tested with testing procedures, which have already been written. 5. Launch Procedures have been written, and they outline the necessary steps for inserting shear pins 6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle 7. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle	1. Safety factor calculations for shear pins can be found in Section 4.3, and all safety factor calculations were approved by both the Safety Officer and Systems Officer 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed 3. 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 4. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 5. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3 6. Launch Procedures for shear pin insertion can be found in Section 9.1.9.8 7. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1 8. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8	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 parachutes deploy early (above 600 ft AGL; 5150 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 have been performed to determine the maximum expected drift radius 2. Redundancy will be implemented in black powder charges 3. Altimeters have been purchased from reputable vendors 4. Altimeters will be properly shielded from interference 5. Black powder and altimeters have been supplied from reputable sources and installed using proper methods 6. Altimeters, system interference, redundancy, and more have been tested with testing procedures, which have already been written. 7. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle 8. Launch Procedures have been written, and they outline the necessary steps for inserting black powder charges.	1. All maximum drift radius calculations and simulations can be found in Section 5.2.3, and they were approved by both the Safety Officer and Systems Officer 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed 3. 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. This includes black powder 4. Ejection charge sizing can be found in Section 4.3 5. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 6. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3	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 have been purchased from reputable vendors and installed using proper methods 4. Altimeters, system interference, redundancy, and more will be tested with testing procedures, which have already been written. All tests will be performed prior to FRR 5. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle 6. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 3. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3 4. Launch Procedures for ACS integration into launch vehicle can be found in Section 9.1.9.1 5. Launch Procedures for ACS preparation for launch can be found in Section 9.1.8 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.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 have been purchased from reputable vendors and installed using proper methods 2. Shock cords have been carefully selected to withstand the forces exerted on the system during flight 3. Recovery system structural materials have been chosen based on their ability to withstand the forces exerted on the system during flight 4. Recovery system ground separation testing procedures have been written and performed in order to evaluate the structural integrity of the system during black powder ignition. 5. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle	1. Safety factor calculations for shock cords can be found in Section 4.3, and all safety factor calculations were approved by both the Safety Officer and Systems Officer 2. Safety factor calculations for recovery structural components can be found in Section 4.3, and the safety factor calculations were approved by both the Safety Officer and Systems Officer 3. All Testing Procedures can be found in Section 10.1, and all tests have been passed 4. 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 5. Launch Procedures for recovery preparation for launch can be found in Section 9.1.6 6. Launch Procedures for recovery integration into launch vehicle can be found in Section 9.1.9.3	1	4	4

9.2.5 Launch Vehicle Identification System (LVIS) Failure Modes and Effects Analysis

Table 58: 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 testing procedures have been written and performed in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements.	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed	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. LVIS testing procedures have been written and performed in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. 2. LVIS sensors have been supplied from reputable sources and installed using proper methods 3. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle 4. Launch Procedures have been written, and they outline the necessary steps for preparing LVIS for launch 5. Launch Procedures have been written, and they outline the necessary steps for integrating LVIS into the launch vehicle 6. Redundancy has been implemented in LVIS in case one set of sensors is unable to detect any data	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Launch Procedures for shake test can be found in Section 9.1.9.5 3. Launch Procedures for LVIS preparation can be found in Section 9.1.7 4. Launch Procedures for LVIS integration can be found in Section 9.1.9.2 5. LVIS design, which includes redundancy, can be found in Section 6.4	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 have been supplied from reputable sources and installed using proper methods 2. A minimum of three identical sensor systems have been implemented in LVIS so there can always be a majority decision 3. LVIS testing procedures have been written and performed in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. All tests will be performed before FRR	1. LVIS overall design can be found in Section 6.4 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed	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 have been supplied from reputable sources and installed using proper methods 2. Maximum grid dimensions (250 ft by 250 ft) reduce necessary precision in calculations 3. LVIS testing procedures have been written and performed in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. 4. The Klaman filtering method will be applied during launch to provide rapid filtering of data 5. The Gauss-Newton filtering method will be applied post launch to provide accurate data	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Information on the LVIS filtering methods an be found in Section 6.5.2	1	4	4
LVIS.5	Antenna Obstruction	LVIS unable to transmit the necessary signal due to landing configuration, distance from computer, improper instillation, 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 has been confirmed to facilitate data transmissibility 2. LVIS testing procedures have been written and performed in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. 3. Launch Procedures have been written, and they outline the necessary steps for preparing LVIS for launch 4. Launch Procedures have been written, and they outline the necessary steps for integrating LVIS into the launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. The material of the payload body tube can be found in Section 3.2.2 3. Launch Procedures for LVIS preparation can be found in Section 9.1.7 4. Launch Procedures for LVIS integration can be found in Section 9.1.9.2	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) reduces the chances of grid intersection 2. Redundancy has been implemented in LVIS design 3. LVIS testing procedures have been written and performed in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements.	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. LVIS design, which includes redundancy, can be found in Section 6.4	1	3	3

9.2.6 Launch Vehicle Identification System (LVIS) Integration Failure Modes and Effects Analysis

Table 59: 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 testing procedures have been written and performed in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. 2. Launch vehicle system components have been designed to mitigate risk of transmission interference 3. The material of the payload body tube has been confirmed to facilitate data transmissibility 4. Launch Procedures have been written, and they outline the necessary steps for preparing LVIS for launch 5. Launch Procedures have been written, and they outline the necessary steps for integrating LVIS into the launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. The material of the payload body tube can be found in Section 3.2.2 3. Launch Procedures for LVIS preparation can be found in Section 9.1.7 4. Launch Procedures for LVIS integration can be found in Section 9.1.9.2	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 testing procedures have been written and performed in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. 2. LVIS materials and design have been carefully selected to withstand the forces exerted on the system during flight 3. Launch Procedures have been written, and they outline the necessary steps for preparing LVIS for launch 4. Launch Procedures have been written, and they outline the necessary steps for integrating LVIS into the launch vehicle	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. LVIS material selection and CAD models can be found in Section 6.3 3. Launch Procedures for LVIS preparation can be found in Section 9.1.7 4. Launch Procedures for LVIS integration can be found in Section 9.1.9.2	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 were properly checked prior to every test, departure for launch site, and before integration at every launch 2. LVIS testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. All tests will be performed before FRR 3. All batteries brought to the launch site are required to be fully charged prior to launch 4. Launch Procedures for LVIS battery storing, transportation, testing, and integration at the launch field have been written and made accessible to all team members 5. Launch Procedures for LVIS integration has been written and made accessible to all team members	1. All Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Launch Procedures for battery storing can be found in Section 9.1.3 3. Launch Procedures for battery transportation can be found in Section 9.1.4 4. Launch Procedures for LVIS battery testing can be found in Sections 9.1.3 and 9.1.7 5. Launch Procedures for LVIS battery integration can be found in Section 9.1.7 6. Launch Procedures for LVIS integration into launch vehicle can be found in Section 9.1.9.2	1	4	4

9.2.7 Launch Equipment Failure Modes and Effects Analysis

Table 60: 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 3. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for aligning both the launch rail and launch pad 4. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for installing the launch vehicle on the launch rail 5. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment 6. Launch procedures have been written and made accessible to all members, and they 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. 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 for launch pad setup can be found in Section 9.1.10 3. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 9.1.10.4 4. Launch Procedures for launch equipment operation can be found in Section 9.1.10 and 9.1.11	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 4. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for aligning both the launch rail and launch pad 5. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for installing the launch vehicle on the launch rail 6. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment 7. Launch procedures have been written and made accessible to all members, and they 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. 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. A protractor will be used to ensure the launch rail angle is between five degrees and ten degrees 3. Launch Procedures for launch pad setup can be found in Section 9.1.10 4. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 9.1.10.4 5. Launch Procedures for launch equipment operation can be found in Section 9.1.10 and 9.1.11	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 3. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for aligning both the launch rail and launch pad 4. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for installing the launch vehicle on the launch rail 5. Launch procedures have been written and made accessible to all members, and they 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. 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 for launch pad setup can be found in Section 9.1.10 3. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 9.1.10.4	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 3. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for aligning both the launch rail and launch pad 4. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for installing the launch vehicle on the launch rail 5. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment 6. Launch procedures have been written and made accessible to all members, and they 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. 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 for launch pad setup can be found in Section 9.1.10 3. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 9.1.10.4 4. Launch Procedures for launch equipment operation can be found in Section 9.1.10 and 9.1.11	1	2	2

9.3 Project Risk Analysis

Table 61: 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 have been assigned to the same task to ensure task completion 2. All team members have been made aware of the task's details to ensure task completion 3. A NDRT Google Drive has been 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 have been 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 completed the necessary safety training prior to construction eligibility. 3. Standard Operating Procedures have been written, and they outline the necessary PPE and operation steps required for such tasks 4. NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn 5. NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines 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. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version has been shared with all members 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 has been 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
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 have been 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 were ordered before January 5th to ensure arrival before the start of Spring Semester (February 3rd) 2. Additional material was always purchased in case a component breaks and/or more material is simply required 3. Squads consulted 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 over NASA requirements 2. Inefficient time management 3. Lack of understanding of expected requirements	Team is ineligible to participate in competition	2	4	8	1. NASA requirements were clearly understood by all team members prior to the start of the design process 2. The Systems squad ensures all teams are meeting all NASA and NDRT requirements 3. Strong communication between all squads, team members, and team leaders	1. All NASA requirements have been 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. Failure to design a reusable launch vehicle, as outlined in NASA Vehicles Requirement 2.4. 2. Project delays and increasing the costs of the project 3. Team may be ineligible to compete in the competition	2	4	8	1. Extensive testing of all subsystems occurred prior to launch 2. Detailed CAD models and drawings were created prior to construction to accurately manufacture all subsystems 3. Construction Procedures have been written to help eliminate all construction-related imperfections. 4. A NDRT Google Drive has been 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. List of all Testing Procedures can be found in Section 10.1, and all tests have been passed 2. Construction Procedures can be found in Sections 3.3, 6.3.1, and 7.3. 3. 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 has been 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	1. Subscale has already been launched, and all information on the results of the launch were documented in CDR. 2. Fullscale has already been launched, and all information on the results of the launch can be found in Section 8 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 began subscale construction at least two weeks before the tentative launch date 5. The team began fullscale construction at least four weeks before the tentative launch date	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 purchased materials and parts as soon as they know the amount necessary in order to ensure availability 2. Design squads make a list of all parts and materials necessary for construction to ensure all necessary parts were accounted for. 3. All CAD drawings include the part's materials 4. Construction Procedures have been written, and they will include all necessary parts and materials for the construction of each component	1. All design squad materials were purchased before January 15th so they would arrive at the University before the start of the Spring Semester (February 3rd). 2. Construction Procedures can be found in Sections 3.3, 6.3.1, and 7.3.	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 3. Launch Procedures have been written, and they outline the necessary steps for ensuring safe transportation of personnel and components to and from the launch field	1. Transportation methods must have no pre-existing mechanical failures 2. Launch procedures for transportation can be found in Section 9.1.4	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 have been written, and they 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 revised to increase the clarity of the steps when need be 4. Launch vehicle and components will be evaluated before departure from the workshop	1. Launch Procedure troubleshooting follows each section of instructions when applicable 2. Launch Procedures for evaluating all components before departure can be found in Section 9.1.3 3. Launch Procedures for evaluating all components at the launch field can be found in Sections 9.1.6, 9.1.7, 9.1.8, and 9.1.9	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 updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version has been shared with all members, and it includes all team-related information on COVID-19 policy compliance	1	4	4
PR.11	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 10.5	2	2	4
PR.12	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.13	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 were 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 reached out to the desired testing facilities early in the year to ensure lab time availability and eligibility 4. Testing Procedures have been written and performed to ensure proper testing methods are used.	1. The team reached out to all applicable test facilities upon knowing they want to possibly be used this year. The team recieved access to all necessary facilities. 2. Testing Procedures can be found in Section 10.1, and all tests have been passed	1	2	2
PR.14	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 have been chosen with both the team's availability and the Team Mentor's availability in mind	1. Subscale has already been launched, and all information on the results of the launch were documented in CDR. 2. Fullscale has already been launched, and all information on the results of the launch can be found in Section 8	1	2	2

9.4 Personnel Hazard Analysis

9.4.1 Construction

Table 62: 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 have completed 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 have been written, and they outline the necessary PPE required and operation steps for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE avaliable, its location in the workshop, and how it should be worn. 4. The NDRT Safety Data Sheet has been updated and made avaliable to all team members, and it outlines all material properties.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer. 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof must have been presented to the Safety Officer. 3. Standard Operating Procedures for hand sanding can be found in SOP Section 1.3.2 4. Standard Operating Procedures for the belt sander can be found in SOP Section 1.2.3 5. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version has been shared with all members 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 has been 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	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 have completed 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 have been written, and they outline the necessary PPE required and operation steps for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn. 4. The NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines all material properties.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer. 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof has been presented to the Safety Officer. 3. Standard Operating Procedures for hand sanding can be found in SOP Section 1.3.2 4. Standard Operating Procedures for the belt sander can be found in SOP Section 1.2.3 5. Standard Operating Procedures for the epoxying can be found in SOP Section 1.3.1 6. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version has been shared with all members 7. The updated NDRT Safety Data Sheet Document is readily available to all members as a physical version in the workshop, and a digital version has been 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	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 have completed the necessary safety training prior to construction eligibility 2. Standard Operating Procedures have been written, and they outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines 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 shown 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 can be found in SOP Section 1.1.1 4. Standard Operating Procedures for the portable drill can be found in SOP Section 1.1.3 5. Standard Operating Procedures for the drill press can be found in SOP Section 1.2.4 6. Standard Operating Procedures for the lathe can be found in SOP Section 1.2.6 7. Standard Operating Procedure for the CNC, Desktop, and Bridgeport mills can be found in SOP Sections 1.2.9,1.2.10, and 1.2.8, respectively 8. Standard Operating Procedures for wire cutters and strippers can be found in SOP Section 1.1.5 9. Standard Operating Procedures for the hand saw can be found in SOP Section 1.1.2 10. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version has been shared with all members 11. 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 have completed 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. The NDRT Safety Handbook has be updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof has been presented to the Safety Officer 4. The updated NDRT Safety Handbook is readily available to all members as a physical version in the workshop, and a digital version has been 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 have been written, and they outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines 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 shown 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 can be found in SOP Section 1.2.3 4. Standard Operating Procedures for hand sanding can be found in SOP Section 1.3.2 5. 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 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.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 have completed 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 have been written, and they will outline the necessary PPE required for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof has been presented to the Safety Officer 3. Standard Operating Procedures for wire cutters and strippers can be found in SOP Section 1.1.5 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 have completed 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 have been written, and they outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn. 4. The NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines all material properties.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof has been presented to the Safety Officer 3. Standard Operating Procedures for epoxying can be found in Section 1.3.1 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 have completed 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 that require clamping highlight this necessity in the procedure 3. Construction Procedures that require clamping will highlight this necessity in the procedure 4. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof has been presented to the Safety Officer 3. 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 4. Construction Procedures can be found in Sections 3.3, 6.3.1, and 7.3.	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 have completed 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 have been written, and they outline the necessary PPE required for loud machinery. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof has been 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	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 have completed 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 work space after operating with flammable materials. 2. Standard Operating Procedures have been written, and they outline the necessary PPE and clean-up steps required for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines 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 has been updated and made available to all team members, and it outlines all material properties. All team members must consult the SDS before operating with any flammable materials. 5. Construction Procedures have been created to ensure safe and consistent results.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof has been presented to the Safety Officer 3. Standard Operating Procedures for soldering can be found in SOP Section 1.1.4 4. Standard Operating Procedure for laser cutter can be found in SOP Section 1.2.5 5. 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 6. 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 7. 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 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 9. Construction Procedures can be found in Sections 3.3, 6.3.1, and 7.3.	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. Construction Procedures have be written, and they include all necessary information for handling heavy materials and/or equipment/ 3. The NDRT Safety Handbook has be updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed 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 5. Construction Procedures can be found in Sections 3.3, 6.3.1, and 7.3.	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 has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed 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 have been written, and they outline the necessary PPE and operation required for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn. 4. The NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines all material properties.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer 2. All team members have signed the NDRT Workshop Safety Agreement, which acknowledges they read, understand, and agree to abide by all team safety documentation and rules, and proof has been presented to the Safety Officer 3. Standard Operating Procedures for soldering can be found in SOP Section 1.1.4 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, 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 have been written, and they outline the necessary PPE required for such tasks. 3. Construction Procedures that require small clearances include the necessary steps 4. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE available, its location in the workshop, and how it should be worn.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown 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 5. Construction Procedures can be found in Sections 3.3, 6.3.1, and 7.3.	2	2	4

9.4.2 Launch Operations Personnel Hazards

Table 63: 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 motors were purchased from a reputable vendor and will be installed using proper techniques. 3. Launch Procedures have been written, and they outline the necessary procedures for motor transportation, inspection, and instillation	1. Launch Procedure Section 9.1.4 outlines the transportation procedures for launch 2. Launch Procedure Section 9.1.9.6.1 outlines the necessary steps for motor inspection prior to launch. 3. Launch Procedure Section 9.1.9.6.2 outlines the necessary steps for motor inspection prior to launch. 4. Section motor selection justification was performed and approved during CDR. 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 have been 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 have been performed and approved by the Project Manager and the Safety Officer. The stability margin is at a safe level	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 have been written and made accessible to all members, and they 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 can be found in Section 9.1.10 4. Launch Procedures for launch vehicle component instillation can be found in Section 9.1.9 5. Stability calculations can be found in Section 5.2	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 have been written, and they outline the necessary steps for all launch vehicle component integration. 2. Recovery system testing procedures have been written and performed in order to ensure the system will 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. 6. Main and drogue parachute drift calculations have been performed and approved by the Project Manager and the Safety Officer.	1. Launch Procedures for launch vehicle component instillation can be found in Section 9.1.9 2. Recovery testing procedures can be found in Section 10.1 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 have been written and made accessible to all members, and they 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 and drogue parachute drift calculations can be found in Section 5.4.3	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 have been written, and they outline the necessary steps for all launch vehicle component integration. 2. Recovery system testing procedures have been written and performed in order to ensure the system will 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. 6. Main and drogue parachute drift calculations have been performed and approved by the Project Manager and the Safety Officer.	1. Launch Procedures for launch vehicle component instillation can be found in Section 9.1.9 2. Recovery testing procedures can be found in Section 10.1 3. A more detailed look at recovery system hazards and mitigations can be found in the recovery Failure Modes and Effects Analysis tables, Section 9.2.4. 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 have been written and made accessible to all members, and they 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 and drogue parachute drift calculations can be found in Section 5.4.3	2	2	4

L.5	Uncon-trolled ACS body tube descent	1. Unintended seperation of ACS body tube from launch vehicle during launch 2. Failure of recovery system's shock cord	1. Personnel injury via impact 2. Damage to nearby buildings or natural structures via impact	3	3	9	1. Launch procedures have been written, and they outline the necessary steps for all launch vehicle component integration. 2. Recovery system testing procedures have been written and performed in order to ensure the system will 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. 6. Main and drogue parachute drift calculations have been performed and approved by the Project Manager and the Safety Officer.	1. Launch Procedures for launch vehicle component instillation can be found in Section 9.1.9 2. Recovery testing procedures can be found in Section 10.1 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 have been written and made accessible to all members, and they 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 and drogue parachute drift calculations can be found in Section 5.4.3	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 Procedure Section 9.1.12.1 outlines the necessary steps for post-launch retrieval of the launch vehicle 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 has been updated and made accessible to all team members, and it outlines how PPE should be worn. 3. Launch Procedures have been written, and they outline the PPE required and the procedure for dealing with damaged batteries. 4. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries. 5. Launch Procedures have been written, and they outline the PPE required and the procedure for checking battery quality.	1. All team members have passed the University of Notre Dame's Engineering Innovation Hub Safety and Tools Quiz and shown proof of completion to the Safety Officer. 2. All team members have signed 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, and a digital version is shared with all members. 4. Launch Procedures for handling damaged batteries can be found in Section 9.1.3 5. Launch Procedures Section 9.1.3 highlight the importance of storing all batteries in fire resistant bags when not in use 6. Launch Procedures for checking battery voltage can be found in Section 9.1.3 and in every other section that involves battery instillation	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 have been written, and they outline the necessary PPE and operation steps required for such tasks. 3. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines how PPE should be worn. 4. Launch Procedures have been written, and they outline all PPE available at the launch site.	1. All team members have passed 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 have signed 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 document has been written and made accessible to all team members. 4. Launch Procedure sections all include all necessary PPE required for completing the procedure. 5. Launch Procedure Section 9.1.3 outlines all PPE brought to the launch 6. The updated NDRT Safety Handbook is readily available to all members, 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.	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. 2. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines how PPE should be worn. 3. Launch Procedures have been written, and they outline all PPE available at the launch site.	1. All team members have passed 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 have signed 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 Procedure sections all include all necessary PPE required for completing the procedure. 4. Launch Procedure Section 9.1.3 outlines all PPE brought to the launch 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	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 is the responsibility of the Safety Officer to provide weather information to all members attending the launch at the day of the launch. 2. It is 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. 4. Launch Procedures Sections 9.1.2 and 9.1.4 mentions that the Safety Officer and Project Manager will notify all team members attending of the weather conditions at the launch field the day before and the day of the launch	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. It is the responsibility of the Safety Officer to provide weather information to all members attending the launch at the day of the launch. 2. It is 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. Launch Procedures Sections 9.1.2 and 9.1.4 mentions that the Safety Officer and Project Manager will notify all team members attending of the weather conditions at the launch field the day before and the day of the launch	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 is the responsibility of the Safety Officer to provide weather information to all members attending the launch at the day of the launch. 2. It is 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. 4. Launch Procedures Sections 9.1.2 and 9.1.4 mentions that the Safety Officer and Project Manager will notify all team members attending of the weather conditions at the launch field the day before and the day of the launch	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 have been written, and they 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 have been written, and they outline the necessary steps for maintaining the launch vehicle components on the tables.	1. Launch Procedures for launch vehicle transportation to the launch rail can be found in Section 9.1.10.4 2. Launch Procedures for maintaining launch vehicle components can be found in Section 9.1.9	1	2	2

9.5 Environmental Hazards

9.5.1 Environmental Risks to the Launch Vehicle

Table 64: 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 fire resistent bags when not in use. 2. Altimeters for recovery, payload, and apogee control system will be shielded. 3. Electrical components will be securely fastened to structural components or brackets in the launch vehicle. 4. Launch Procedures have been written, and they outline the necessary steps for ensuring all electrical components are safe and ready before integration and launch 5. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO	1. Launch Procedures to ensure the recovery electronics are safe and ready for integration can be found in Section 9.1.6 2. Launch Procedures to ensure the LVIS electronics are safe and ready for integration can be found in Section 9.1.7 3. Launch Procedures to ensure the ACS electronics are safe and ready for integration can be found in Section 9.1.8 4. Launch Procedures to ensure all system electronics are safe and ready for integration can be found in Section 9.1.9 5. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 9.1.11 and 9.1.5	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. Computer simulations and calculations have been performed in order to ensure the stability margin is at least 2.0 at the point of rail exit (NASA Vehicle Requirement 2.14) 2. Launch will be postponed if wind speeds exceed 20 miles per hour. 3. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO	1. Calculations and simulations for the fins and stability margin can be found in Section 5.2, and they were approved by both the Safety Officer and the Systems Officer 2. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 9.1.11 and 9.1.5	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. 2. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO	1. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 9.1.11 and 9.1.5 2. The Range Safety Officer will always have full authority as to when launches may proceed.	1	3	3
EV.4	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 parachute and main parachute sizings were based on calculations and flight simulations. 2. Computer simulations and calculations have been performed in order to ensure the maximum drift radius is below 2,500 ft (NASA Vehicle Requirement 3.10) 3. Launches will occur in an open field away from any trees. 4. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is clear of structures through a discussion with the RSO and LCO	1. Calculations in Section 5.4.3 show the maximum possible simulated drift of the vehicle is within the acceptable range of 2,500 ft (NASA Recovery Requirement 3.10). 2. Launch Procedures for ensuring the launch is safe to occur and free from obstacles can be found in Sections 9.1.11 and 9.1.5	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. All electrical components will be stored in fire resistant bags when not in use. 4. Launch Procedures have been written, and they outline the necessary steps for ensuring the transmissibility of LVIS prior to launch 5. Launch Procedures have been written, and they outline the necessary steps for ensuring the recovery system is working properly prior to integration and launch. 6. Transmitter testing procedures have been written to ensure the transmitters work. All tests will be performed prior to FRR 7. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO	1. All transmitter frequencies will be reported to NASA prior to competition launch and compared to other devices at the launch site. 2. All Testing Procedures can be found in Section 10.1, and all tests have been passed 3. Launch Procedures for ensuring LVIS transmissibility can be found in Section 9.1.9.2 4. Launch Procedures for ensuring recovery system is working properly can be found in Sections 9.1.6 and 9.1.9.3 5. The Range Safety Officer will always have full authority as to when launches may proceed. 6. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 9.1.11 and 9.1.5	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. 2. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch pad is positioned at a 0° ± 1° angle with respect to the ground	1. Launch Procedures for ensuring the launch pad is positioned at a 0° ± 1° angle with respect to the ground can be found in Sections 9.1.10.3 and 9.1.10.4.5	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. 3. Launch Procedures have been written, and they ouline the necessary steps for ensuring the launch is clear of animals through a discussion with the RSO and LCO	1. Launch Procedures for ensuring the launch is safe to occur and free from animals can be found in Sections 9.1.11 and 9.1.5	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. 3. Launch Procedures have been written, and they outline that only individuals with a NAR/TRA Level 2 Certification may transport the energetics to the launch. This includes the motor and black powder. 4. Launch Procedures have been written, and they outline the necessary steps for motor inspection and integration	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. 2. Launch Procedures highlighting who can transport energetics can be found in Section 9.1.4 3. Launch Procedures for the motor inspection and Integration can be found in Section 9.1.9.6	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 were 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. 4. Standard Operating Procedures have been written, and they will outline the correct procedure for epoxying.	1. Standard Operating Procedures for epoxying can be found in SOP Section 1.3.1 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 fire resistent bags when not in use. 2. All electronics will be protected from direct sunlight once integrated into launch vehicle. 3. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries.	1. Launch Procedures Section 9.1.3 highlight the importance of storing all battieris in fire resistant bags when not in use 2. Launch Procedures for Recovery system preparation can be found in Section 9.1.6 3. Launch Procedures for LVIS preparation can be found in Section 9.1.7 4. Launch Procedures for ACS preparation can be found in Section 9.1.8 5. Launch Procedures for launch vehicle preparation can be found in Section 9.1.9	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. Launch Procedures are 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. 7. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries. 8. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO	1. Launch Procedures Section 9.1.3 highlight the importance of storing all batteries in fire resistant bags when not in use 2. Launch Procedures for checking battery voltage can be found in Section 9.1.3 and in every other section that involves battery instillation 3. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 9.1.11 and 9.1.5 4. All Launch Procedures can be found in Section 10.1	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. Computer simulations and calculations have been performed in order to ensure the stability margin is at least 2.0 at the point of rail exit (NASA Vehicle Requirement 2.14) 2. Launch will be postponed if wind speeds exceed 20 miles per hour. 3. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO	1. Calculations and simulations for the fins and stability margin can be found in Section 5.2, and they were approved by both the Safety Officer and the Systems Officer 2. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 9.1.11 and 9.1.5	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 to optimise reduction of both descent velocity and drift radius. 2. Launch will be postponed if wind speeds exceed 20 miles per hour. 3. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO	1. Calculations and simulations for the drogue parachute and main parachute can be found in Section 5.4.3, and they have been verified by the Safety Officer and Systems Officer. 2. Expected drift calculations can be found in Section 5.4.3, and they have been verified and approved by the Safety Officer and Systems Officer. 3. Launch Procedures for ensuring the launch is safe to occur and free from obstacles can be found in Sections 9.1.11 and 9.1.5	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. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO 2. Launch Procedures have been written, and they outline the necessary steps for complete launch vehicle assembly 3. Components of the vehicle will be reliable, durable, and able to withstand minor physical forces.	1. Launch Procedures for ensuring the launch is safe to occur and free from obstacles can be found in Sections 9.1.11 and 9.1.5 2. All Launch Procedures can be found in Section 10.1 3. 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. Launch Procedures have been written, and they outline the necessary steps for a safe component transportation to the launch site 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. 3. Components of the vehicle will be reliable, durable, and able to withstand minor physical forces. 4. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch is safe to occur through a discussion with the RSO and LCO	1. Launch Procedures for ensuring the launch is safe to occur and free from obstacles can be found in Sections 9.1.11 and 9.1.5 2. All Launch Procedures can be found in Section 10.1 3. The Range Safety Officer will always have full authority as to when launches may proceed. 4. Launch Procedures outlining the entire launch checklist list can be found in Section 9.1.3 5. Launch Procedures for all component transportation can be found in Section 9.1.4	1	2	2

9.5.2 Launch Vehicle Risks to the Environment

Table 65: 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 have been written, and they 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 for soldering can be found in SOP Section 1.1.4 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 system testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. All tests will be performed before FRR 4. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR 5. Launch Procedures have been written, and they outline the necessary steps for motor integration 6. Launch Procedures have been written, and will outline the necessary procedure for recovery system preparation and integration	1. Launch procedures have been written by FRR and accessible to all members, and they 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 has been procured from a trusted vendor and was approved by the Vehicles Lead, Systems Lead, and Project Manager. Motor selection information was provided and approvied by during CDR. 3. All recovery information can be found in Section 4. Notably, recovery systems can be found in Section 4.5 4. Recovery Testing Procedures have been written, and they can be found in Section 10.1, and all tests have been passed 5. Launch Procedures for recovery preparation and integration can be found in Sections 9.1.6 and 9.1.9.3, respectively 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 Procedures have been written, and they 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. Standard operating procedures for hand sanding can be found in SOP Section 1.3.2 4. NDRT Safety Data Sheet Document Section 4.10 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 have been written and made accessible to all members, and they 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 4.4 contains safety data sheeets for Black Powder 3. NDRT Safety Data Sheet Document contains the Aerotech Igniter and Motor information in Sections 4.2 and 4.3, respectively, and the SDS 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. 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. Launch Procedures Section 9.1.9.6 outlines motor instillation into launch vehicle	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 3. ACS flaps extend during motor burnout, and the shear pins are unable to withstand the intense drag induced by the flaps	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 testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. All tests will be performed before FRR 3. Recovery system testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. All tests will be performed before FRR 4. Integration testing Procedures have been performed in order to test how all components engage with each other when put together. All tests will be performed before FRR	1. Calculations and simulations for vehicle structural components(Section 3.2) and recovery structural components (Section 4.5) have been verified and approved by both the Safety Officer and Systems Lead 2. All Testing Procedures have been written, and they can be found in Section 10.1, and all tests have been passed 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 system testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. All tests will be performed before FRR 4. Vehicle testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. All tests will be performed before FRR 5. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR 6. Launch Procedures have been written, and they outline the necessary steps for motor integration 7. Launch Procedures have been written, and will outline the necessary procedure for recovery system preparation and integration	1. Launch procedures have been written by FRR and accessible to all members, and they 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 has been procured from a trusted vendor and was approved by the Vehicles Lead, Systems Lead, and Project Manager. Motor selection information was provided and approvied by during CDR. 3. All recovery information can be found in Section 4. Notably, recovery deployment can be found in Section 4.5 4. Recovery and Vehicles Testing Procedures have been written, and they can be found in Section 10.1, and all tests have been passed 5. Launch Procedures for recovery preparation and integration can be found in Sections 9.1.6 and 9.1.9.3, respectively 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. All tests will be performed before FRR 5. Launch Procedures for battery storing, transportation, testing, and integration at the launch field have been and made accessible to all team members	1. NDRT Safety Data Sheet Document Section 4.13 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 testing procedures have been written, and they can be found in Section 10.1, and all tests have been passed 4. Launch Procedures for battery storing can be found in Section 9.1.3 5. Launch Procedures for battery transportation can be found in Section 9.1.4 6. Launch Procedures for battery testing can be found in Section 9.1.3	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. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines all PPE and fire-prevention materials avaliable, their locations in the workshop, and how they should be worn or used. 3. The NDRT Safety Data Sheet will be updated and made avaliable to all team members, and it will outline all material properties. All team members must consult the SDS before operating with any flammable materials. 4. The motor will be installed correctly and carefully by an individual with at least NAR/TRA Level 2 certification 5. All electronics will be inspected prior to departure to the launch site, and again immediately prior to integration into vehicle 6. All electronics will remain OFF until necessary 7. The launch pad will be positioned in an area free of debris or flammable objects 8. Launch procedures have be written, and they will outline the necessary steps for all electronics integration	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. 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. 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 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. Launch Procedures for electronics integration can be found in Sections 9.1.6, 9.1.7, 9.1.8, and 9.1.9 7. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR 8. Launch procedures have been written and made accessible to all members, and they 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 have been written and made accessible to all members, and they 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 contains the Aerotech Igniter and Motor information in Sections 4.2 and 4.3, respectively, and the SDS is 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 Vehicles Requirement 3.12 2. Long-distance testing procedures have been written, and it wil ensure all electronics can send signals at far distances. All tests will be performed before FRR 3. Calculations for maximum expected drift radius have been performed	1. Long-distance Testing Procedures can be found in Section 10.1, and all tests have been passed 2. All parachute calculations and simulations will have to be verified and approved by both the Safety Officer and Systems Officer, and they can be found in Section 5.4.3	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 have been written, and they outline the procedure for launch vehicle integration on launch rail 4. Launch Procedures have been written, and they outline the procedure for setting up the launch pad 5. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR	1. Launch Procedures for launch pad setup can be found in Section 9.1.10 2. Launch Procedures for launch vehicle integration on launch pad can be found in Section 9.1.10.4 3. The Range Safety Officer will designate safe areas to view the launch in accordance with NAR guidelines 4. The Range Safety Officer will always have full authority as to when launches may proceed 5. 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 6. The Safety Handbook has been 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 have been written, and they outline the necessary steps for vehicle transportation and integration 6. Fin can and nose cone impact testing procedures have been written, and they will help gauge to amount of paint that will fall of the launch vehicle during launch and impact. All tests will be performed prior to FRR	1. All professional paint shops must have proper licenses and certifications 2. NDRT Safety Data Sheet Document Section 4.1 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 nose cone impact testing procedures can be found in Section 10.1, and all tests have been passed 5. Launch Procedures for vehicle transportation and instillation on launch pad can be found in Section 9.1.10.4	1	1	1

9.6 Hazard Occurrences

All hazards that have occurred throughout the year have been documented through the use of an anonymous survey system as a honest log of the success of the safety hazards at mitigating risks. The Appendix lists all the incidents that have occurred up March 3rd, 2022. As of March 3rd, 2022, 95.7% of all hazards never occurred. Of the 5 hazards that did occur, the situation has been safely and fully resolved, and the hazards have not occurred since then.

10 Project Plan

10.1 Testing

The team has developed and implemented a testing and demonstration plan to comprehensively analyze the performance of the launch vehicle and its internal systems, as well as verify all relevant requirements, included in this section. The team has been careful to perform each of these tests and demonstrations and analyze their results to improve the vehicle's systems throughout the months of January and February. The ultimate goal has been to maximize confidence in the launch vehicle for the competition flight in April.

Table 66: Testing Overview

Test ID	Title	Requirements Satisfied	Result
LVT.1	Launch Vehicle Demonstration Flight	NASA 2.1, NASA 2.4, NASA 2.19.1, NASA 2.19.1.1, NASA 2.19.1.4, NASA 2.21 NASA 3.1, NASA 3.1.1, NASA 3.1.2, NASA 4.2.1.1, LV.1, LV.5	Attempted
LVT.2	Subscale Demonstration Flight	NASA 2.18	Pass
LVT.3	Bulkhead Static Loading Test	LV.2	Omitted
LVT.4	Motor Mount Tube Static Loading Test	LV.2	Omitted
LVT.5	Body Tube Static Loading Test	LV.2	Omitted
LVT.6	Bulkhead Dynamic Loading Test	LV.2	Omitted
RT.1	Launch Vehicle Demonstration Flight	R.2	Attempted
RT.2	Subscale Demonstration Flight	NASA 2.18	Pass
RT.3	Ground Ejection Demonstration	NASA 3.2	Pass
RT.4	Simulated Flight Demonstration	N/A	Pass
RT.5	Altimeter Disarming Demonstration	N/A	Pass
RT.6	GPS Functionality and Range Demonstration	NASA 3.12, NASA 3.12.2	Pass
RT.7	Electronics Isolation Demonstration	NASA 3.13, NASA 3.13.3, NASA 3.13.4	Pass
RT.8	Battery Duration Demonstration	R.4	Pass
RT.9	Bulkhead Static Loading Test	R.1	Pass
RT.10	Bulkhead Dynamic Loading Test	R.1	Omitted
LVIST.1	Payload Demonstration Flight	NASA 2.19.2.1, NASA 2.19.2.2, NASA 4.2.2.6, R.1	Incomplete
LVIST.2	Subscale Demonstration Flight	N/A	Pass
LVIST.3	Electronics Unit Demonstrations	N/A	Pass
LVIST.4	Sensor Module Demonstration	N/A	Pass
LVIST.5	Transmission Module Functionality and Range Demonstration	NASA 4.2.2.6	Incomplete
LVIST.6	Full System Integration Demonstration	R.3, LVIS.3, 4.2.2.6	Incomplete
LVIST.7	Battery Duration Demonstration	NASA 2.7, LVIS.4, LVIS.5	Pass
LVIST.8	Main Parachute Impulse Event Demonstration	LVIS.6	Incomplete

Table 66: Testing Overview (continued)

Test ID	Title	Requirements Satisfied	Result
LVIST.9	Algorithm Drift Test	N/A	Incomplete
ACST.1	Launch Vehicle Demonstration Flight	NASA 2.19.1.1, NASA 2.19.1.4 ACS.1, ACS.4, ACS.5	Pass
ACST.2	Payload Demonstration Flight	N/A	Incomplete
ACST.3	Subscale Demonstration Flight	N/A	Pass
ACST.4	Electronics Unit Demonstrations	N/A	Pass
ACST.5	Full System Integration Demonstration	NASA 2.19.1.1, ACS.1 ACS.5	Incomplete
ACST.6	Battery Duration Demonstration	ACS.7	Pass
ACST.7	Limit Switch Detection Demonstration	N/A	Pass
ACST.8	Loaded Flap Actuation Demonstration	ACS.8, ACS.9	Pass
ACST.9	Bulkhead Static Loading Test	ACS.6	Pass
ACST.10	Bulkhead Dynamic Loading Test	ACS.6	Omitted

10.1.1 Launch Vehicle Testing

LVT.1, RT.1: Launch Vehicle Demonstration Flight

Objective: Verify nominal performance of full-scale launch vehicle airframe and internal systems

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.1	Launch vehicle launches, descends, and lands safely	NASA 2.1, NASA 2.4, NASA 2.19.1, NASA 2.19.1.1, NASA 2.19.1.4, NASA 2.21 NASA 3.1, NASA 3.1.1, NASA 3.1.2, NASA 4.2.1.1, LV.1, LV.5	Attempted
RT.1	All separation events occur as designed, parachutes open without tangling, and launch vehicle is safely recovered	R.2	Attempted

Materials and Equipment Needed: Refer to Launch Operating Procedures for PPE, tools, and equipment required for launch.

Test Setup: Follow all Launch Rehearsal steps described in the Launch Operating Procedures. Note: Test setup should take no more than 2 hours (NASA 2.6).

Test Procedure: Follow all steps described in the Launch Operating Procedures.

Analysis Procedure:

1. Inspect launch vehicle and subsystems for visible signs of damage from launch.
2. Inspect video footage from on-board camera and ground viewers to verify proper timing of recovery events.

Results: Incomplete. Main parachute tangled after separation event, resulting in minor damage to epoxy bonds on a fin. Figure 121 shows an image of the tangled parachute after the vehicle landed.

Next Steps: The team has formally requested a VDF re-flight to be completed along with the PDF before the FRR Addendum deadline.

LVT.2, RT.2, LVIST.1, ACST.3: Subscale Demonstration Flight

Objective: Verify nominal performance of subscale launch vehicle airframe, recovery, and internal systems

Figure 121: Tangled main parachute after landing

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.2	Launch vehicle launches, descends, and lands safely	NASA 2.18	Pass
RT.2	All separation events occur as designed, parachutes open without tangling, and launch vehicle is safely recovered	NASA 2.18	Pass
LVIST.2	Sensor module records desired flight data	N/A	Pass
ACST.3	Sensor module records desired flight data	N/A	Pass

Materials and Equipment Needed:

- Subscale launch vehicle
- Subscale parachute
- LVIS sensor sled
- ACS sensor sled
- Computer monitor and power source
- All PPE required in Launch Operating Procedures
- Refer to Launch Operating Procedures for other PPE, tools, and equipment required for launch.

Test Setup: Follow all Launch Rehearsal steps described in the Launch Operating Procedures, following all steps which are applicable to subscale.

Test Procedure: Follow all steps described in the Launch Operating Procedures.

Analysis Procedure:

1. Inspect subscale launch vehicle and subsystems for visible signs of damage from launch.
2. Verify proper timing of parachute deployment at apogee
3. Inspect sensor sled computers for verification of data collection

Results: The subscale vehicle safely launched, deployed its parachute, and landed. There were no visible signs of damage, and the parachute was properly deployed. Further discussion of subscale demonstration results can be found in Section **??**, and discussion of data collected from the subscale flight by LVIS is discussed in Section **??**. The ACS sled was unable to collect usable data.

Next Steps: If success criteria for LVT.2 and RT.2 are met, subscale demonstration flight is passed. If one or both success criteria are not met, identify and address causes of failure and repeat demonstration flight. If success criteria for LVIS.2 and/or ACS.3 are not met, re-flight is not necessary, as they are not critical for subscale demonstration.

LVT.3, RT.9, ACST.9: Bulkhead Static Loading Test

Objective: Verify that bulkheads within the launch vehicle can withstand all loads due to launch and main parachute deployment with a factor of safety of 2.0

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.3	Fin can and payload tube bulkheads withstand static loading up to and beyond twice the maximum expected in-flight load	LV.2	Complete
RT.9	PRM and SRM bulkhead assemblies withstand static loading up to and beyond twice the maximum expected in-flight load	R.1	Complete
ACST.9	ACS bulkheads withstand static loading up to and beyond twice the maximum expected in-flight load	ACS.6	Complete

Materials and Equipment Needed:

- Carbon-fiber body tube sections (about 4-6 inches needed)
- One carbon-fiber bulkhead (same dimension as PRM bulkheads) with holes to simulate U-bolt attachment points
- Four air-frame mounting blocks and associated hardware
- Epoxy
- Load frame
- Safety Glasses

Test Setup:

1. Epoxy bulkheads into the center of one body tube and the coupler section; allow time to cure. Be sure to create clean fillets on both sides of the bulkheads.
2. Assemble mounting blocks onto ACS and PRM bulkheads, secure within carbon-fiber body tube sections

Test Procedure:

1. For each test article:
   (a) Load article into load frame such that the coupler/body tube section rests upon bottom plate and push rod is attached to eye-bolt hole
   (b) Increase load on load cell until the desired load (1400 lbf for carbon-fiber bulkheads, 650 lbf for fiberglass bulkheads)
   (c) If test article is still in good condition, continue increasing load until failure (if load frame allows)

Analysis Procedure:

1. Calculate actual factor of safety for each bulkhead
2. Inspect failure mode for each test article
3. If bulkhead material failed first, evaluate whether bulkhead material and thickness selection is appropriate for use in the full-scale vehicle
4. If epoxy bond failed first, evaluate whether quantity of epoxy used and application method are sufficient for use in full-scale vehicle
5. If interface hardware failed first, evaluate whether quantity and size of bolts are sufficient for use in full-scale vehicle
6. Compare results with FEA results for same loading scenarios

Results: Complete. Carbon fiber bulkhead held 1,330 lbf before the test was stopped due to safety concerns regarding the load cell setup. The test article had only elastic deformation and returned to its original state without any damage. This test yields a FOS of 1.9. While this does not meet the team FOS of 2.0, it has a high confidence in the integrity of the bulkhead to sustain repeated impulses due to recovery events. Note that the fiberglass bulkheads were not tested due to material availability. The team has however used this material in past years and conducted FEA for each load case, and has a high confidence in its structural integrity. Figure 122 shows an image of the test setup, and Figure 123 shows the data collected from the test.

Next Steps: Proceed to vehicle demonstration flight.

LVT.4: Motor Mount Tube Static Loading Test

Objective: Verify that motor mount tube can withstand the maximum thrust force with a factor of safety of 2.0

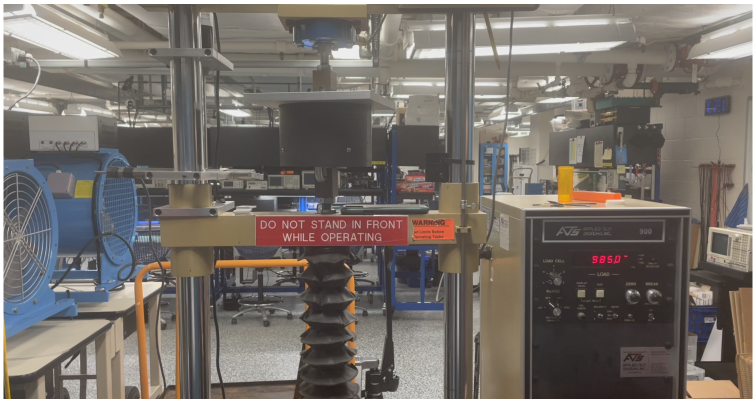


Figure 122: Test setup for carbon-fiber bulkhead test

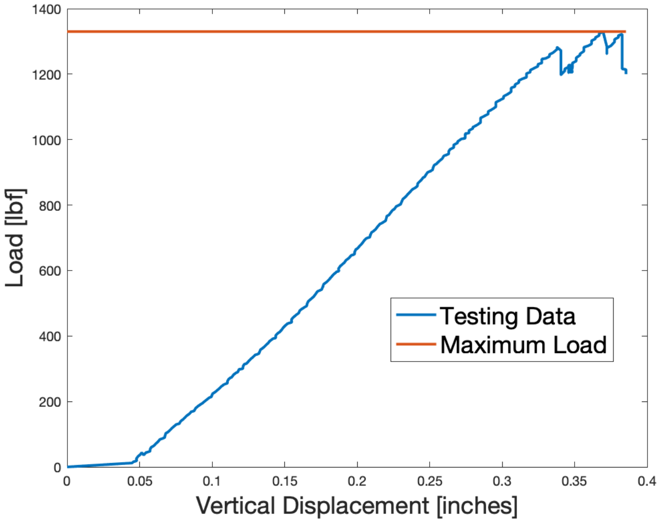


Figure 123: Load vs. vertical displacement for carbon-fiber test bulkhead

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.4	Motor mount tube withstands static loading up to and beyond twice the maximum expected thrust force (700 lbf)	LV.2	Omitted

Materials and Equipment Needed:

- Carbon-fiber motor mount tube
- Assembly rig for loading
- 700 lbf of known weight for loading
- Safety Glasses

Test Setup:

1. Mount motor tube onto load frame

Test Procedure:

1. For each test article:
   (a) Load the bottom plate incrementally, putting the motor tube in compression.
   (b) Continue loading until force matches maximum expected thrust force (700 lbf).
   (c) Safely unload the tube for post-test inspection.
   (d) Note: This test only verifies the motor tube up to a factor of safety of 1.0. The team does not deem it safe to continue loading, and does not have access to test equipment to safely load past this value.

Analysis Procedure:

1. Inspect the motor tube for visible signs of damage

Results: Test was canceled due to poor load-frame availability and lack of a safe alternative method of completing the test. The team has however used this material in past years and has a high confidence in its structural integrity.

Next Steps: If motor tube does not show any visible signs of damage, test is passed. If motor tube is damaged, material selection and thickness must be reconsidered and the test repeated.

LVT.5: Body Tube Static Loading Test

Objective: Verify that body tubes can withstand the maximum thrust force with a factor of safety of 2.0

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.5	Body tube test article withstands static loading up to and beyond twice the maximum expected thrust force (700 lbf)	LV.2	Omitted

Materials and Equipment Needed:

- Carbon-fiber body tube (length of longest unsupported section on vehicle - 17 in.)
- Assembly rig for loading
- 700 lbf of known weight for loading
- Safety Glasses

Test Setup:

1. Mount body tube onto a plywood board, centered over a hole through which a shock cord can pass through
2. Mount a plate with an eyebolt attached above the body tube and hang another board below the original, connected to the plate via an eyebolt and shock cord

Test Procedure:

1. For each test article:
   (a) Load the bottom plate incrementally, putting the motor tube in compression.
   (b) Continue loading until force matches maximum expected thrust force (700 lbf).
   (c) Safely unload the tube for post-test inspection.

(d) Note: This test only verifies the body tube up to a factor of safety of 1.0. The team does not deem it safe to continue loading, and does not have access to test equipment to safely load past this value.

Analysis Procedure:

1. Inspect the body tube for visible signs of damage

Results: Test was canceled due to poor load-frame availability and lack of a safe alternative method of completing the test. The team has however used this material in past years and has a high confidence in its structural integrity.

Next Steps: If body tube does not show any visible signs of damage, test is passed. If body tube is damaged, material selection and thickness must be reconsidered and the test repeated.

LVT.6, RT.10, ACST.10: Bulkhead Dynamic Loading Test

Objective: Verify that load-bearing bulkheads within the launch vehicle can withstand the maximum impulse force from parachute deployment with a factor of safety of 2.0

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.6	Fin can bulkhead and payload bulkhead assembly test articles withstand dynamic loading up to and beyond twice the maximum expected parachute force (338 lbf for fin can bulkhead, 211 lbf for payload bay bulkhead)	LV.2	Omitted
RT.10	PRM/SRM bulkhead assembly test article withstands dynamic loading up to and beyond twice the maximum expected parachute force (780 lbf)	R.1	Omitted
ACST.10	ACS bulkhead assembly test article withstands dynamic loading up to and beyond twice the maximum expected parachute force (600 lbf)	ACS.6	Omitted

Materials and Equipment Needed:

- Three carbon-fiber body tube section (about 4-6 inches needed)
- Fiberglass coupler section (about 4-6 inches needed)
- Three G-10 fiberglass bulkheads (same dimensions as fin can bulkhead, payload tube bulkhead, and ACS bulkheads) with holes in each to simulate eye-bolt/U-bolt attachment points
- One carbon-fiber bulkhead (same dimension as PRM bulkheads) with holes to simulate U-bolt attachment points
- Eight airframe mounting blocks and associated hardware
- Epoxy
- Frame for securing shock cord above an overhang
- Safety Glasses

Test Setup:

1. Epoxy bulkheads into the center of one body tube and the coupler section; allow time to cure. Be sure to create clean fillets on both sides of the bulkheads.
2. Assemble mounting blocks onto ACS and PRM bulkheads, secure within carbon-fiber body tube sections
3. Secure eyebolts/U-bolts onto the center of bulkheads
4. Secure other eyebolt to frame
5. Connect the two harnesses with shock cord
6. Calculate the height from which the test article can fall and generate the expected parachute deployment force upon the shock cord becoming taut

Test Procedure:

1. For each test article:

   (a) Locate frame above a balcony such that the test article can free fall without obstruction
   (b) Drop test article such that it falls the calculated height

Analysis Procedure:

1. Inspect the body tube and bulkhead assembly for visible signs of damage

Results: Test canceled. The team deemed there was not a safe way to conduct this test. FEA and static testing were deemed to be representative of bulkhead strength.

Next Steps: If body tube and bulkhead assemblies do not show any visible signs of damage, test is passed. If any test article is damaged, material selection and thickness must be reconsidered and the test repeated.

10.1.2 Recovery Testing

RT.3: Ground Ejection Demonstration

Objective: Verify that black powder charges for each separation point are properly sized

Test ID	Success Criteria	Requirements Satisfied	Result
RT.3	Vehicle sections separate completely	NASA 3.2	Incomplete

Materials and Equipment Needed:

- Assembled launch vehicle
- Black powder charges sized by calculations
- E-match and wire leads to 12V battery
- Safety Glasses

Test Setup:

1. For fin can separation point:
   (a) Team mentor only: load black powder into a single SRM charge well along with an E-match
   (b) Integrate SRM into ACS tube such that the e-match wires feed through key switch holes
   (c) Connect shock cord to SRM U-bolt and fin can eye bolt
   (d) Assemble body tubes and install five 4-40 shear pins
2. For main parachute separation point:
   (a) Team mentor only: load black powder into a single PRM charge well along with an E-match
   (b) Integrate PRM into recovery tube such that the e-match wires feed through key switch holes
   (c) Connect shock cord to PRM U-bolt and payload tube eye bolt and place parachute inside tubes
   (d) Assemble body tubes and install five 4-40 shear pins
3. For drogue parachute separation point:
   (a) Team mentor only: load black powder into a single PRM charge well along with an E-match
   (b) Integrate PRM into recovery tube such that the e-match wires feed through key switch holes
   (c) Connect shock cord to PRM U-bolt and ACS U-bolt and place parachute inside tubes
   (d) Assemble body tubes and install five 4-40 shear pins
4. Place vehicle sections on stand, clear of any obstructions

Test Procedure:

1. For each separation point:

   (a) Team mentor only: close circuit on 12V battery to ignite black powder
   (b) Wait for launch vehicle sections to come to rest before handling them

Analysis Procedure:

1. If black powder does not separate vehicle sections, charge must be increased and the test repeated
2. If black powder separates vehicle sections with too much force (as deemed by RSO or team mentor), charge should be decreased and the test repeated

Results: Test completed. All charges successfully separated the body tube sections as expected. Figure 124 shows an image of this test.

Next Steps: Demonstration passed. Proceed to RT.1.

RT.4: Simulated Flight Demonstration

Objective: Verify that altimeters activate at simulated expected altitudes

Figure 124: Drogue separation point ejection charge test

Test ID	Success Criteria	Requirements Satisfied	Result
RT.4	Both E-match terminal lights turn on at the appropriate stage of the pressure cycle	N/A	Pass

Materials and Equipment Needed:

- Flight altimeters
- Holiday light bulbs
- Altimeter programming software

Test Setup:

1. Plug a light into each E-match terminal on altimeter
2. Plug battery into altimeter; turn switch to "ON" position
3. Load simulated flight feature on programming software

Test Procedure:

1. For each altimeter:
    (a) Run flight simulation program
    (b) Watch for proper activation of e-match ports

Analysis Procedure:

If either light does not turn on, troubleshoot cause of failure and repeat test.

Results: Demonstrations passed for 5/6 altimeters. One altimeter displayed an error that could be reset by a successful flight profile. Figure 125 shows the LED lighting up from the altimeter.

Next Steps: The faulty altimeter will be activated during the vehicle demonstration flight, but will not have any black powder charges. This allows the altimeter to reset itself while not putting the flight at risk. Simulated flight demonstration will be repeated after vehicle demonstration flight.

RT.5: Altimeter Disarming Demonstration

Objective: Verify that arming switches can disable E-match terminals

Test ID	Success Criteria	Requirements Satisfied	Result
RT.5	Altimeters and charge terminals turn off when arming switch is turned to the "OFF" position	N/A	Incomplete

Materials and Equipment Needed:

- Flight altimeters
- Holiday light bulbs
- Altimeter programming software

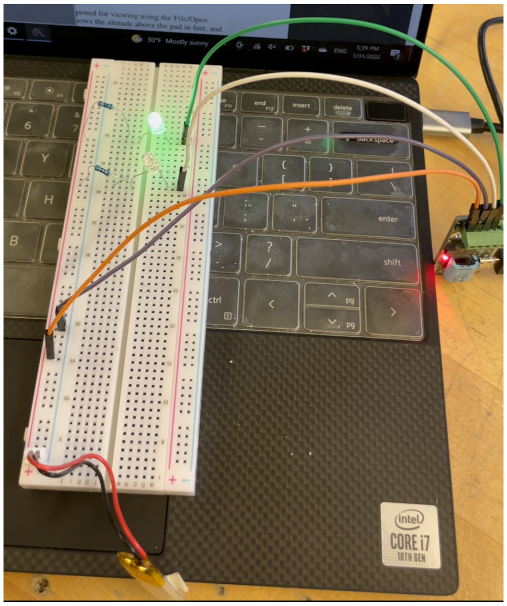


Figure 125: LED lighting up from terminal on altimeter

Test Setup:

1. Plug a light into each E-match terminal on altimeter
2. Plug battery into altimeter; turn switch to "ON" position
3. Load simulated flight feature on programming software

Test Procedure:

1. For each altimeter:
    (a) Run flight simulation program
    (b) Watch for proper activation of e-match ports
    (c) When simulated flight is complete, turn key switches to the "OFF" position, verifying that both altimeter and e-match terminals are deactivated

Analysis Procedure:

If any charge terminals or altimeters do not turn off, troubleshoot wiring and repeat demonstration.

Results: Demonstration passed. All altimeters and charge terminals were deactivated upon key switch being turned off.

Next Steps: Proceed to launch vehicle demonstration flight.

RT.6: GPS Functionality and Range Demonstration

Objective: Verify that the GPS module can transmit coordinates across the full landing zone range

Test ID	Success Criteria	Requirements Satisfied	Result
RT.6	GPS sends coordinates across full range of 5000 feet (2X the maximum allowable drift radius)	NASA 3.12, NASA 3.12.2	Incomplete

Materials and Equipment Needed:

- GPS transmitter and battery
- GPS Receiver
- Charged computer

Test Setup:

1. Plug GPS receiver into computer and load user interface
2. Be sure to complete this test outside; buildings can block GPS signal

Test Procedure:

1. For each altimeter:
   (a) Plug battery into GPS transmitter and wait for transmitter and receiver to connect
   (b) Drive with the GPS transmitter until the two devices are approximately 5000 feet apart

Analysis Procedure:

1. Verify that the GPS transmitter can connect with its receiver and they maintain connection when separated by 5000 feet

Results: Demonstration passed. GPS module successfully transmitted coordinates to ground station at full range.

Next Steps: Proceed to launch vehicle demonstration flight.

ACST.7: Limit Switch Detection Demonstration

Objective: Verify that the ACS detects the travel limits of the central lead screw and responds appropriately to avoid mechanical damage to system or damage to motor

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.7	ACS detects both travel limits by use of limit switches	N/A	Pass

Materials and Equipment Needed:

- Fully integrated ACS
- Computer for controlling flap actuation

Test Setup:

1. Connect computer to ACS PCB
2. Activate ACS by attaching battery

Test Procedure:

1. Override flap movement in one direction until contact with limit switch stops travel
2. Repeat in opposite direction
3. Repeat test to ensure actuation stopped as a result of push arm contact with the limit switch

Analysis Procedure:

1. Verify that actuation stops because of contact with limit switch rather than the motor stalling

Results: Completed on February 17, 2022. Actuation stopped because of contact with the limit switch rather than the motor stalling

Next Steps: No further action necessary, demonstration passes

RT.8, LVIST.7, ACST.6: Battery Duration Demonstration

Objective: Verify that flight batteries can operate for up to two hours in extreme cold weather

Test ID	Success Criteria	Requirements Satisfied	Result
RT.8	Altimeters remain powered on throughout demonstration	R.4	Incomplete
LVIST.7	LVIS remains powered on throughout demonstration	NASA 2.7, LVIS.4, LVIS.5	Incomplete
ACST.6	ACS remains powered on throughout demonstration	ACS.7	Pass

Materials and Equipment Needed:

- Assembled PRM and SRM
- Assembled LVIS

- Assembled ACS

Test Setup:

1. Note: This test should be completed when the outside temperature is below 20°F
2. Assemble each system to be in its flight-ready condition
3. Charge all batteries to full charge

Test Procedure:

1. Plug in batteries and activate all systems
2. Place each system indoors in a location which can be easily supervised from indoors
3. Set a timer for two hours and wait
4. After two hours, bring systems inside, careful not to unplug or deactivate them

Analysis Procedure:

1. Inspect that all systems remain on and functional

Results:

1. All recovery batteries lasted the full two hours
2. LVIS batteries lasted the full two hours
3. ACS battery lasted the full two hours

Next Steps: Demonstrations passes. Proceed to vehicle demonstration flight.

LVIST.1: Payload Demonstration Flight

Objective: Verify performance of final LVIS design

Test ID	Success Criteria	Requirements Satisfied	Result
LVIST.1	LVIS successfully identifies location of landed launch vehicle, determines grid box, and transmits grid box number to the ground station.	NASA 2.19.2.1, NASA 2.19.2.2, NASA 4.2.2.6, R.1	Incomplete

Materials and Equipment Needed: See LVIS equipment list in the Launch Operating Procedures.

Test Setup: See LVIS launch prep in the Launch Operating Procedures.

Test Procedure:

1. Activate LVIS and integrate into launch vehicle
2. Activate ground station
3. Following procedures outlined in the Launch Operating Procedures, launch the vehicle and await grid location transmission upon landing

Analysis Procedure:.

1. Verify grid location with GPS coordinates collected at landing site

Results: Incomplete. Scheduled for mid-March.

Next Steps: If success criteria is met, payload demonstration flight is passed. If one or more criteria is not met, the cause of failure must be identified and addressed. Payload demonstration flight must be repeated.

LVIST.3, ACST.4: Electronics Unit Tests

Objective: Verify ability to read data into flight computers from each individual sensor

Test ID	Success Criteria	Requirements Satisfied	Result
LVIST.3	Each sensor's data can individually be read into LVIS flight computer .	N/A	Pass
ACST.4	Each sensor's data can individually be read into ACS flight computer .	N/A	Pass

Materials and Equipment Needed:

- LVIS and ACS flight computers
- Computer monitor, mouse, and keyboard
- Jumper cables for connecting sensors with flight computers

Test Setup:

1. For each sensor:
   (a) Connect sensor to its respective flight computer
   (b) Load code necessary for reading respective sensor's data onto flight computer

Test Procedure:

1. For each sensor:
   (a) Run code
   (b) View monitor to verify that sensor data displays

Analysis Procedure:

1. Inspect sensor data to verify its validity

Results: Demonstrations passed. All sensors for both LVIS and ACS function as intended.

Next Steps:

1. For ACST.4, move onto ACST.5

LVIST.4: Sensor Module Demonstration

Objective: Verify ability for each LVIS sensor module to read in data from all connected sensors

Test ID	Success Criteria	Requirements Satisfied	Result
LVIST.4	Every sensor's data can be read into its corresponding LVIS flight computer while all sensors are connected	N/A	Pass

Materials and Equipment Needed:

- LVIS flight computers
- Computer monitor, mouse, and keyboard
- All LVIS flight sensors
- Jumper cables for connecting sensors with flight computers

Test Setup:

1. For each module:
   (a) Connect each sensor to its respective flight computer
   (b) Load code necessary for reading all sensor data onto flight computer

Test Procedure:

1. For each module:
   (a) Run code
   (b) View monitor to verify that sensor data displays

Analysis Procedure:

1. Inspect sensor data to verify its validity

Results: Demonstration passes. Each sensor module collects and synthesizes data as intended.

Next Steps: If data from all sensors can be read onto flight computers, demonstration passes. If one or more sensor can not be read, cause of failure must be identified and addressed. Repeat demonstration until all sensors pass.

LVIST.5: Transmission Module Functionality and Range Demonstration

Objective: Verify ability for the LVIS transmission module to transmit landing grid coordinates over full landing field range

Test ID	Success Criteria	Requirements Satisfied	Result
LVIST.5	Transmission module successfully transmits flight coordinates both in short range and over 5,000 feet	NASA 4.2.2.6	Incomplete

Materials and Equipment Needed:

- LVIS flight computers
- LVIS transmission module
- LVIS ground station
- Computer monitor, mouse, and keyboard

Test Setup:

1. Connect transmission module with a flight computer
2. Connect flight computer to monitor
3. Power on ground station

Test Procedure:

1. Send command through flight computer with coordinates to the transmission module
2. Transmission module should read in coordinates and transmit them to the ground station
3. Repeat demonstration, but drive in a car with the transmission module until there is 5,000 feet of distance between it and the ground station

Analysis Procedure:

1. Inspect coordinate received on the ground station. Coordinate should be the same as the input from the flight computer for both demonstrations

Results: Incomplete. Demonstration to be completed before payload demonstration flight.

Next Steps: If the success criteria are met, the demonstration passes. If the transmission module fails to transmit, or the transmission gets changed, the cause of failure must be identified and addressed. The demonstration must be repeated until successful.

LVIST.6: Full System Integration Demonstration

Objective: Verify ability for fully integrated LVIS to perform all design functions

Test ID	Success Criteria	Requirements Satisfied	Result
LVIST.6	LVIS successfully identifies flight stages, collects sensor data, calculates total displacement, and transmits a landing coordinate to the ground station	NASA 4.2.2.6, LVIS.3	Incomplete

Materials and Equipment Needed:

- Fully integrated LVIS
- LVIS ground station
- Computer monitor, mouse, and keyboard

Test Setup:

1. Power on LVIS and ground station
2. Power on ground station
3. Calculate a pre-determined direction and distance to which LVIS will travel during the test

Test Procedure:

1. Place LVIS vertically on a table and let it rest to represent waiting on the launch pad

2. Pick up LVIS and travel to pre-determined "landing" location
3. Place LVIS on the ground and wait for transmission to the ground station

Analysis Procedure:

1. Inspect coordinate received on the ground station and compare to calculation performed prior to the demonstration

Results: Incomplete. Demonstration to be completed before payload demonstration flight.

Next Steps: If the transmission module successfully transmits the coordinate to the ground station, demonstration passes. If any part of the LVIS fails, cause of failure must be identified and addressed. Demonstration must be repeated until successful.

LVIST.8: Main Parachute Impulse Event Demonstration

Objective: Verify ability for the LVIS to read high acceleration due to main parachute deployment

Test ID	Success Criteria	Requirements Satisfied	Result
LVIST.8	LVIS sensors successfully identify high-g event	LVIS.6	Incomplete

Materials and Equipment Needed:

- Fully integrated LVIS
- LVIS ground station
- Computer monitor, mouse, and keyboard
- Frame for securing payload tube over a balcony
- Shock cord
- Safety glasses

Test Setup:

1. Power on LVIS
2. Power on ground station
3. Integrate LVIS into payload tube
4. Secure payload to frame using the shock cord

Test Procedure:

1. Drop payload tube from balcony from a height such that magnitude of impulse from the shock cord becoming taut simulates the main parachute deployment
2. Remove LVIS from payload tube and connect to monitor

Analysis Procedure:

1. Inspect collected data to verify that data collected shows a spike in acceleration due to the shock cord impulse

Results: Incomplete. Demonstration to be completed before payload demonstration flight.

Next Steps: If LVIS successfully detects spike in acceleration, the demonstration passes. If not, sensor selection and data collection frequency must be reconsidered and the demonstration repeated until successful.

LVIST.9: Algorithm Drift Test

Objective: Quantify drift error over time from the LVIS algorithm

Test ID	Success Criteria	Requirements Satisfied	Result
LVIST.9	The team is able to extract data for accumulated error vs. time	N/A	Incomplete

Materials and Equipment Needed:

- Fully integrated LVIS

- LVIS ground station
- GPS transmitter
- GPS Receiver
- Fully charged computer
- Computer monitor, mouse, and keyboard
- Safety glasses

Test Setup:

1. Power on LVIS
2. Power on ground station
3. Integrate LVIS into payload tube
4. Power on GPS transmitter and receiver
5. Connect GPS receiver to computer

Test Procedure:

1. Collect GPS coordinates at origin where LVIS is powered on
2. Walk to a pre-determined point B over a period of five minutes. Note: path taken does not need to be in a straight line
3. Collect GPS coordinates at point B
4. Place LVIS on the ground and wait for coordinates to be transmitted to the ground station
5. Repeat procedure over periods of 10, 15, and 20 minutes

Analysis Procedure:

1. For each time period, compare the transmitted coordinate with the displacement between the two GPS coordinates. If a correlation for error vs. period is present in the data, fit a line to the curve

Results: Incomplete. Demonstration to be completed before payload demonstration flight.

Next Steps: The team should be able to use this data to have an idea of how much algorithm drift error to expect on launch day.

10.1.3 ACS Testing

ACST.1: Launch Vehicle Demonstration Flight

Objective: Verify that flap actuation will not negatively impact the stability of the launch vehicle or recovery systems

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.1	ACS flaps actuate in a pre-programmed manner during the coast phase, all separation events occur as designed, and launch vehicle is safely recovered	NASA 2.19.1.1, NASA 2.19.1.4 ACS.1, ACS.4, ACS.5	Pass

Materials and Equipment Needed: Refer to Launch Operating Procedures for PPE, tools, and equipment required for launch.

Test Setup:

1. Follow all Launch Rehearsal steps described in the Launch Operating Procedures
2. Load the ACS with code which actuates the flaps when burnout is detected, regardless of projected apogee

Test Procedure: Follow all steps described in the Launch Operating Procedures.
Analysis Procedure:

1. Inspect launch vehicle and subsystems for visible signs of damage from launch.
2. Inspect video footage from on-board camera and ground viewers to verify proper timing of recovery events.
3. Inspect video footage from on-board camera and ground viewers to verify actuation of ACS flaps in flight.

Results: Demonstration passed. Drag flaps actuated after burnout. Figure 126 shows a screenshot of the flaps deployed from the on-board camera.

Figure 126: ACS flap actuation as seen from on-board camera

Next Steps: If all success criteria are met, demonstration flight is passed. If one or more success criteria are not met, identify and address cause(s) of failure and repeat demonstration flight.

ACST.2: Payload Demonstration Flight

Objective: Verify that the ACS identifies flight stages, accurately predicts projected apogee, and responds appropriately with flap actuation

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.2	ACS responds appropriately to sensor inputs with flap actuation to bring the launch vehicle's projected apogee towards the NDRT target apogee	N/A	Incomplete

Materials and Equipment Needed: Refer to Launch Operating Procedures for PPE, tools, and equipment required for launch.

Test Setup:

1. Follow all Launch Rehearsal steps described in the Launch Operating Procedures
2. Load the ACS with final flight code

Test Procedure: Follow all steps described in the Launch Operating Procedures.

Analysis Procedure:

1. Inspect launch vehicle and subsystems for visible signs of damage from launch.
2. Inspect video footage from on-board camera and ground viewers to verify proper timing of recovery events.
3. Inspect video footage from on-board camera and ground viewers to verify actuation of ACS flaps in flight.
4. Inspect flight data collected to verify proper system response to sensor inputs

Results: Incomplete. Scheduled for Mid March

Next Steps: If all success criteria are met, ACS demonstration is passed. If one or more success criteria are not met, identify and address cause(s) of failure and repeat demonstration flight.

ACST.5: Full System Integration Demonstration

Objective: Verify that the ACS identifies flight stages, accurately predicts projected apogee, and responds appropriately with flap actuation based on simulated flight data

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.5	ACS responds appropriately to simulated flight data with flap actuation	NASA 2.19.1.1, ACS.1 ACS.5	Pass

Materials and Equipment Needed:

- Fully integrated ACS
- Simulated flight data

Test Setup:

1. Load simulated flight data onto ACS

Test Procedure:

1. Activate ACS with instruction to use simulated data rather than sensor inputs
2. Observe ACS flap movement as system moves through flight data

Analysis Procedure:

1. Verify that ACS responds appropriately to flight data with flap actuation as expected for all stages of flight (inactive, armed, active, fully active, and inactive)

Results: Completed February 19, 2022. ACS system actuated for all stages of flight at the correct time.

Next Steps: No further action necessary, demonstration passes.

ACST.7: Limit Switch Detection Demonstration

Objective: Verify that the ACS detects the travel limits of the central lead screw and responds appropriately to avoid mechanical damage to system or damage to motor

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.7	ACS detects both travel limits by use of limit switches	N/A	Pass

Materials and Equipment Needed:

- Fully integrated ACS
- Computer for controlling flap actuation

Test Setup:

1. Connect computer to ACS PCB
2. Activate ACS by attaching battery

Test Procedure:

1. Override flap movement in one direction until contact with limit switch stops travel
2. Repeat in opposite direction
3. Repeat test to ensure actuation stopped as a result of push arm contact with the limit switch

Analysis Procedure:

1. Verify that actuation stops because of contact with limit switch rather than the motor stalling

Results: Completed on February 17, 2022. Actuation stopped because of contact with the limit switch rather than the motor stalling

Next Steps: No further action necessary, demonstration passes

ACST.8: Loaded Flap Actuation Demonstration

Objective: Verify that the ACS motor is powerful enough and the flaps are strong enough to actuate the flaps during the point of maximum drag on the flaps with a factor of safety of 2.0

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.8	ACS can actuate through the full range of motion under twice the maximum drag force	ACS.8, ACS.9	Incomplete

Materials and Equipment Needed:

- Fully integrated ACS
- Load Frame
- ACS flap movement override panel
- Weights to simulate drag force on the flaps

Test Setup:

1. Set up load frame such that ACS inverted through frame and is above the ground, but secure
2. Activate ACS

Test Procedure:

1. Place maximum drag force in weights on top of the bottom bulkhead
2. Repeat in opposite direction

Analysis Procedure:

1. Verify that flaps can travel to both limits of extension in both directions without stalling the motor

Results: Incomplete. On February 20, 2022, this demonstration was attempted. However, connection necessary for flap actuation was unavailable. The ACS supported 180 pounds of weight, but the team was not able to confirm that it could actuate under weight.

Next Steps: Repeat test once correct materials for safe completion are present. Test will be re-attempted before the payload demonstration flight

10.2 Requirements Compliance

10.2.1 NASA General Requirements

Table 67: NASA General Requirements

Req. ID	Description	Status	Verification Method	Verification Description	Location
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.	Complete	I	Students on the team have completed all work with the exception of motor assembly, handling black powder charges, and installing electric matches, which will only be done by Dave Brunsting, the team mentor.	8.1.9.6.2
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.	Complete	I	The Project Manager is responsible for creating and maintaining a project plan.	9
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.	Complete	I	The team has been notified that the NASA management panel does not plan to collect this data.	N/A
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:	Complete	I	The Project Manager has created and maintains an active team roster which has been submitted with the CDR.	See team roster
1.4.1	Students actively engaged in the project throughout the entire year.	Complete	I	The team plans to bring approximately 25 team members to attend Launch Week activities. Team leadership will select these students from the eligible pool of team members based upon project contribution and STEM outreach event volunteering. All students eligible to be selected for Launch Week attendance have been identified.	8.1
1.4.2	One mentor (see requirement 1.13).	Complete	I	The team has identified the team mentor to be Dave Brunsting.	1.1
1.4.3	No more than two adult educators.	Complete	I	The team includes one faculty mentor and one graduate student mentor.	1.1
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.	Complete	I	The team has engaged with over 250 participants in direct STEM activities.	1
1.6	The team will establish and maintain a social media presence to inform the public about team activities.	Complete	I	The team has established a social media presence on Instagram, Twitter, Facebook, and LinkedIn. The Social Media Lead is tasked with updating these platforms with new content throughout the year.	1.1

Table 67: NASA General Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Description	Location
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.	In Progress	I	The Project Manager and Technical Editors have developed an aggressive timeline which allows for ample time to solve issues related to document submission. This timeline ensures timely submission of each deliverable.	1.1
1.8	All deliverables must be in PDF format.	Complete	I	The team writes all deliverables in LaTex, which allows for easy PDF generation for submissions.	N/A
1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.	Complete	I	The team has created a report template, from which it builds every report. This template includes a detailed table of contents which includes major sections and respective sub-sections.	See Table of Contents
1.10	In every report, the team will include the page number at the bottom of the page.	Complete	I	The team has created a report template, from which it builds every report. This template includes a page number at the bottom of every page.	N/A
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.	Complete	I	The team loans a video camera and microphone which can be connected to any computer for use in teleconferences. The team has the option of utilizing either the university Wi-Fi network or an Ethernet connection for teleconferences.	N/A
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.	Complete	I	The launch vehicle has been designed to utilize rail buttons which are compatible with 12-foot 1515 aluminum rails, and mission performance predictions account for launch rail angles between 5 and 10 degrees from vertical.	8.1.10.4
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.	Complete	I	The team has identified Dave Brunsting as its team mentor. He is certified with both the NAR (# 85879, Level 3), and the TRA (# 12369, Level 3), and will travel to Launch Week with the team.	1.1

Table 67: NASA General Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Description	Location
1.14	Teams will track and report the number of hours spent working on each milestone.	Complete	I	The team utilizes a time-tracking feature on its project management software for use in reporting the number of hours spent working on each milestone.	1.1

10.2.2 NASA Launch Vehicle Requirements

Table 68: NASA Launch Vehicle Requirements

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	D,A	The vehicle's apogee altitude will be simulated using OpenRocket, RockSim, and an in-house simulation code. The apogee will be verified for each demonstration flight as well as the competition launch to be within this range.	The range of simulated apogees is well within the 4,000 ft to 6,000 ft range. The launch vehicle went to an apogee of 5463 feet during the 3/1 launch vehicle demonstration flight attempt. This is well within the allowable range.	5, LVT.1
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.	Complete	I	Inspection will verify that the NDRT target altitude be identified at the PDR milestone.	The declared target altitude (4,800 ft) has been identified at the PDR milestone.	See PDR
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.	Complete	I	Inspection will verify the use of two altimeters in the launch vehicle.	The launch vehicle recovery system has been designed to carry six commercially available barometric altimeters.	See CDR
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.	In Progress	D	Demonstration will verify vehicle reusability.	The team will observe that the vehicle remains undamaged from successful flights. Safe descent and landing of the launch vehicle during a demonstration flight will verify recoverability.	LVT.1

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	I	Visual inspection will verify four or less independent sections.	The launch vehicle consists of a payload section, a recovery section, an ACS section, and a fin can section.	See CDR
2.5.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.	Complete	I	Inspection by measurement will verify size and location of coupler shoulders both in system design and on actual flight hardware.	Couplers at the main parachute separation point, drogue parachute separation point, and fin can separation point are all 6 inches long, which is equal to the body tube diameter.	See CDR
2.5.2	Nosecone shoulders which are located at in-flight separation points will be at least 1/2 body diameter in length.	Complete	I	Inspection by measurement will verify size and location of nosecone shoulders both in system design and on actual flight hardware.	The nosecone shoulder is not located at an in-flight separation point.	See CDR
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.	Complete	D	Demonstration on launch day will verify a vehicle preparation time of less than 2 hours.	The team launched the vehicle at 11:53 AM on 2/24, less than two hours after the launch waiver opened at 10:00 AM.	8.1.9
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.	Complete	D	Demonstration on launch day as well as battery duration tests will verify an on-pad wait time of up to 2 hours.	All flight batteries remained on throughout assembly and launch during the 2/24 launch vehicle demonstration test, and battery duration tests were passed.	LVIST.7
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.	Complete	I	Inspection of launch system will verify capability for launch via 12-volt DC firing system.	The team plans on using the provided 12-volt firing system provided at both the team's home field and at the competition launch.	See CDR
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).	Complete	I	Inspection will verify the absence of an external launch support system in the system design. Demonstration will verify launch without such equipment.	The launch vehicle motor was ignited using a standard 12V firing system.	8.1.10

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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).	Complete	I	The motor propulsion system will be inspected to verify it is commercially purchased and in accordance with NAR, TRA and/or CAR.	The selected motor is a commercially available solid propellant motor using APCP propellant.	See CDR
2.10.1	Final motor choices will be declared by the Critical Design Review (CDR) milestone.	Complete	I	Motor selection has been finalized for the CDR milestone.	The selected motor is an Aerotech L-2200G-P.	??
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.	Complete	I,A	Inspection will show that the final motor has not changed from the motor selection at CDR. Analysis of flight simulations will ensure proper motor selection prior to CDR such that motor will not need to be changed.	The motor selection has not changed after the CDR deadline.	See CDR
2.11	The launch vehicle will be limited to a single stage.	Complete	I	Visual inspection will insure that the vechile will be limited to a single stage.	The vehicle has a single stage.	See CDR
2.12	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).	Complete	I	Inspection of selected motor will ensure that impulse rating does not exceed an L-class.	The selected motor is an L-class motor.	See CDR
2.13	Pressure vessels on the vehicle will be approved by the RSO and will meet the following criteria:	Complete	I	N/A - Launch vehicle and subsystem designs will not include pressure vessels.	N/A - Launch vehicle and subsystem designs will not include pressure vessels.	See CDR
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.	Complete	I	N/A - Launch vehicle and subsystem designs will not include pressure vessels.	N/A - Launch vehicle and subsystem designs will not include pressure vessels.	See CDR
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.	Complete	I	N/A - Launch vehicle and subsystem designs will not include pressure vessels.	N/A - Launch vehicle and subsystem designs will not include pressure vessels.	See CDR

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	I	N/A - Launch vehicle and subsystem designs will not include pressure vessels.	N/A - Launch vehicle and subsystem designs will not include pressure vessels.	See CDR
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.	Complete	A	Flight Simulations will be used to verify a minimum off-rail static stability margin of 2.0.	The off-rail stability margin is above 2.0.	5.1
2.15	The launch vehicle will have a minimum thrust to weight ratio of 5.0 : 1.0.	Complete	I	Launch vehicle weight and average motor thrust will be used to calculate thrust to weight ratio. Inspection will verify a minimum value of 5.0.	The vehicle thrust to weight ratio is 9.55.	See CDR
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.	Complete	I, A	Inspection will verify that launch vehicle fins and ACS drag flaps will be located aft of the burnout center of gravity. CFD analysis will verify that the camera housing will not affect the launch vehicle's stability.	The ACS flaps are located 2.25 inches behind the burnout center of gravity, and CFD shows flow reattachment after camera housing.	See CDR
2.17	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	Complete	A	Flight Simulations will be used to verify a minimum off-rail velocity of 52 fps.	The minimum vehicle off-rail velocity is 75.4 ft/s.	5.1
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).	Complete	I, D	Successful launch and recovery of a subscale vehicle will be verified by the subscale vehicle demonstration flight. Inspection will verify that flight data will be provided in the CDR report.	The team has successfully launched and recovered a subscale vehicle.	LVT.2, RT.2
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.	Complete	D, A	Analysis will verify similar stability properties and thrust to weight ratio between the subscale and full-scale vehicles. The subscale demonstration flight will show that both vehicles have good flight properties.	The subscale vehicle T/W ratio is 7.71 with a stability margin of 2.75. These metrics are as similar as possible to the full-scale vehicle.	See CDR
2.18.2	The subscale model will carry an altimeter capable of recording the model's apogee altitude.	Complete	I	Inspection will verify that the subscale vehicle will carry an altimeter for recording the vehicle's apogee.	The subscale vehicle had an altimeter which recorded the vehicle's altitude.	See CDR

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.18.3	The subscale rocket shall be a newly constructed rocket, designed and built specifically for this year's project.	Complete	I	Inspection will verify that the subscale vehicle design and construction is done specifically for this years' project.	The subscale vehicle was constructed solely from new materials and built to resemble this years' full-scale vehicle.	See CDR
2.18.4	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.	Complete	I	Inspection will verify that proof of a successful flight will be included in the CDR report.	Proof of successful flight has been provided in CDR.	See CDR
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.	Complete	I	Inspection will verify that the subscale vehicle's dimensions do not exceed 75% of the full-scale vehicle dimensions.	The subscale vehicle is a 50% scale of the full-scale vehicle.	See CDR
2.19	All teams will complete demonstration flights as outlined below.	In Progress	D	See requirement verifications 2.19.1 through 2.19.2.4	The team attempted vehicle demonstration flights on 2/24 and 3/1, each with minor recovery failure. The team has requested a re-flight to be completed by the FRR addendum deadline.	12.19.1
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:	In Progress	D	The launch vehicle will be launched in its final flight configuration on one of multiple possible launch dates.	The team attempted vehicle demonstration flights on 2/24 and 3/1, each with minor recovery failure. The team has requested a re-flight to be completed by the FRR addendum deadline.	LVT.1

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.19.1.1	The vehicle and recovery system will have functioned as designed.	In Progress	D, A	Launch vehicle and recovery system performance during the launch vehicle demonstration flight will be compared to mission performance predictions and intended system design to verify proper functionality.	The team attempted vehicle demonstration flights on 2/24 and 3/1, each with minor recovery failure. The team has requested a re-flight to be completed by the FRR addendum deadline.	LVT.1
2.19.1.2	The full-scale rocket shall be a newly constructed rocket, designed and built specifically for this year's project.	Complete	I	Inspection will verify that the launch vehicle's design and fabrication are specific to this years' project.	The design and all materials are new and specific to this years' launch vehicle.	3.1
2.19.1.3	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. The following requirements still apply:	Complete	I	See requirement verifications 2.19.1.3.1 through 2.19.1.3.2.	The launch vehicle demonstration flight is scheduled for early February.	2.19.1.3.1
2.19.1.3.1	If the payload is not flown, mass simulators will be used to simulate the payload mass.	Complete	I	Inspection will verify that a mass simulator of the same weight as the payload will be flown if the payload is not ready by the launch vehicle demonstration flight.	The payload, although not in its final configuration, was on the launch vehicle at its final mass during the 2/24 launch vehicle demonstration flight.	LVT.1
2.19.1.3.2	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.	Complete	I	If a payload mass simulator needs to be flown, inspection will verify that the simulator will use the same airframe interface holes as the payload to be secured, ensuring proper location within the vehicle.	Mass substitutes were not utilized during the 2/24 launch vehicle demonstration flight.	LVT.1
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.	In Progress	D	The ACS system, having drag surfaces that change the external surfaces of the vehicle, will actuate its flaps in a pre-programmed manner during the first vehicle demonstration flight to verify that the system will not have a negative effect on the stability of the vehicle	The ACS flaps deployed after burnout as designed on the 3/1 launch vehicle demonstration flight attempt. The changing surfaces did not adversely affect vehicle stability.	LVT.1, ACST.1
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.	Complete	I	The team will verify with Michiana Rocketry that the launch field has the capability to support the launch vehicle's selected motor. If the launch field cannot support the selected motor, the team will make plans to launch with another motor and submit a waiver to use an alternative motor.	The L2200G motor which the team selected for CDR was used for the 2/24 launch vehicle demonstration flight.	8.1
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.	Complete	D, A	Flight simulations and measured hardware masses will be used to determine the maximum ballast weight potentially needed during the competition launch, and that ballast weight will be flown on the launch vehicle demonstration flight.	The launch vehicle was flown with 41.1 oz of ballast during the 2/24 launch vehicle demonstration flight, which is the maximum amount that the team plans on using.	8.1

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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).	In Progress	I	The team will be sure to contact the NASA RSO with any necessary changes to the launch vehicle after the launch vehicle demonstration flight.	The launch vehicle demonstration re-flight is scheduled for mid March.	LVT.1
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.	In Progress	D	The team will utilize redundant systems to ensure the collection of necessary flight data for providing proof of successful flight in FRR. The LVIS and the ACS will both be collecting altitude and velocity versus time data, and the recovery system altimeters will also be collecting data.	The team attempted vehicle demonstration flights on 2/24 and 3/1, each with minor recovery failure. The team has requested a re-flight to be completed by the FRR addendum deadline.	8.1
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.	In Progress	I	The team has identified multiple potential dates for completing the launch vehicle demonstration flight to account for weather or fabrication delays.	The team attempted vehicle demonstration flights on 2/24 and 3/1, each with minor recovery failure. The team has requested a re-flight to be completed by the FRR addendum deadline.	9.5

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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:	Incomplete	D	The team has identified multiple potential dates for completing the payload demonstration flight to account for weather, fabrication, or payload integration delays.	The launch vehicle demonstration flight is scheduled for mid-March.	9.5
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.	Complete	D	If the payload does not remain fully retained for the full duration of flight or the retention mechanism sustains damage, the payload demonstration flight will be repeated until successful.	The payload remained fully retained for the full duration of the 2/24 and 3/1 launch vehicle demonstration flights.	LVT.1
2.19.2.2	The payload flown shall be the final, active version.	Incomplete	D	If the payload changes after or is inactive for the payload demonstration flight, it will be re-flown.	The payload demonstration flight is scheduled for mid March.	LVIST.1
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.	Incomplete	D	The team's project plan intends for payload demonstration to be completed prior to and be included in FRR. If this is not possible, then the team will submit an FRR addendum.	The payload demonstration flight is scheduled for mid February.	9.5
2.19.2.4	Payload Demonstration Flights shall be completed by the FRR Addendum deadline. NO EXTENSIONS WILL BE GRANTED.	Incomplete	D	The team has identified multiple potential dates for completing the payload demonstration flight to account for weather, fabrication, or payload integration delays.	The payload demonstration flight is scheduled for mid March.	9.5

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Incomplete	I	If the team needs to complete a payload demonstration flight or a vehicle demonstration re-flight after the FRR deadline, then it will submit an FRR addendum. The project plan has an aggressive timeline for both the vehicle demonstration flight and the payload demonstration flight to minimize the chances of needing to submit an addendum.	The payload demonstration flight is scheduled for mid March.	9.5
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.	Incomplete	I	The team will be sure to submit an FRR addenum, if necessary, prior to the deadline to avoid exclusion from launching at the competition.	The launch vehicle demonstration re-flight is scheduled for mid March.	9.5
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.	Incomplete	I	The team's project plan has multiple backup dates for completing the payload demonstration flight before the FRR addendum deadline to avoid exclusion from launching at the competition.	The payload demonstration flight is scheduled for mid March.	9.5
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.	Incomplete	I	The team's project plan has multiple backup dates for completing the payload demonstration flight before the FRR addendum deadline to avoid the necessity to petition.	The payload demonstration flight is scheduled for mid March.	9.5
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.	Complete	I	Inspection will verify that the team's information are in or on the vehicle airframe.	The team's name and contact info have been written on the inside of the payload tube.	LVT.1
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.	Complete	I	Inspection will verify that all batteries are sufficiently secured to their respective payloads and are brightly colored and marked as a fire hazard.	All batteries are secured to their system using velcro strips, and have all been marked as fire hazards with red electrical tape.	See CDR

Table 68: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.23	Vehicle Prohibitions	Complete	I	See requirement verifications 2.23.1 through 2.23.10	All subsequent prohibitions have been noted.	2.23.1
2.23.1	The launch vehicle will not utilize forward firing motors.	Complete	I	Inspection will verify that neither the launch vehicle nor any sub-system utilizes forward firing motors in the design.	The launch vehicle does not use forward firing motors.	See CDR
2.23.2	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)	Complete	I	Inspection of information from motor vendor will verify that the selected motor does not expel titanium sponges.	The selected motor does not expel titanium sponges.	See CDR
2.23.3	The launch vehicle will not utilize hybrid motors.	Complete	I	Inspection of the motor selection will verify that the launch vehicle will utilize a solid motor propulsion system.	The launch vehicle does not use a hybrid motor.	See CDR
2.23.4	The launch vehicle will not utilize a cluster of motors.	Complete	I	Inspection of the motor selection will verify that the launch vehicle will not use a cluster of motors.	The launch vehicle only uses a single motor.	See CDR
2.23.5	The launch vehicle will not utilize friction fitting for motors.	Complete	I	Visual inspection will verify that the constructed launch vehicle will have a motor retaining ring.	The launch vehicle uses a motor retaining ring.	3.3.4
2.23.6	The launch vehicle will not exceed Mach 1 at any point during flight.	Complete	A	Flight simulations will be used to verify that the maximum Mach number achieved by the launch vehicle is less than 1.0.	The maximum expected Mach number is 0.58.	See CDR
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).	Complete	I, A	Flight simulations and measured hardware masses will be used to determine the maximum allowable ballast	The launch vehicle utilizes 36.4 oz of ballast.	8.1
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).	complete	I	Inspection will verify that onboard transmitter power will not exceed 250 mW of power.	The LVIS transmission module will transmit at a maximum of 250 mW.	See CDR
2.23.9	Transmitters will not create excessive interference. Teams will utilize unique frequencies, hand- shake/passcode systems, or other means to mitigate interference caused to or received from other teams.	Complete	I	Inspection will verify the use of a unique frequency for the LVIS transmission module and for the GPS transmitter.	The LVIS will be using a transceiver with frequency modulation.	See CDR
2.23.10	Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of light- weight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses.	complete	I, A	Inspection will be used to identify areas where use of light-weight metal might be necessary. Analysis will verify that light-weight metal is used only wherever needed for airframe or system structural integrity.	Metals are only used in high-load applications, such as the motor tube, recovery hardware, and ACS flap supports.	See CDR

10.2.3 NDRT Launch Vehicle Requirements

Table 69: NDRT Launch Vehicle Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	A, D	Flight simulations will be used to analyze the launch vehicle's predicted apogee for all possible launch conditions, and verify that they are all above the target apogee. The vehicle model will be verified in the launch vehicle demonstration flight.	The range of possible apogees based upon the given flight conditions is between 5155 (min apogee) and 5521 (max apogee) without ballast. The launch vehicle demonstration flight is scheduled for early February.	LVT.1
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 2.0.	All airframe components must maintain function by withstanding the maximum expected load by a factor of saftey of 1.5 to reduce the risk of strucutral failures in flight and ensure durability for subsequent flights.	Complete	T, A	FEA will give an estimated factor of safety for each component of the launch vehicle, and static and dynamic testing will verify that the as-built vehicle can withstand expected loads.	FEA resuts show that all vehicle components can withstand expected loads with a factor of safety of at least two. Static bulkhead testing results show structural integrity of the launch vehicle structure.	LVT.3, LVT.4, LVT.5, LVT.6
LV.3	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.	Complete	D	Airframe material selection will be made with repeated-use wear in mind and informed by team experience.	Carbon-fiber has been selected for the airframe, which is the most wear-resistant material considered.	See CDR
LV.4	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.	Complete	I	Inspection will verify that any airframe components on a section which contains a transmission device be made of RF transparent materials.	The communication device containing parts of the rocket will be made of fiberglass. Fiberglass is a material which allows good RF transparency. This can also be proven on the ground by communicating with the rocket at a distance when the rocket is fully assembled.	See CDR
LV.5	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.	Complete	I, D	Inspection will verify that any epoxy joints located near the motor be made of high-temperature epoxy. The ability for this epoxy to withstand the heat of motor burn will be verified in the launch vehicle demonstration flight.	The team used JB Weld to attach the centering rings, fins, and motor retaining ring to the motor mount tube.	3.3.4, LVT.1

10.2.4 NASA Recovery Requirements

Table 70: NASA Recovery Requirements

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	In Progress	D	The staged demonstration of recovery device deployment will be demonstrated at the launch vehicle demonstration flight.	The launch vehicle demonstration re-flight will take place in mid March	LVT.1
3.1.1	The main parachute shall be deployed no lower than 500 feet.	In Progress	D	The deployment of the main parachute above 500 feet will be demonstrated at the launch vehicle demonstration flight.	The launch vehicle demonstration re-flight will take place in mid March	LVT.1
3.1.2	The apogee event may contain a delay of no more than 2 seconds.	In Progress	D	The deployment of the drogue parachute no later than 2 seconds after apogee will be demonstrated at the launch vehicle demonstration flight.	The launch vehicle demonstration re-flight will take place in mid March	LVT.1
3.1.3	Motor ejection is not a permissible form of primary or secondary deployment.	Complete	I	Inspection will verify the design of a recovery system for the deployment of all separation events	The PRM and SRM are designed to separate the launch vehicle sections and deploy all recovery devices.	4.3
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.	Complete	T	The team will perform black powder ground ejection tests for each separation point until all charges are sized appropriately.	Ground ejection testing was performed and passed before the vehicle demonstration flight attempt.	RT.3
3.3	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.	Complete	A	The team will calculate the descent kinetic energy of each launch vehicle section.	The maximum expected kinetic energy of a launch vehicle section upon landing is under 74.88 ft-lb.	5.5
3.4	The recovery system will contain redundant, commercially available altimeters. The term “altimeters” includes both simple altimeters and more sophisticated flight computers.	Complete	I	Inspection of the recovery system design will verify the use of redundant, commercially available altimeters.	Each recovery module will use three different commercially available altimeters.	See CDR
3.5	Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.	Complete	I	Inspection will verify the use of dedicated commercially available batteries for each altimeter.	The recovery system design includes the use of dedicated commercially available batteries for each altimeter.	See CDR
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.	Complete	I	Inspection will verify the use of dedicated mechanical arming switches for each altimeter.	The recovery system design includes the use of dedicated mechanical arming switches for each altimeter.	4.2

Table 70: NASA Recovery Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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).	Complete	I	Inspection will verify the ability for switches to be locked in the ON position for launch.	Switches will be flush with the body tube, and require a key to turn on or off.	4.2
3.8	The recovery system electrical circuits will be completely independent of any payload electrical circuits.	Complete	I	Inspection will verify the independence of recovery and payload circuits from one another.	The payload and recovery systems are located in separate vehicle tubes with completely independent circuits.	See CDR
3.9	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	Complete	D	The team will use removable shear pins for all separation events for the launch vehicle demonstration flight and all subsequent flights. Verification requires the successful retention of each separation point until its intended separation event.	All separation points separated at the designed point in the flight profile during the vehicle demonstration flight attempt	RT.1
3.10	The recovery area will be limited to a 2,500 ft. radius from the launch pads.	In Progress	D, A	Flight simulations will verify a predicted drift radius under 2,500 ft for all NASA defined launch conditions. The launch vehicle demonstration flight will verify the flight simulation predictions.	Flight simulations show a maximum drift radius of 2,488 ft., and the launch vehicle demonstration re-flight is scheduled for mid March	5.5.3, RT.1
3.11	Descent time of the launch vehicle will be limited to 90 seconds (apogee to touch down).	In Progress	D, A	Flight simulations will verify a predicted descent time under 90 seconds for all NASA defined launch conditions. The launch vehicle demonstration flight will verify the flight simulation predictions.	Flight simulations show a maximum descent time of 84 seconds, and the launch vehicle demonstration re-flight is scheduled for mid March	5.5.2, RT.1
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.	Complete	I	The team will use a GPS tracking module in the payload bay of the tethered launch vehicle. GPS functionality will be verified prior to launch vehicle demonstration.	The GPS functionality and range demonstration was completed, and the GPS was active for the launch vehicle demonstration flight attempt.	RT.6
3.12.1	Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active electronic GPS tracking device.	Complete	I	If any section or payload component is designed to land untethered from the launch vehicle, inspection will verify the use of a GPS tracking device inside the section.	No part of the launch vehicle or payload will land untethered from the rest of the vehicle.	See CDR
3.12.2	The electronic GPS tracking device(s) will be fully functional during the official competition launch.	In Progress	D, T	The team will use a GPS tracking module in the payload bay of the tethered launch vehicle. GPS functionality will be verified prior to the official launch.	The GPS functionality demonstration was completed and passed	RT.6
3.13	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	Complete	D, T	The team will conduct an RF isolation test to verify that external electronics will not interfere with altimeters during flight. Launch vehicle demonstration flight will verify this result.	The RF isolation test was completed and passed	RT.7

Table 70: NASA Recovery Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
3.13.1	The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.	Complete	I	Inspection will verify the physical isolation of recovery system altimeters from all other devices.	Recovery system altimeters will be physically isolated from all other devices by a carbon-fiber body tube and carbon-fiber body tube.	See CDR
3.13.2	The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.	Complete	D	Inspection will verify the shielding of recovery system altimeters from all other devices.	Recovery system altimeters will be shielded from all other devices by a carbon-fiber body tube and carbon-fiber body bulkhead.	RT.7
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.	Complete	D	The team will conduct an electronics isolation test to verify that external electronics will not interfere with altimeters during flight. Launch vehicle demonstration flight will verify this result.	The electronics isolation test was completed and passed.	RT.7
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.	Complete	D	The team will conduct an electronics isolation test to verify that external electronics will not interfere with altimeters during flight. Launch vehicle demonstration flight will verify this result.	The electronics isolation test was completed and passed.	RT.7

10.2.5 NDRT Recovery Requirements

Table 71: NDRT Recovery Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
R.1	All structural recovery system components shall be designed to withstand the expected loads from separation events with a factor of safety of 2.0.	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 Requirement 2.4).	Complete	T, A	All load-path critical components will be sized using expected loads from calculations. Components which do not have well-understood material properties will be analyzed using FEA, and the full load-path assembly will be tested using static and dynamic testing.	FEA shows that the carbon-fiber bulkheads will be able to withstand the maximum expected load due to main parachute deployment of 720 lbf. Bulkhead testing was completed and gives the team high confidence in the structural integrity of the system.	RT.9, RT.10

Table 71: NDRT Recovery Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Comlpete	D	The recovery system will use a deployment bag for the main parachute and nomex blankets for all other recovery devices. Thermal protection of recovery devices will be verified during the Launch Vehicle Demonstration flight	All parachutes and shock cords remain undamaged due to black powder charges from ground testing and both vehicle demonstration flight attempts	RT.1
R.3	All electronics components shall be rated to operate between 0F and 100F	Electronic components must be functional in all feasible launch environments. Expected launch day temperatures are approximated to be within the range 0F - 75F between winter in Three Oaks, MI and spring in Huntsville, Al.	Complete	D	Demonstration will verify the functionality of all electronic components in both ends of the launch window range.	The battery duration demonstration shows system functionality for the full two hours in cold weather.	RT.8
R.4	Flight batteries shall be sized for 2 hours of operation in all expected flight conditions.	This meets 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.	Complete	D	The battery duration demonstration will verify that flight batteries can power the recovery system for at least two hours in extreme cold weather.	The battery duration demonstration was completed and passed.	RT.8
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.	Complete	I	Inspection will verify that epoxy joints which are near black powder ejection charges will use high-temperature epoxy.	JB-Weld was used for all epoxy joints near black powder charges.	4.5.1

Table 71: NDRT Recovery Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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 Requirement 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.	Complete	I	Inspection will verify that each separation event will be controlled by at least two dissimilar altimeters.	The PRM, which controls the drogue and main separation events, will use a Raven4, a Stratologger CF, and a Stratologger SL100. The SRM, which controls the fin can separation event, will use two Stratologger CFs and a Stratologger SL100.	See CDR

10.2.6 NASA Payload Requirements

Table 72: NASA Payload Requirements

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	In Progress	I, D	Inspection will verify the payload design fulfills all written requirements, and the design functionality will be demonstrated during the payload demonstration flight.	The team has designed a payload capable of autonomously locating the launch vehicle upon landing by identifying a grid position from an aerial image of the launch field without the use of GPS obeying all FAA and legal requirements. The payload will be demonstrated at the payload demonstration flight.	6.1
4.2	Launch Vehicle Landing Zone Mission Requirements	In Progress	I	Inspection will verify that all landing zone requirements are fulfilled.	All landing zone requirements are either completed, incomplete, or in-progress.	4.2.1

Table 72: NASA Payload Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	I	Hand calculations conducted with the aerial image scale will verify the size of the gridded launch field will not exceed 5,000 feet by 5000 feet.	The dimensions of the gridded area are 5,000 feet by 5,000 feet.	See CDR
4.2.1.1	Your launch vehicle and any jettisoned components must land within the external borders of the launch field.	In Progress	D, A	Mission performance predictions will verify that the predicted drift radius for all launch conditions is below 2,500 feet, and the launch vehicle demonstration flight will verify the mission performance predictions.	The maximum expected drift for the launch vehicle is 2,456.5 feet, and the launch vehicle demonstration re-flight is scheduled for mid March.	LVIST.1
4.2.2	A legible gridded image with a scale shall be provided to the NASA management panel for approval at the CDR milestone.	Complete	I	Prior to submitting CDR, the team will create a gridded image with a scale with computer software and included in the CDR document.	A gridded image with a scale has been included in the CDR document.	See CDR
4.2.2.1	The dimensions of each grid box shall not exceed 250 feet by 250 feet.	Complete	I	Hand calculations conducted with the aerial image scale will verify the size of each grid box is within 250 feet by 250 feet.	All grid boxes are 250 feet by 250 feet.	See CDR
4.2.2.2	The entire launch field, not to exceed 5,000 feet by 5,000 feet, shall be gridded.	Complete	I	The gridded launch field shall be inspected to verify the length and width of the field are no longer than 5,000 feet.	The entire launch field is gridded, and the dimensions of the gridded area are 5,000 feet by 5,000 feet.	See CDR
4.2.2.3	Each grid box shall be square in shape.	Complete	I	The gridded launch field shall be inspected to verify that each grid has equal length and width.	The gridded image was created in MATLAB to ensure uniform grid box sizing.	See CDR
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.	Complete	I	The grid boxes shall be inspected to ensure each box has equal dimensions.	Grid boxes on the perimeter of the launch field all retain their square shape, despite partially falling outside the allowable landing area.	See CDR
4.2.2.5	Each grid box shall be numbered	Complete	I	The grid boxes shall be inspected to verify each box is numbered.	All grid boxes have been numbered using X and Y integers on a 2-D cartesian grid.	See CDR
4.2.2.6	The identified launch vehicle's grid box, upon landing, will be transmitted to your team's ground station.	Incomplete	D	Transmission from any location inside the launch field to the ground station will be demonstrated by the transmission range test and the payload demonstration flight.	The transmission range test will be performed in early March, and the payload demonstration flight is scheduled for Mid March.	LVIST.5, LVIST.1
4.2.3	GPS shall not be used to aid in any part of the payload mission.	Complete	I	Inspection will verify that the payload design does not use the aid of GPS.	The payload consists of an INS which uses accelerometers and gyroscopes for position tracking, and magnetometer measurements for initial orientation. GPS coordinates will only be used for locating the launch rail on the satellite image and verifying the final location of the launch vehicle.	See CDR

Table 72: NASA Payload Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	I	Inspection will verify that the GPS module does not communicate with the payload in any way.	The GPS, although housed physically with the payload, does not share any electronic or RF connection with the payload. Each system independently communicates with separate ground stations.	See CDR
4.2.3.2	GPS verification data shall be included in your team's PLAR.	In Progress	I	Prior to submission, the team's PLAR will be inspected to ensure the GPS coordinates of the launch vehicle's landing location are included.	The team will collect the necessary GPS verification data at the competition launch and include it in PLAR.	See CDR
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.	Complete	I	The satellite image of the launch site will be inspected to ensure it is high quality to be verified by the NASA management team.	The satellite images used are from Google Earth, which is the highest quality image of the launch field that the team has access to.	See CDR
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).	Complete	I	The satellite image of the launch site will be inspected to ensure it depicts the location of the launch pad.	The location of the coordinates given by the NASA management panel are depicted on the image submitted for CDR. the team's actual launch rail location for the competition flight will be updated in the image submitted in PLAR.	See CDR
4.2.5	No external hardware or software is permitted outside the team's prep area or the launch vehicle itself prior to launch.	Complete	I	The team's launch vehicle and prep area will be inspected prior to launch to ensure that no external hardware or software is present.	The payload design does not include any external hardware or software outside the launch vehicle or ground station, which will be located within the team's prep area.	See CDR
4.3	General Payload Requirements	Complete	I	Inspection will verify that all general payload requirements are met.	All general payload requirements are met.	4.3.1
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.	Complete	I	Inspection will verify that energetics are used solely for in-flight recovery systems.	The payload does not use any energetics.	See CDR
4.3.2	Teams shall abide by all FAA and NAR rules and regulations.	Complete	I	Inspection will verify that the team abides by all FAA and NAR rules and regulations.	Applicable regulations, including the NAR High PowerRocketry Safety Code and FAA regulation 14 CFR 101.22-101.29, have been read and the launch vehicle has been designed with compliance to these regulations in mind.	9
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.	Complete	D	During any demonstration flights, RSO permission will be received prior to experiment jettison events.	No experiment element is jettisoned during the launch vehicle's flight.	See CDR

Table 72: NASA Payload Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	D	During any demonstration flights, RSO permission will be received prior to UAS release.	The payload does not utilize an UAS.	See CDR
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).	Complete	I	Inspection will verify that the team will follow all applicable FAA regulations if the payload utilizes an UAS.	The payload does not utilize an UAS.	See CDR
4.3.6	Any UAS weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.	Complete	I	Inspection will verify registration of any UAS weighing more than 0.55 lbs with the FAA.	The payload does not utilize an UAS.	See CDR

10.2.7 NDRT Scoring Payload Requirements

Table 73: NDRT Scoring Payload Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
LVIS.1	The LVIS 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.	Complete	I	The LVIS system will be inspected to ensure each sensor data type has a minimum of one redunduant source.	The LVIS has three sub-modules, each of which have two sources of every type of necessary data.	See CDR
LVIS.2	All structural LVIS components shall be designed to withstand the maximum loads of launch and landing with a factor of safety of 2.0. The maximum expected load in flight is 211.3 lbf.	All structural LVIS components must maintain function by withstanding the maximum expected load by a factor of saftey of 2.0 to reduce the risk of components coming loose during flight	Complete	T, A	The maximum load applied to each structural component is determined using hand calculations. The structural integrity of the system will be verified by bulkhead testing, FEA, and full-system dynamic testing.	FEA performed on the payload bulkheads shows that all bulkheads are able to withstand the loads of launch and landing.	See CDR
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.	Complete	D	Demonstration will verify the functionality of all electronic components in cold weather.	The system remained operational for the full battery duration test in the cold weather.	LVIST.6

Table 73: NDRT Scoring Payload Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
LVIS.4	LVIS flight batteries shall be sized for 2 hours of operation in all expected flight conditions.	This meets 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.	Complete	D	The battery duration demonstration will verify that flight batteries can power the LVIS for at least two hours in extreme cold weather.	The battery duration demonstration was passed.	LVIST.7
LVIS.5	The ground station power supply shall be capable of powering the system for a minimum of two 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.	Complete	D	The battery duration demonstration will verify that flight batteries can power the ground station for at least three hours in extreme cold weather.	The ground station will be plugged into a car's power outlets, eliminating the need for a battery.	LVIST.7
LVIS.6	LVIS shall have sensors capable of recording the maximum 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.	In Progress	I, D	Inspection will verify the incorporation of a high-g accelerometer capable of reading accelerations due to main parachute deployment. The sensor components of the LVIS system will be subjected to high-g impacts to show that the sensors are able to accurately record accelerations similar to those experienced by the launch vehicle due to main parachute deployment.	The maximum expected acceleration of the payload tube due to main parachute deployment is 23.64 g, and the payload will be using accelerometers capable of reading up to 100 g. The payload's ability to record high-g events will be demonstrated at the payload impulse demo, which is scheduled for early March.	See CDR

10.2.8 NDRT Non-Scoring Payload Requirements

Table 74: NDRT Non-Scoring Payload Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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 during the coast phase without compromising other phases of flight.	Complete	D	The ability for the ACS to identify the current stage of flight will be verified during the ACS integration test.	The ACS system code uses input from the altimeter to actuate to a certain degree when a particular altitude is reached.	ACST.1 ACST.2 ACST.3 ACST.4 ACST.5
ACS.2	The ACS shall be capable of recording launch vehicle altitude, linear acceleration, and angular acceleration.	Collecting these measurements is the minimum necessary dataset to track vehicle position and orientation, which allows the system to calculate the projected apogee.	Complete	I, D	Inspection will verify that the ACS has sensors capable of recording this information.	The ACS system code records all flight data from the altimeter, accelerometer, and inertial movement unit to determine location data for the launch vehicle. This assists the system in determining the correct time and altitude to actuate and reach the predetermined apogee.	ACST.2 ACST.3 ACST.4 ACST.5

Table 74: NDRT Non-Scoring Payload Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	I	The ACS design will be inspected to ensure each sensor data type has a minimum of one redunduant source.	The ACS sensor selection covers redundancies in all necessary measurement types.	N/A
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.	Complete	A, D	CFD will aid in determining a Cd vs. α for the ACS flaps, and further analysis will be used to calculate the system's capacity for lowering projected apogee. The ability for ACS to bring the launch vehicle to the NDRT target apogee will be verified in the payload demonstration flight.	Using the ACS sensors, the ACS system code can determine the projected altitude and adjust to bring the final altitude to within the predetermined apogee range.	ACST.2 ACST.3 ACST.4 ACST.5
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.	Complete	D	The ACS full-system integration demonstration, performed at both ends of the launch temperature range, will verify functionality of electronics throughout the entire range of launch conditions.	The ACS system has been operated in many weather conditions including extreme cold and moderate temperatures. It has also been operated in both wet and dry conditions.	ACST.1 ACST.5 ACST.6
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 2.0. The maximum calculated load comes from the main parachute deployment, and is 600 lbf.	Ensures that the ACS stay secure inside the launch vehicle at launch	Complete	T, A	Physical bulkhead testing and FEA will be used to verify the structural integrity of the bulkhead. Shear calculations will be used to determine the bolt size necessary for securing the ACS bulkheads to the body tubes.	FEA results show the bulkhead will withstand main parachute deployment. Bulkhead testing has been completed and shear pin calculations have been verified.	ACST.9 ACST.10
ACS.7	ACS flight batteries shall be sized for 2 hours of operation in all expected flight conditions, including continuous actuation of drag surfaces between motor burnout and apogee.	Sizing batteries for two hours of operation meets the 2 hour standby requirement given by NASA 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.	Complete	D	The battery duration demonstration will verify that flight batteries can power the ACS for at least three hours in extreme cold weather.	The team has decided to alter this requirement from the original three hours. The ACS system remained fully actuated in an environment of 0° F for two and a half hours. This does not meet the original safety factor that the team proposed, but it is unlikely that the temperature will be this extreme for launch conditions. Therefore, this time amount was accepted as completing this requirement.	ACST.6

Table 74: NDRT Non-Scoring Payload Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
ACS.8	The ACS motors shall have sufficient torque to actuate the drag surfaces at motor burnout with a factor of safety of 2.0.	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.	Complete	D, A	CFD will be used to determine the estimated maximum drag force on the system, and the corresponding torque on the motor. Flap actuation under full load will be verified in the ACS flap actuation demonstration.	The ACS system has been tested to sustain 180 pounds of force while actuated and the motor did not stall.	ACST.2 ACST.8
ACS.9	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 2.0. The maximum allowable drag force is 180 lbf	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.	In Progress	D, A	CFD will be used to determine the estimated maximum drag force on the system. Flap actuation under full load in the ACS flap actuation demonstration will verify the structural integrity of the system.	The ACS loaded flap actuation demonstration is scheduled for January.	ACST.8 ACST.9

10.2.9 NASA Safety Requirements

Table 75: NASA Safety Requirements

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	In Progress	I	Inspection will verify that the team develops, maintains, and uses a launch and safety checklist and that the final version is included in the FRR document.	The team's most current launch and safety checklist is included in the FRR document.	Section 8.1 is where the checklist starts
5.2	Each team shall identify a student safety officer who will be responsible for all items in section 5.3.	Complete	I	Inspection will verify that a safety officer is identified and is responsible for all requirements under 5.3.	Michael Bonaminio has been identified as the team's safety officer.	Start of Section 8 lists who safety officer is. See Section 5.3 for additional info.
5.3	The role and responsibilities of the safety officer will include, but are not limited to:	In Progress	I	Inspection will verify that the safety officer fulfills the responsibilities of items 5.3.1 - 5.3.4.	All items are either complete or in-progress.	5.3.4
5.3.1	Monitor team activities with an emphasis on safety during:	In Progress	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles

Table 75: NASA Safety Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
5.3.1.1	Design of vehicle and payload	Complete	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles
5.3.1.2	Construction of vehicle and payload components	Complete	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles
5.3.1.3	Assembly of vehicle and payload	Complete	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles
5.3.1.4	Ground testing of vehicle and payload	Complete	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles
5.3.1.5	Subscale launch test(s)	Complete	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles
5.3.1.6	Full-scale launch test(s)	Complete	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles
5.3.1.7	Competition Launch	In Progress	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles

Table 75: NASA Safety Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
5.3.1.8	Recovery activities	Complete	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles
5.3.1.9	STEM Engagement Activities	Complete	I	Inspection will verify that the safety officer understands and develops plans for fulfilling this responsibility.	The responsibilities have been layed out and fully understood by the safety officer at the beginning of the project and verified by the project manager.	Section 8 of CDR lists all the Safety Officer's responsibilities in full with a statement about the importance of their understanding of their roles
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	Complete	I	Inspection will verify that the safety officer and safety team members develop and maintain SOPs.	SOPs have been written in their respective document, and Launch Procedures have been written in CDR.	Section 8.1 and SOP document
5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	Complete	I	Inspection will verify that the safety officer and safety team members develop and maintain FMEA tables and an SDS sheet.	The SDS sheet has been updated in its respective document.	The Safety Officer's responsibilities can be found in Section 8. The SDS sheet is also accessible to all team members via a physical version in the workshop and a digital version
5.3.4	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	Complete	I	Inspection will verify that the safety officer and safety team members develop and maintain FMEA tables.	The FMEA tables have been updated for CDR.	Section 8 lists the responsibility, and the following sections are the hazard tables: 8.2, 8.3, 8.4, 8.5
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.	Complete	I	Inspection will verify that the safety officer and the team develop a plan to ensure they abide by all rules and guidance given by the local RSO.	The safety officer has developed a launch procedure plan which includes guidance on abiding by RSO instructions. All rules and guidelines have been followed at each launch, and the team will continue to abide for future launches	Section 8, and Launch Procedures Section 8.1.1

Table 75: NASA Safety Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
5.5	Teams will abide by all rules set forth by the FAA.	Complete	I	Inspection will verify that the safety officer and the team develop a plan to ensure they abide by all rulesset forth by the FAA.	The safety officer has developed a launch procedure plan which includes guidance on abiding by FAA instructions. All rules and guidelines have been followed at each launch, and the team will continue to abide for future launches	Section 8, and Launch Procedures Section 8.1.1

10.3 Budgeting and Funding Summary

An overview of NDRT's funding sources can be seen in Table 76. Rollover funds from 2020-2021 and a generous contribution from the Boeing Company are the main sources are funding and support, as well as an anonymous donation in November 2021 of roughly $12,500. Future apparel sales will also tentatively fundraise an estimated $250 in Spring 2022. NDRT intends to pair with additional sponsors and donors in 2022 for technical support, funding, and mentorships.

Table 76: Funding Overview 2021-22

Allocation	Amount
Rollover from 2020-21	$16,430.00
The Boeing Company	$10,000.00
Anonymous Donor	$12,599.59
Apparel Sales (Future)	$250
Total	**$39,279.59**

A system-level overview of the NDRT 2021-22 budget is shown in Table 77. Each category or system in Table 77 has an itemized budget displayed in Tables 78 through 85. Items delivered to the team, either shipped or picked up, are marked green in the status column. 3D printed items are also colored in green. Shipping or ordered items are marked with yellow, and budgeted items yet to be ordered are marked with red. For Table 84, the travel budget, additional contributions from the University of Notre Dame have not been included in the current budget amount. The University of Notre Dame historically has agreed to contribute some amount to a daily per diem for each traveling member. Additionally, NDRT is currently re-evaluating the travel itinerary for the final launch in Huntsville, AL, which may reduce travel costs. NDRT is committed to traveling to Huntsville, AL, but may adjust travel dates and/or travel roster size based on the updated launch week format.

One additional note is relevant to Table 81, the LVIS budget. The power and transmission components of the LVIS are a senior design project in the Electrical Engineering Department at the University of Notre Dame, and bill some costs to a separate account. These separated costs are noted in Table 81 with extra columns labeled "EE Dept?" and "EE Cost".

Table 77: Overall Budget Summary

Allocation	Amount	Funds Spent/Budgeted	Margin
Launch Vehicle	$4,200.00	$4,326.29	103.01%
Apogee Control System	$1,300.00	$1,476.11	113.55%
Recovery System	$1,500.00	$1,663.35	110.89%
LVIS	$1,000.00	$729.54	72.95%
Vehicle Subtotal	**$8,000.00**	**$8,195.29**	**102.44%**
Safety	$200.00	$184.84	92.42%
STEM Engagement	$200.00	$128.99	64.50%
Competition Travel	$10,500.00	$10,500.00	100.00%
Miscellaneous	$600.00	$680.81	113.47%
TOTAL	**$19,500.00**	**$19,689.93**	**100.97%**
Total Revenue	$39,279.59	$39,279.59	
Remaining Funds	$19,779.59	$19,589.66	

Table 78: Launch Vehicle Budget

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
Subscale Vehicle					$543.94	
G12 Fibergalss Airframe 3in ID, 3.125inch OD, 60 inch length, Standard Wall, Black		1	$100.00			🟩
	Madcow Rocketry			$12.71	$187.71	

G12 Fiberglass Coupler 3in OD, 9in length, Green		1	$22.00			Delivered
G12 Fiberglass Coupler 3in OD, 6in length, Green		1	$15.00			
G12 Fiberglass Motor Tube 1.645in OD, 1.520in ID, 12in length		1	$13.00			
Motor Retainer Assembly, 38mm – P		1	$25.00			
Nose Cone	N/A	1	$0.00	$0.00	$0.00	3D Printed
AeroTech I300T-14A Blue Thunder Rocket Motor	Chris' Rocket Supplies	2	$61.99	$59.25	$188.23	Delivered
Rail Buttons		2	$2.50			
AeroTech I300T-14A Blue Thunder Rocket Motor	Impulse Buys	3	$56.00	$0.00	$168.00	Delivered
Full Scale Vehicle					$3,702.35	
AeroTech L2200G-P Rocket Motor	Balsa Machining	2	$290.69	$51.00	$632.38	Delivered
AeroTech L2200G-P Rocket Motor	Chris' Rocket Supplies	1	$322.99	$59.28	$382.27	Delivered
AeroTech L2200G-P Rocket Motor	Impulse Buys	1	$293.00	$0.00	$293.00	Ordered
Fiberglass Body Section, Length: 1 foot	Composite Warehouse	1	$45.00	$9.99	$114.99	Delivered
Fiberglass Coupler, Length: 1 foot		1	$60.00			
Motor Mount tube	N/A	1	$0.00	$0.00	$0.00	On Hand
Motor Retainer, add JBWeld Pack	Madcow Rocketry	1	$56.50	$5.40	$61.90	Delivered
EXTREME Carbon Fiber Tubing 6 inch ID; 60 inch length	LOC/PML	2	$539.95	$11.49	$1,474.19	Delivered
Full Scale Nose Cone		1	$149.95			
Full Scale Couplers		2	$109.95			
Rail Guides Full Scale (1.5 inch), Count: 2		1	$12.95			
RocketPoxy	Apogee	2	$13.13	$12.11	$38.37	Delivered
Paint	TBD	1	$500.00	$0.00	$500.00	Budgeted
Threaded Inserts	Amazon	1	$8.99	$0.63	$9.62	Delivered
JB Weld 5 Minute	Home Depot	2	$6.28	$0.61	$13.17	Delivered
New 12ft 1515 Launch Rail w Joiners	McMaster	1	$144.56	$37.90	$182.46	Delivered
Licenses					$80.00	
RockSim Licenses	Apogee Rockets	4	$20.00	$0.00	$80.00	Delivered
				TOTAL COST	**$4,326.29**	
				Budget Allocation	**$4,200.00**	
				Remaining	**-$126.29**	

Table 79: Recovery Budget

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
Electronics					$660.98	
GPS Tracker + Ground Station + Battery	Featherweight	1	$352.00	$10.00	$379.00	Delivered
GPS Battery Charger		1	$17.00			
GPS Tracker + Battery	Featherweight	1	$165.00	$10.00	$199.00	Delivered
GPS Battery		2	$12.00			
StratologgerCF	Perfectflite	1	$70.00	$0.00	$70.00	Budgeted
StratologgerCF	N/A	2	$0.00	$0.00	$0.00	On Hand
StratologgerCF	N/A	2	$0.00	$0.00	$0.00	On Hand
Stratologger SL100	N/A	2	$0.00	$0.00	$0.00	On Hand
Featherweight Raven4	N/A	1	$0.00	$0.00	$0.00	On Hand
150mAh 1S 3.7V 45C Lipo	PowerHobby	1	$9.99	$2.99	$12.98	Delivered
Hardware					$372.76	
Fray Check Glue	Joann Fabrics	1	$7.99	$13.60	$51.58	Delivered
Grommets		1	$29.99			
Garolite Test Piece	McMaster-Carr	24	$1.47	$12.58	$47.86	Delivered
Airframe Interfacing Block Aluminum Stock	McMaster-Carr	1	$10.39	$10.00	$76.53	Delivered
1" 4-40 Screws, 100 Pack		1	$5.26			
4-40 Washers, 100 Pack		1	$1.43			
4-40 Locknuts, 100 Pack		1	$4.03			
1/2" 8-32 Screws		1	$5.36			
1/2-13 U-bolt		3	$6.05			
1/2-13 Locknuts, 100 Pack		1	$4.76			
1/2" 4-40 Screw, 100 Pack		1	$4.20			
3.5" 4-40 Standoff		6	$2.33			
Keyed Switch	Digi-Key	1	$9.47	$4.99	$14.46	Delivered
Keyed Switch	N/A	5	$0.00	$0.00	$0.00	On Hand
12" x 24" Carbon Fiber Sheet	Elevated Materials	2	$98.79	$96.00	$293.58	Delivered
0.1" 4-40 Standoff	Amazon	1	$9.90	$0.69	$10.59	Delivered

1/8" Eye Bolt	N/A	2	$0.00	$0.00	$0.00	On Hand
3/8" Quicklink	N/A	9	$0.00	$0.00	$0.00	On Hand
3000 lbf Swivel	N/A	1	$0.00	$0.00	$0.00	On Hand
12 ft Rocketman Elliptical Main Parachute	N/A	1	$0.00	$0.00	$0.00	On Hand
2 ft Fruity Chutes Elliptical Pilot Parachute	N/A	1	$0.00	$0.00	$0.00	On Hand
24 in Rocketman Elliptical Drogue Parachute	Rocketman	1	$50.00	$0.00	$139.00	Delivered
Drogue Shock Cord		1	$33.50			
Main Shock Cord		1	$55.50			
Fin Can Shock Cord	OneBadHawk	1	$12.00	$4.00	$16.00	Delivered
Parachute Protector	Dino Chutes	2	$14.55	$8.50	$37.60	Delivered
3.5" 4-40 Standoff	McMaster	4	$2.33	$3.86	$13.18	Delivered
Steel U-Bolt	McMaster-Carr	1	$6.05	$10.94	$42.98	Delivered
Socket Head Screw, 4-40 Thread Size, 3/8" Long		1	$6.30			
Socket Head Screw, 4-40 Thread Size, 3/4" Long		1	$7.33			
Shear Pins		1	$8.43			
Nylon-Insert Locknut, 6-32 Thread Size		1	$3.93			
Gage-It Hardware Gauge	Home Depot	2	$2.48	$1.00	$11.48	Delivered
Mending Plate		2	$2.76			
				TOTAL COST	**$1,663.35**	
				Budget Allocation	**$1,500.00**	
				Remaining	**-$163.35**	

Table 80: LVIS Budget

Item	Vendor	Qty	Cost/unit	Fees	EE Dept?	EE Cost	NDRT Cost	Status
DFRobot Gravity I2C H3LIS200DL	Mouser	3	$13.90	$0.00	No	$0.00	$41.70	Delivered
HiLetgo MPU9250	Amazon	3	$15.99	$3.36	No	$0.00	$51.33	Delivered
Soft Mount Shock Absorption Balls	Amazon	1	$10.99	$2.50	No	$0.00	$39.32	Delivered
2.54mm 2x20 40-Pin Female Pin Header Socket Connector Strip, 10 Pcs		1	$7.99					
#6 Rubber Washers, 50 Pack		1	$17.77					
PowerBoost 500 Charger	Adafruit	1	$14.95	$4.00	No	$0.00	$18.95	Delivered
Raspberry Pi Zero	Vilros	1	$7.50	$3.48	No	$0.00	$10.98	Delivered
9-Axis Inertial Navigation Module for Arduino (D65)	Vetco	6	$32.95	$13.95	No	$0.00	$211.65	Delivered
Battery	Adafruit	1	$19.95	$11.13	No	$0.00	$31.08	Delivered
Raspberry Pi ZeroW	Amazon	2	$34.99	$4.90	No	$0.00	$74.88	Delivered
Alloy Steel Shoulder Screws	McMaster-Carr	4	$2.56	$10.00	No	$0.00	$24.18	Delivered
Al Hex Nut		1	$3.94					
Sande Plywood (1/4 in)	Home Depot	1	$29.92	$0.00	No	$0.00	$29.92	Delivered
Bulkhead Garolite Stock	N/A	2	$0.00	$0.00	No	$0.00	$0.00	On Hand
Phillips Pan Head Screws, Nuts, Washers Assortment	Amazon	1	$21.69	$7.51	No	$0.00	$29.20	Delivered
1/4" Hex Standoff, Female, 4" Overall Length, 10 Pack	Grainger	1	$17.37	$10.98	No	$0.00	$28.35	Delivered
Cable Glands	Amazon	1	$16.49	$1.15	No	$0.00	$17.64	Delivered
Perma Proto Bonnet Mini	Adafruit	4	$4.50	$11.85	No	$0.00	$29.85	Delivered
Full-Scale LiPo Battery	Amazon	1	$19.59	$1.37	No	$0.00	$20.96	Delivered
New Standoffs	McMaster	10	$2.42	$7.72	No	$0.00	$31.92	Delivered
Rubber Damper Shock Absorption Balls	Amazon	1	$10.99	$0.77	No	$0.00	$11.76	Delivered
2 x 20-pin Strip Dual Male Header Double Row Straight Connector Pin Header	Amazon	1	$8.99	$0.63	No	$0.00	$9.62	Delivered
Battery Connectors	Amazon	1	$6.99	$1.61	No	$0.00	$24.59	Delivered
Long screws		1	$15.99					
3.3V LDO Regulator	Digikey	4	$2.07	$0.00	Yes	$116.88	$0.00	
PIC32 Microcontroller		4	$2.67					
RF Transceiver		4	$13.44					
SMA Antenna Connector		4	$2.96					
Antenna		2	$4.64					
5V Buck Regulator		4	$1.45					
Inductor		5	$0.61					
Capacitor (Buck output)		5	$0.84					

Delivered

Capacitor (Buck input)		5	$0.83					
Rectifier Diode		5	$0.64					
Jumper connector		6	$0.21					
Ring terminals		6	$0.23					
PCB		1	$5.00	$0.00	Yes	$5.00	$0.00	Delivered
					TOTAL COST	**$121.88**	**$729.54**	
					Budget Allocation	**$500.00**	**$1,000.00**	
					Remaining	**$378.12**	**$270.46**	

Table 81: ACS Budget

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
Electronics					$959.59	
BMP390 - Precision Barometer	Digikey	2	$10.95	$9.01	$30.91	Delivered
Raspberry Pi Zero	Vilros	1	$7.50	$3.47	$10.97	Delivered
MPL3115A2 - I2C Altimeter	Adafruit	2	$9.95	$12.61	$97.26	Delivered
ICM-20948 9-DoF IMU		2	$14.95			
PowerBoost 500 Charger		1	$14.95			
INA260 High or Low Side Voltage, Current, Power Sensor		2	$9.95			
PNY 32GB MicroSD Cards, 3 Pack	Amazon	2	$17.99	$2.52	$38.50	Delivered
2 Channel DC 5V Relay Module	SunFounder	2	$6.99	$0.00	$13.98	Delivered
ADXL377 3 Axis Accelerometer	Digikey	2	$25.95	$6.99	$58.89	Delivered
ADXL345 3 Axis Accelerometer	Sparkfun	2	$18.95	$11.19	$49.09	Delivered
Continuous Servo Motor	ServoCity	1	$209.99	$8.99	$218.98	Delivered
Raspberry Pi 4	Amazon	2	$95.00	$13.30	$203.30	Delivered
PCB	OshPark	1	$75.00	$0.00	$75.00	Delivered
Limit Switches	Automation Direct	2	$12.50	$10.00	$35.00	Delivered
Piezo	Adafruit	1	$1.50	$0.00	$2.45	Delivered
On Off Switch		1	$0.95			
Limit Switches	Automation Direct	2	$12.50	$10.00	$35.00	Delivered
DFRobot Gravity I2C H3LIS200DL	Mouser	1	$13.90	$22.99	$36.89	Delivered
BMP388 - Precision Barometer	Adafruit	1	$9.95	$59.27	$69.22	Delivered
Hardware					$516.52	
Leadscrew	Thompson	1	$55.63	$11.61	$67.24	Delivered
Leadscrew	Thomson	1	$80.76	$12.48	$93.24	Ordered
Motor Bulkhead Garolite Stock	N/A	1	$0.00	$0.00	$0.00	On hand
Bottom Bulkhead Garolite Stock	N/A	1	$0.00	$0.00	$0.00	On hand
Sensor Mount Garolite Stock	N/A	1	$0.00	$0.00	$0.00	On hand
Top Bulkhead Garolite Stock	N/A	1	$0.00	$0.00	$0.00	On hand
Carbon Fiber Inlaid Resin Flaps	3D Printed	4	$0.00	$0.00	$0.00	3D Printed
Carbon Fiber Inlaid Resin Sensor Cover	3D Printed	1	$0.00	$0.00	$0.00	3D Printed
L bracket	N/A	8	$0.00	$0.00	$0.00	On hand
Mechanism Hinges Aluminum Stock	McMaster-Carr	1	$30.70	$10.00	$167.83	Delivered
Central Hub Aluminum Stock		1	$39.24			
Flap Support Arms Aluminum Stock		1	$19.69			
Pusher Arms Aluminum Stock		1	$5.15			
Upper Standoffs Aluminum Stock		1	$6.23			
U Bolt		1	$1.49			
Flap Face Screws, 50 Pack		1	5.81			
Flap Shoulder Screws		8	3.17			
Central Hub Shoulder Screws		4	$2.87			
Flap Shoulder Screw Nuts, 100 Pack		1	$4.60			
Hinge Interfacing Screws, 100 Pack		1	$4.90			
6-32 Nuts, 100 Pack		1	$3.18			
Smaller Limit Switches	Amazon	2	$9.59	$3.25	$49.75	Delivered
USB female to Micro USB male		1	$7.99			
Mini HDMI to HDMI		1	$8.99			
Micro HDMI to HDMI		1	$10.34			
Servo Clamp	ServoCity	1	$5.99	$8.99	$14.98	Delivered
Bearing	McMaster	1	$11.55	$7.70	$19.25	Delivered
Bearing Take Two	McMaster	1	$2.57	$16.84	$35.54	
U Bolt		1	$7.27			
Upper Standoffs Aluminum Stock		1	$3.74			

Delivered

AIB Stock		2	$2.56			
Socket Head Screw M4 x 0.7 mm Thread, 10 mm Long	McMaster	1	$8.72	$3.86	$12.58	Delivered
6-32 Locknuts	McMaster	1	$6.40	$7.73	$14.13	Delivered
6-32 Rounded Head Screws	McMaster	1	$5.81	$7.77	$13.58	Delivered
ACS Test Stand Hardware	Home Depot	1	$32.05	$2.24	$34.29	Delivered
					TOTAL COST	**$1,476.11**
					Budget Allocation	**$1,300.00**
					Remaining	**-$176.11**

Table 82: Safety/PPE Budget

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
Nitrile Gloves	CVS	2	$15.99	$2.24	$34.22	Delivered
Disposable Respirator, N95, PK 20	Grainger	2	$13.99	$22.10	$150.62	Delivered
Knit Cust-Resistant Gloves, Cotton		2	$3.93			
Coated Heat-Resistant Gloves		2	$19.31			
Nitrile Gloves		2	$27.03			
				TOTAL COST	**$184.84**	
				Budget Allocation	**$300.00**	
				Remaining	**$115.16**	

Table 83: STEM Engagement Budget

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
350 Pack "Hello My Name is" Stickers	Amazon	1	$7.48	$3.86	$39.30	Delivered
Crayola Washable Markers, 12 Count		4	$6.99			
Toothpicks	Martins Supermarket	2	$3.39	-$0.60	$19.29	Delivered
Mini Marshmallows		2	$1.99			
Mini Marshmallows		2	$1.19			
Large Marshmallows		3	$1.39			
Spaghetti		2	$1.29			
Toothpicks	Martins Supermarket	1	$3.39	$0.93	$14.28	Delivered
Bamboo Skewers		3	$2.49			
Paper Plates		1	$2.49			
				TOTAL COST	**$72.87**	
				Budget Allocation	**$200.00**	
				Remaining	**$127.13**	

Table 84: Travel Budget

Item	Description	Cost	Status
Accomodations	Team AirBnB for 4 nights	$2,962.66	Ordered
Vehicle Rentals	4 vans for 5 days, $58 per van per day	$1,160.00	Ordered
Team Mentor Hotel	4 nights, $120 per night	$480	Budgeted
Travel Gas	$3.18 per gallon with 4 vans @ 18.1 MPG for 1500 miles	$1,054.14	Budgeted
Food	Remaining Allocation (before University contribution)	$4,843.20	Budgeted
	TOTAL COST	**$10,500.00**	
	Allocation	**$10,500.00**	
	Remaining	**$0.00**	

Table 85: Miscellaneous Budget

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
Workshop Monitor	Amazon	1	$139.97	$14.28	$264.06	Delivered
Expo Markers		1	$25.09			
Belt Sander Belts		1	$35.99			
Drill Chuck		1	$41.41			
Drill Chuck Removal Tool		1	$7.32			
Belt Sander Discs	Amazon	1	$12.99	$0.91	$13.90	Delivered
Dremel Cutoff Wheels	Grainger	3	$3.26	$12.43	$22.21	Delivered
Wires	Adafruit	1	$15.95	$13.27	$51.12	Delivered
Heat Shrink		1	$9.95			
Automatic Wire Stripper/Cutter		1	$11.95			
Centering Ring Jig Hardware	Home Depot	1	$33.08	$0.00	$33.08	Delivered
LiPo Battery Charger	Amazon	1	$36.99	$2.59	$39.58	Delivered
15/16"-16 UNS HSS Plug Tap	DrillsandCutters.com	1	$30.77	$17.11	$70.56	Delivered
6-32 UNC HSS Taper Tap		3	$2.26			
4-40 UNC HSS Taper Tap		3	$2.96			
8-32 UNC HSS Taper Tap		3	$2.34			
VDF Lunch	Jimmy John's	1	$132.71	$9.27	$141.98	Delivered
Launch Snacks	Martin's Grocery	1	$44.32	$0.00	$44.32	Delivered
TOTAL COST					**$405.83**	
Budget Allocation					**$500.00**	
Remaining					**$94.17**	

A Hazard Occurrence List

A.1 Incident 1

SAFETY HAZARD REPORT FORM

Personnel Hazard

Responsible Individual: NDRT Safety Officer

Date	Individual	Hazard(s)
2/18/2022	ACS squad member	C.14

Description

On February 18, 2022, an Apogee Control System squad member was injured during the testing of the ACS flap actuation. In particular, a battery got stuck in the ACS flaps when the flaps tried to close, and they individual went to remove the battery, but when the battery moved, the ACS flaps closed on them. The individual suffered minor bleeding, and the bleeding stopped soon after the event occurred. No major damage was endured.

Moving Forward

Moving forward, the safety team will address the team during our weekly meeting to ensure everyone understands the necessary procedures for a situation like this:

- Turn off the system
- Ensure the system is powered off before engaging If the system can be ensured to be turned off, proceed with caution
- If the system cannot be ensured to be turned off no matter what is done, dislodge the component with the use of a Popsicle stick or something else that doesn't require the individual's extremities to be in harms' way.

A.2 Incident 2

SAFETY HAZARD REPORT FORM

Failure Mode

Responsible Individual: NDRT Safety Officer

Date	System	Hazard(s)
2/24/2022	Recovery System and Launch Vehicle Failure	R.5, VS.7

Description

On February 24th, 2022, the full-scale launch vehicle was launched. On the descent, the mail parachute failed to deploy,and the launch vehicle landed with a higher than anticipated velocity. As a result, two fins separated from the fin can, and the fin can aft was partially damaged. The main parachute failed to deploy because the pilot parachute was integrated with tape still covering the parachute in order to secure the folds in place; this tape was required to be removed prior to launch. As well, the Secondary Recovery Module shock cords became tangled mid descent.

Moving Forward

Moving forward, the Launch Operating Procedures for the parachute folding and integration have been re-analyzed and updated to ensure all personnel follow the correct criteria to ensure a safe and consistent launch.

A.3 Incident 3

Safety Hazard Report Form

Failure Mode

Responsible Individual: NDRT Safety Officer

Date	System	Hazard(s)
2/24/2022	Apogee Control System Failure	ACS.3, ACS.5

Description

On February 24th, 2022, the full-scale launch vehicle was launched. However, the Apogee Control System was unable to successfully deploy due to software issues. Because of this, the actual apogee was not close to the target apogee.

Moving Forward

Moving forward, the ACS squad has been working diligently to test the software with sub-scale flight data in order to determine the quality of the source code. As well, the Launch Operating Procedures for the ACS preparation and integration have been re-analyzed and updated to ensure all personnel follow the correct criteria to ensure a safe and consistent launch.