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**NOTRE DAME ROCKETRY TEAM  
CRITICAL DESIGN REVIEW**

**NASA STUDENT LAUNCH 2022**

**LAUNCH VEHICLE IDENTIFICATION SYSTEM AND APOGEE CONTROL SYSTEM**

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# Contents

<b>Contents</b>	<b>i</b>
<b>1 Summary of Report</b>	<b>2</b>
1.1 Team Summary . . . . .	2
1.2 Vehicle Summary . . . . .	2
1.3 Payload Summary . . . . .	2
<b>2 Changes Made Since PDR</b>	<b>3</b>
2.1 Changes To Vehicle Criteria . . . . .	3
2.2 Changes To Payload Criteria . . . . .	3
2.3 Changes To Project Plan . . . . .	3
<b>3 Technical Design: Launch Vehicle</b>	<b>4</b>
3.1 Mission Statement . . . . .	4
3.1.1 Mission Success Criteria . . . . .	4
3.2 Launch Vehicle Design Overview . . . . .	4
3.3 Vehicle Component Analysis . . . . .	6
3.3.1 Nose Cone . . . . .	6
3.3.2 Airframe Tube . . . . .	7
3.3.3 Camera Shroud . . . . .	11
3.3.4 Fixed Bulkheads . . . . .	13
3.3.5 Fins . . . . .	14
3.3.6 Motor Retention . . . . .	15
3.3.7 Tail Cone . . . . .	17
3.4 Launch Vehicle Integrated Design . . . . .	18
3.4.1 Vehicle Layout and Design Summary . . . . .	18
3.4.2 Detailed Mass Statement . . . . .	20
3.4.3 Motor Selection . . . . .	21
3.5 Subscale Flight Results . . . . .	22
3.5.1 Subscale Test Priorities and Flight Summary . . . . .	22
3.5.2 Scaling Factor and Dimensions . . . . .	23
3.5.3 Launch Day Conditions . . . . .	24
3.5.4 Subscale Launch Analysis . . . . .	24
3.5.5 Implications for Full Scale Design . . . . .	26
<b>4 Technical Design: Vehicle Recovery System</b>	<b>26</b>
4.1 Mission Statement and Success Criteria . . . . .	26
4.2 Design Overview . . . . .	27
4.3 Separation and Deployment . . . . .	27
4.3.1 Separation and Deployment Sequence . . . . .	27
4.3.2 Ejection Charge Sizing . . . . .	28
4.4 Recovery Devices . . . . .	29
4.4.1 Main Parachute Assembly . . . . .	29
4.4.2 Drogue Parachute Assembly . . . . .	31

4.4.3	Fin Can Separation Assembly . . . . .	33
4.5	Primary and Secondary Recovery Modules . . . . .	34
4.5.1	Primary Structural Elements . . . . .	34
4.5.2	Secondary Structures . . . . .	37
4.6	Electronics . . . . .	40
4.6.1	Altimeters . . . . .	40
4.6.2	GPS . . . . .	41
4.6.3	Other Electronics . . . . .	42
4.7	Mass Statement . . . . .	42
<b>5</b>	<b>Mission Performance Predictions</b>	<b>45</b>
5.1	Flight Ascent Analysis . . . . .	45
5.1.1	Simulation Results . . . . .	46
5.1.2	Target Apogee . . . . .	50
5.1.3	Stability . . . . .	50
5.2	Flight Descent Analysis . . . . .	51
5.2.1	Kinetic Energy . . . . .	52
5.2.2	Descent Time . . . . .	52
5.2.3	Drift Radius . . . . .	53
5.3	Structural Analysis . . . . .	53
5.3.1	Peak Thrust . . . . .	54
5.3.2	Main Deployment . . . . .	55
<b>6</b>	<b>Technical Design: Launch Vehicle Identification System</b>	<b>60</b>
6.1	Design of Payload Equipment . . . . .	60
6.2	System Level Design Overview . . . . .	60
6.3	Mission Success Criteria . . . . .	60
6.4	Mechanical Component Level Design . . . . .	60
6.5	Electrical Component Level Design . . . . .	62
6.5.1	Sensors . . . . .	62
6.5.2	Wireless Transmission . . . . .	63
6.5.3	Microcontroller . . . . .	63
6.5.4	Battery . . . . .	64
6.5.5	Power Distribution . . . . .	64
6.6	Software . . . . .	65
6.6.1	Overall Control Flow . . . . .	65
6.6.2	Data Filters . . . . .	67
6.6.3	Software Testing . . . . .	70
6.7	Imaging . . . . .	70
6.8	Vehicle Integration . . . . .	71
6.9	Comprehensive Mass Statement . . . . .	72
6.10	Subscale . . . . .	73
<b>7</b>	<b>Technical Design: Apogee Control System</b>	<b>74</b>
7.1	Mission Statement and Success Criteria . . . . .	74
7.1.1	Mission Success Criteria . . . . .	74

7.2	Mechanical Design . . . . .	74
7.2.1	Changes Made Since PDR . . . . .	75
7.2.2	Drag Flaps . . . . .	76
7.2.3	Flap Support Arms . . . . .	76
7.2.4	Bulkhead Hinges . . . . .	77
7.2.5	Pusher Arms . . . . .	78
7.2.6	Lead Screw . . . . .	79
7.2.7	Central Hub . . . . .	79
7.2.8	Mounting Blocks . . . . .	80
7.2.9	Load Path Analysis . . . . .	80
7.2.10	Motor Sizing and Selection . . . . .	81
7.3	Aerodynamic Analysis . . . . .	82
7.4	Electrical Design . . . . .	83
7.4.1	Accelerometer . . . . .	83
7.4.2	Altimeter . . . . .	84
7.4.3	Inertial Measurement Unit . . . . .	84
7.4.4	Limit Switches . . . . .	84
7.4.5	Battery Selection . . . . .	85
7.4.5.1	3.7 Volt Circuit . . . . .	85
7.4.5.2	7.4 Volt Circuit . . . . .	86
7.4.5.3	Battery Sensor Selection . . . . .	86
7.4.6	Printed Circuit Board Design . . . . .	86
7.5	Control System Design . . . . .	86
7.5.1	Microcontroller Selection . . . . .	88
7.5.1.1	Servo Controller Selection . . . . .	88
7.5.2	Kalman Filter . . . . .	88
7.5.3	Proportional Control Algorithm Design . . . . .	90
7.6	Integration . . . . .	91
7.7	Detailed Mass Estimate . . . . .	91
<b>8</b>	<b>Safety</b> . . . . .	<b>92</b>
8.1	Launch Concerns and Operation Procedures . . . . .	93
8.1.1	Introduction . . . . .	93
8.1.2	Launch Rehearsal . . . . .	94
8.1.3	Launch Checklist . . . . .	94
8.1.4	Transportation . . . . .	96
8.1.5	Upon Arrival at Launch Field . . . . .	97
8.1.6	Recovery Preparation . . . . .	97
8.1.6.1	Inspection Checklist . . . . .	97
8.1.6.2	Recovery Pre-Flight Checklist . . . . .	98
8.1.6.2.1	Main Parachute Folding . . . . .	98
8.1.6.2.2	Drogue Parachute Folding . . . . .	99
8.1.6.2.3	Primary Recovery Module (PRM) Pre-Flight Assembly . . . . .	100
8.1.6.2.4	Secondary Recovery Module (SRM) Pre-Flight Assembly . . . . .	101
8.1.6.2.5	Black Powder Separation Charges . . . . .	101



8.1.6.2.6	Parachute Integration . . . . .	102
8.1.7	Launch Vehicle Identification System (LVIS) Preparation . . . . .	102
8.1.7.1	Inspection Checklist . . . . .	102
8.1.7.2	LVIS Pre-Flight Checklist . . . . .	103
8.1.8	Apogee Control System (ACS) Preparation . . . . .	104
8.1.8.1	Inspection Checklist . . . . .	104
8.1.8.2	ACS Pre-Flight Checklist . . . . .	104
8.1.8.2.1	Ballast Integration . . . . .	105
8.1.8.2.2	Battery Integration . . . . .	105
8.1.9	Launch Vehicle Preparation . . . . .	105
8.1.9.1	ACS Integration . . . . .	106
8.1.9.2	LVIS Integration . . . . .	106
8.1.9.3	Recovery Integration . . . . .	107
8.1.9.3.1	PRM Integration . . . . .	107
8.1.9.3.2	SRM Integration . . . . .	107
8.1.9.4	Flight Camera Integration . . . . .	108
8.1.9.5	Shake Test . . . . .	108
8.1.9.6	Motor Preparation . . . . .	109
8.1.9.6.1	Motor Inspection . . . . .	109
8.1.9.6.2	Motor Integration . . . . .	109
8.1.9.7	Stability Test . . . . .	109
8.1.9.8	Shear Pin Integration . . . . .	110
8.1.10	Setup on Launch Pad . . . . .	111
8.1.10.1	Launch Pad Inspection . . . . .	111
8.1.10.2	Launch Site Evaluation . . . . .	111
8.1.10.3	Launch Equipment Setup . . . . .	112
8.1.10.4	Launch Rail Checklist . . . . .	112
8.1.10.4.1	Place Launch Vehicle on Launch Pad . . . . .	112
8.1.10.4.2	Activate Recovery Electronics . . . . .	112
8.1.10.4.3	Verify ACS Power . . . . .	113
8.1.10.4.4	Verify LVIS Power . . . . .	113
8.1.10.4.5	Finalize the Launch Rail Position . . . . .	114
8.1.10.4.6	Igniter Installation . . . . .	114
8.1.11	Launch Flight Procedures . . . . .	115
8.1.12	Post Launch Procedures . . . . .	116
8.1.12.1	Retrieving the Launch Vehicle . . . . .	116
8.1.12.1.1	Post Launch Analysis . . . . .	116
8.2	Failure Modes and Effects Analysis . . . . .	118
8.2.1	Vehicle Flight Mechanics Failure Modes and Effects Analysis . . . . .	118
8.2.2	Vehicle Structures Failure Modes and Effects Analysis . . . . .	124
8.2.3	Apogee Control System Failure Modes and Effects Analysis . . . . .	128
8.2.4	Recovery Failure Modes and Effects Analysis . . . . .	134
8.2.5	Launch Vehicle Identification System (LVIS) Failure Modes and Effects Analysis . . . . .	143
8.2.6	Launch Vehicle Identification System (LVIS) Integration Failure Modes and Effects Analysis . . . . .	145
8.2.7	Launch Support Equipment Failure Modes and Effects Analysis . . . . .	147

8.3	Project Risk Analysis . . . . .	151
8.4	Personnel Hazard Analysis . . . . .	158
8.4.1	Construction Personnel Hazards . . . . .	158
8.4.2	Launch Operations Personnel Hazards . . . . .	167
8.5	Environmental . . . . .	174
8.5.1	Environmental Risks to Vehicle . . . . .	174
8.5.2	Vehicle Risks to Environment . . . . .	182
<b>9</b>	<b>Project Plan</b>	<b>189</b>
9.1	Testing . . . . .	189
9.1.1	Launch Vehicle Testing . . . . .	190
9.1.2	Recovery Testing . . . . .	195
9.1.3	LVIS Testing . . . . .	200
9.1.4	ACS Testing . . . . .	204
9.2	Requirements Compliance . . . . .	208
9.2.1	NASA General Requirements . . . . .	208
9.2.2	NASA Launch Vehicle Requirements . . . . .	210
9.2.3	NDRT Launch Vehicle Requirements . . . . .	220
9.2.4	NASA Recovery Requirements . . . . .	220
9.2.5	NDRT Recovery Requirements . . . . .	223
9.2.6	NASA Payload Requirements . . . . .	225
9.2.7	NDRT Scoring Payload Requirements . . . . .	228
9.2.8	NDRT Non-Scoring Payload Requirements . . . . .	229
9.2.9	NASA Safety Requirements . . . . .	231
9.3	STEM Engagement Plan . . . . .	234
9.3.1	General Update . . . . .	234
9.4	Budget . . . . .	234
9.5	Timeline . . . . .	239
<b>A</b>	<b>Streamer Drift Experiment</b>	<b>246</b>
<b>B</b>	<b>MATLAB Hand Calculations Script</b>	<b>247</b>

**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 Summary of Report

## 1.1 Team Summary

<b>Team Information:</b>	Notre Dame Rocketry Team (NDRT) University of Notre Dame 365 Fitzpatrick Hall of Engineering Notre Dame, IN 46556
<b>Mentor:</b>	Dave Brunsting NAR # 85879 (Level 3), TRA # 12369 (Level 3) e: dacsmem@gmail.com p: (269) 838-4275
<b>NAR/TRA Section:</b>	TRA #12340, Michiana Rocketry
<b>Team Hours Logged: (NASA 1.14)</b>	1348
<b>Primary Final Launch:</b>	Huntsville, AL on April 23, 2022
<b>Backup Final Launch:</b>	Three Oaks, MI on April 9, 2022

## 1.2 Vehicle Summary

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

**Table 2:** Summary of Launch Vehicle Design

Feature	Value
Target altitude (ft.)	4800
Selected Motor	Aerotech L2200G-P
Length (in.)	134
Outer diameter (in.)	6.17
Total Mass (oz)	821.0
Rail Size	12-foot 1515

The vehicle will be recovered using a traditional dual deploy parachute recovery with an additional separation to reduce the kinetic energy of the vehicle sections at landing. The Primary Recovery Module (PRM) controls drogue parachute separation at apogee and main parachute separation at 591 ft. The drogue parachute is a 2 ft diameter, 1.6  $C_d$  Rocketman elliptical parachute. The drogue parachute is connected to a 20 ft braided kevlar shock cord rated for 2520lb. Drogue deployment is located at separation of the Payload Bay and Recovery Bay. The main parachute is a 12 ft diameter, 0.97  $C_d$  Rocketman parabolic parachute. The main parachute is connected to a 40ft braided kevlar shock cord rated for 2520lb. A 2 ft, 1.6  $C_d$  FruityChutes elliptical pilot parachute assists in main deployment, located at separation of the Recovery Bay and ACS Bay. The Secondary Recovery Module (SRM) controls fin can separation at 520 ft, at which no parachute is deployed. The SRM separates the ACS Bay and Fin Can to decrease kinetic energy at landing.

## 1.3 Payload Summary

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

### 2.1 Changes To Vehicle Criteria

The body tube material has changed from fiberglass to carbon fiber for a lighter material with high strength and material properties. However, the nose cone, payload bay, and payload coupler remain fiberglass to allow data transmission to the ground station.

The recovery design has changed from using a drogue streamer to using a 2 ft drogue parachute. Experimentation with Team Mentor, Dave Brunsting, determined that a streamer would not significantly decrease drift as the supplier had stated. A drogue parachute is lighter, cheaper, and easier to integrate on launch day. The ejection altitude for the drogue event remains the same. The delay between backup charges for the main parachute deployment has been reduced to 0.5 s, and the main deployment altitude was then decreased to 590 ft AGL. The fin can separation event has been changed to occur at 520 ft AGL such that it does not occur beneath the 500 ft AGL energetics limit set by NASA. In addition to these changes, several changes were made to the PRM and SRM design. The bulkhead material was changed to carbon fiber to provide shielding from electromagnetic waves and radio transmissions. The altimeter shield was deemed unnecessary after the body tube material was switched to carbon fiber, since the electronics would already be shielded on all sides by the airframe and bulkheads.

### 2.2 Changes To Payload Criteria

The location of the payload has changed to the nose cone and nose cone shoulder to reduce the overall mass of the launch vehicle. This configuration is achieved by only having one fiberglass section of the vehicle body for RF transmission with the rest of the vehicle as carbon fiber. The overall length of the system is reduced by changing the number of sensor bulkheads from three to one to fit into the nose cone. For electronics, the team will not be purchasing a commercially available wireless transmission module. Instead, the power distribution printed circuit board will contain a custom built-in transceiver. For sensors, the team will only be using magnetometers on the launch pad and not during flight. Lastly, there are two different IMUs for the purpose of redundancy.

The non-scoring ACS design has also changed since PDR. The flaps are now 6 in. in length instead of 10 in. The number of flaps was increased from three to four. The internal mechanism is mostly unchanged, with a lead screw driving extension arms that open the flaps. Electronics, including a PCB, are stored fore of the lead screw to save space.

### 2.3 Changes To Project Plan

The project plan remains generally unchanged aside from some small adjustments. First, the subscale test flight was originally planned for November 13, 2021, but was postponed to November 20, 2021 due to inclement weather on November 13 and 14. This postponement did allow for more subscale preparations prior to launch on November 20, specifically in regard to data collection and software configurations.

Furthermore, some procurements for the full-scale vehicle were needed much earlier than expected. Both the motors and airframe selected were purchased on an accelerated timeline due to increased lead times from both motor manufacturers and body tube manufacturers. Three of four total Aerotech L2200G-P motors have been delivered from vendors, with the fourth on an 8-week lead time from Impulse Buys, an Aerotech vendor. These

selections limited later design decisions, especially regarding mass, but assured the team that material would be delivered in time to construct the vehicle, complete wind tunnel testing the week of January 31, 2022, and aim to complete the vehicle demonstration flight on February 5, 2022, weather permitting. Additional backup dates are February 6 and the following weekend of February 12 and 13.

As noted, a Hessert Laboratories 2 ft by 2 ft subsonic wind tunnel at the University of Notre Dame has been reserved for the week of January 31, 2022. This additional testing will help the team better understand barometric pressure changes during ACS flap actuation and help estimate vehicle  $C_d$

## 3 Technical Design: Launch Vehicle

### 3.1 Mission Statement

The overall mission of the launch vehicle is to safely and reliably facilitate the mission goals of each payload. The vehicle design is driven by certain NASA-specified requirements as well as additional requirements identified by the team that are deemed necessary for mission success.

The main NASA Requirements that drive the vehicle design are to reach apogee at an altitude between 4,000 feet and 6,000 feet (NASA Req. 2.1) with a maximum motor impulse of 5,120 Newton-seconds (NASA 2.12) and to reach a minimum velocity of 52 feet per second (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 vehicles 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. Additionally, 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).

#### 3.1.1 Mission Success Criteria

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

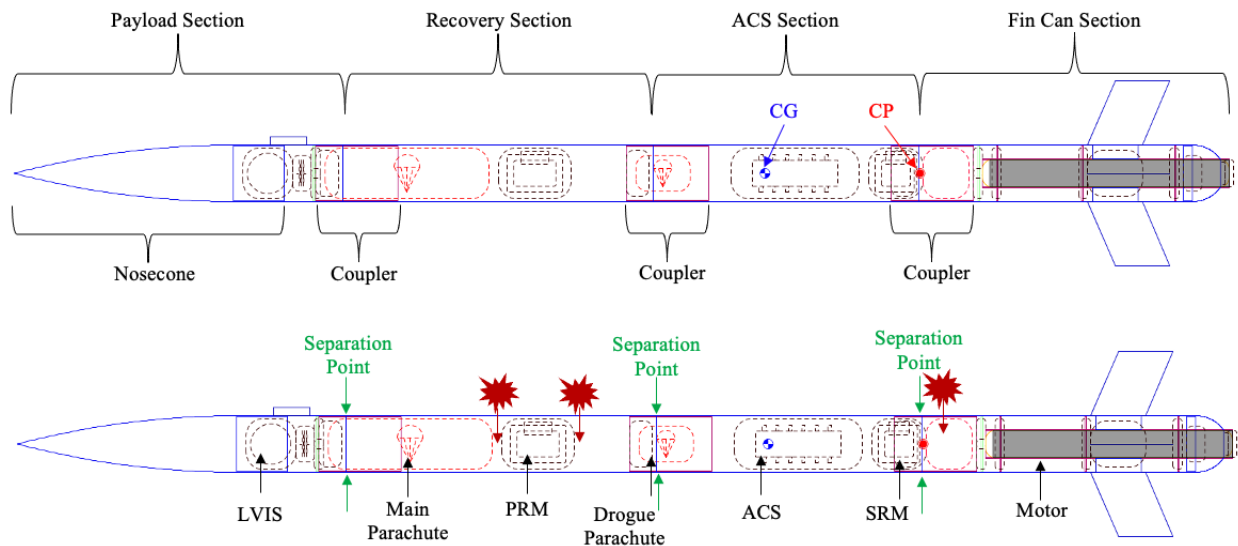
### 3.2 Launch Vehicle Design Overview

The design of the vehicle was driven by the the listed mission goals and the NASA and NDRT requirements. A rendered CAD model of the launch vehicle is shown in Figure 1.



**Figure 1:** Final Launch Vehicle CAD Model

The launch vehicle consists of four independent sections: the payload section, the recovery section, the ACS section and the fin can section. The vehicle has a single outer diameter of 6.17 inches spanning from the nose cone shoulder to the tail cone shoulder. There are three distinct in-flight separation points: one at the fore end of the recovery section, one at the aft end of the recovery section, and one at the aft end of the ACS section. The launch vehicle does not include any pressure vessels (NASA 2.13, NASA 2.13.1, NASA 2.13.2, NASA 2.13.3). All vehicle sections, major payloads, black powder charge locations, and separation points are diagrammed and labeled in Figure 2.



**Figure 2:** Final Launch Vehicle Layout Diagram

This vehicle layout and design informed the design decisions detailed in the following section. A summary of the important vehicle design values is included in Table 3.

**Table 3:** Vehicle Overview Important Parameters

Parameter	Value
CG location (in.)	82.2
CP location (in.)	99.1
Overall length (in.)	134
Thrust-to-Weight Ratio	9.65
Rail-exit velocity (ft/s)	89.2
Static Stability Margin	2.75
Overall mass (oz)	820

### 3.3 Vehicle Component Analysis

The material and shape specifications of each vehicle component were initially determined through trade studies. Further analysis was completed for each component based on refined payload needs, manufacturing capabilities, and commercial availability. This analysis demonstrates that each component is ready for manufacturing and is accounted for in mission performance predictions. The structural integrity of each component was also analysed and the results of this analysis were used to inform the design where necessary (LV.3). The results of this structural analysis are included in Section 5.3.

#### 3.3.1 Nose Cone

The FNC-6.0 Fiberglass nose cone from Public Missiles LTD was selected as the vehicle's nose cone. The only design requirement for the nose cone was that it must have an outer shoulder diameter of 6 in, matching the inner diameter of the payload bay. Major design criteria included drag minimization and material durability. Mass and price minimization were minor design criteria. Thus, the team chose to purchase the FNC-6.0 nose cone which has a 4:1 ogive shape and a total exposed length of 24 in. Additionally, the nose cone shoulder is not located at an in-flight separation point (NASA 2.5.2). Table 4 shows a summary of the nose cone's characteristics, and the CAD drawing in Figure 3 shows the dimensions of the nose cone.

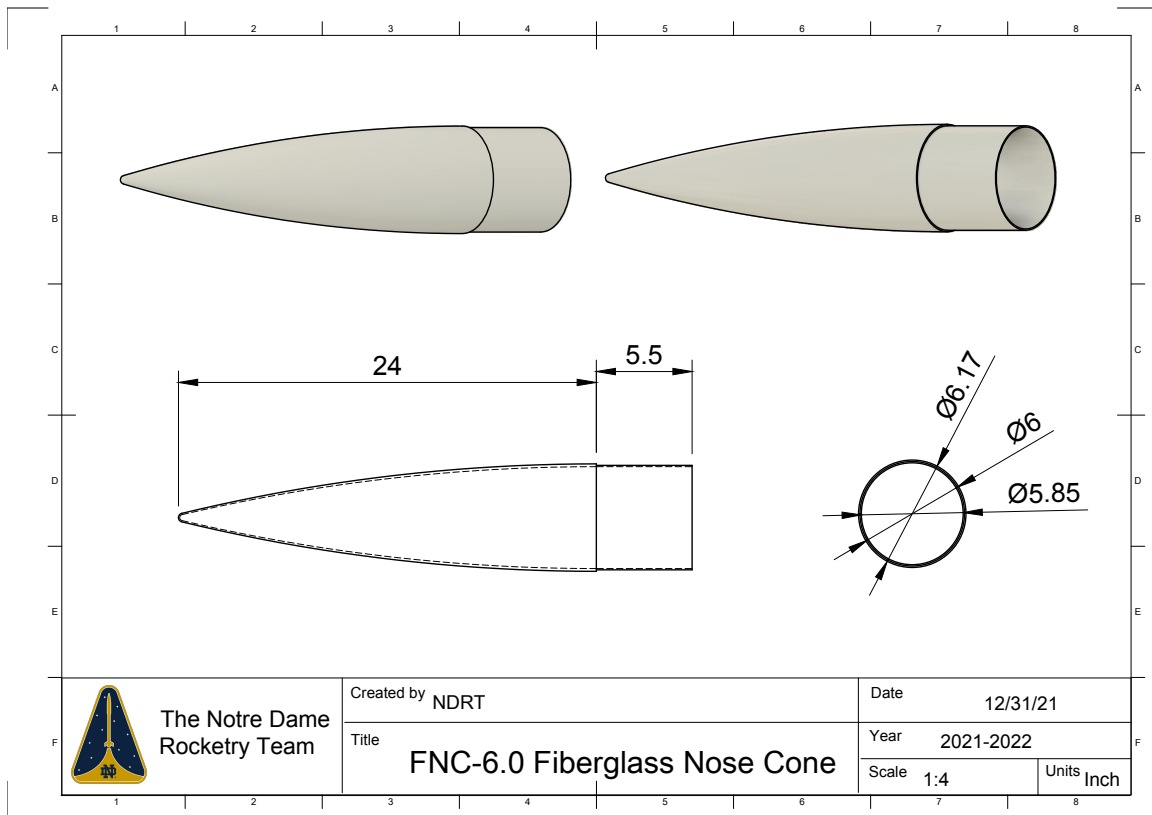


Figure 3: CAD Drawing of FNC-6.0 Fiberglass Nose Cone



**Table 4:** FNC-6.0 Nose Cone Specifications

Feature	Value
Exposed length (in.)	24.00
Shoulder length (in.)	5.50
Shape parameter	4:1 Ogive
Weight (oz)	28.00
Material	Fiberglass

### 3.3.2 Airframe Tube

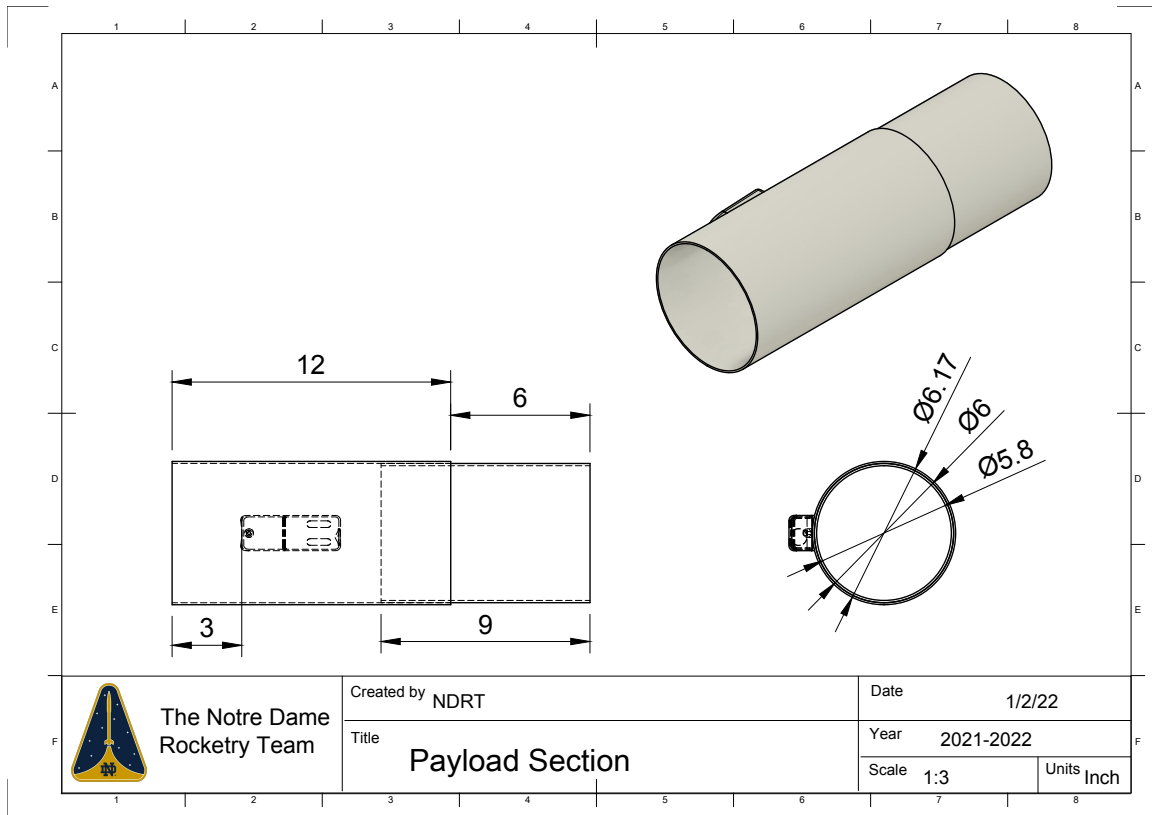
There are four independent sections of tubing that make up the airframe: the payload bay, the recovery bay, the ACS bay, and the fin can ([NASA 2.5](#)).

The payload bay is located at the fore end of the vehicle directly aft of the nose cone and houses the LVIS. The nose cone shoulder slides into the fore end of the payload bay and is screwed in. A coupler is epoxied inside the aft end of the payload bay for insertion into the recovery bay. The G12 Fiberglass was selected as the payload bay and coupler material due to its RF transparency, yield strength, and durability. RF transparency is needed to allow communication with the payload and GPS inside the payload bay ([LV.4](#)). Durability is also important for the vehicle to withstand multiple launches and transportation throughout the year.

The fiberglass tubes will be purchased from Composite Warehouse at the correct diameters and then cut to length. The coupler will be cut to a length of 9 in. and epoxied at 3 in. inside of the payload bay. The remaining 6 in. of the coupler will insert into the recovery bay, equal to 1 body diameter in length ([NASA 2.5.1](#)). A summary of the important characteristics of the payload bay is provided in [Table 5](#), and a CAD drawing of the payload bay is shown in [Figure 4](#).

**Table 5:** Payload Bay Specifications

Parameter	Value
Length (in.)	12
Inner Diameter (in.)	6.00
Outer Diameter (in.)	6.17
Weight (oz.)	24.3
Material	G12 Fiberglass
Coupler Length (in.)	9
Coupler Inner Diameter (in.)	5.8
Coupler Outer Diameter (in.)	5.998
Coupler Weight (oz.)	20.3
Coupler Material	G12 Fiberglass



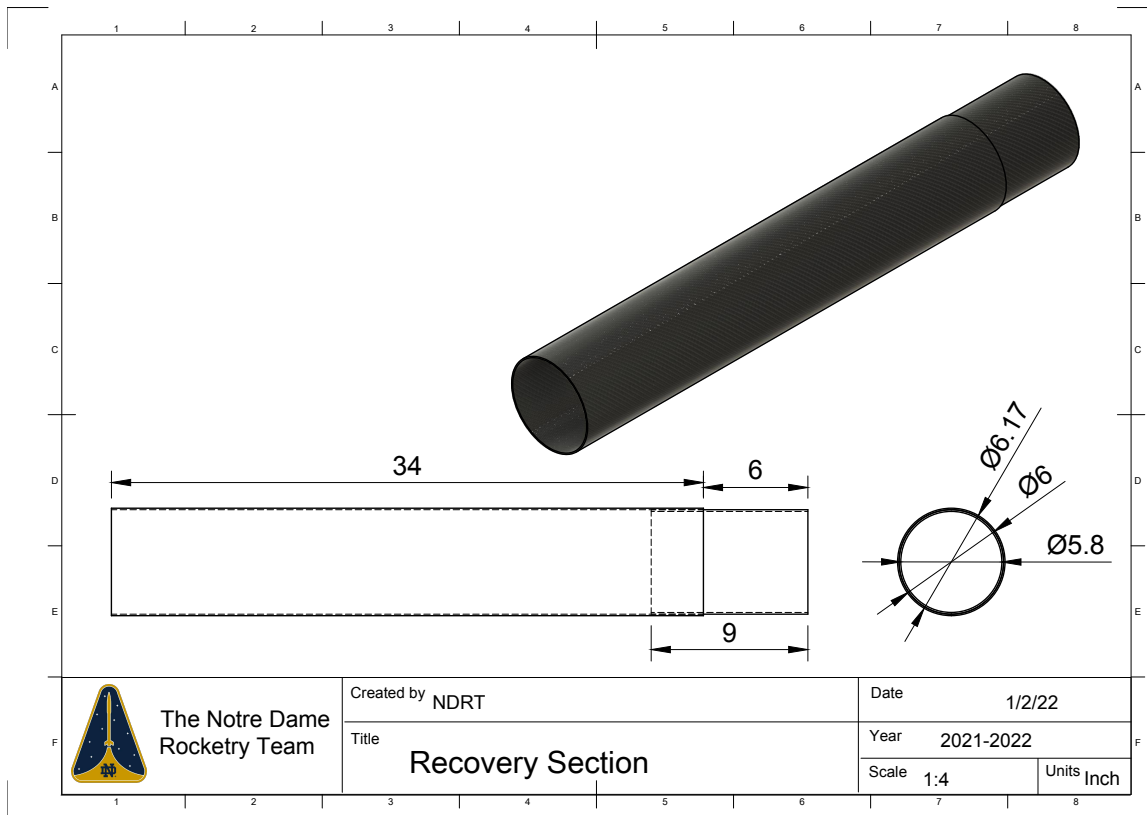
**Figure 4:** Payload Bay CAD Drawing

The recovery bay is located aft of the payload bay and fore of the ACS bay and holds the main recovery subsystem including the PRM, main parachute, and drogue parachutes. Carbon fiber was the selected material for the recovery bay, recovery coupler, and the remainder of the airframe tubes due to carbon fiber's high yield strength, low weight, and high durability since RF transparency is not needed.

The tube will be purchased from PML with the required diameter and then cut to length. The payload coupler will slide into the fore end of the recovery bay, and the recovery coupler is epoxied inside the aft end of the recovery bay for insertion into the fin can. The coupler will be cut to a length of 9 inches and epoxied at 3 in. inside of the recovery bay. The remaining 6 inches of the coupler will insert into the ACS bay. A summary of the important characteristics of the recovery bay is provided in Table 6, and an engineering drawing of the recovery bay is shown in Figure 5.

**Table 6:** Recovery Bay Specifications

Parameter	Value
Length (in.)	34
Inner Diameter (in.)	6.00
Outer Diameter (in.)	6.17
Weight (oz.)	49.7
Material	Carbon Fiber
Coupler Length (in.)	9
Coupler Inner Diameter (in.)	5.8
Coupler Outer Diameter (in.)	5.998
Coupler Weight (oz.)	14.9
Coupler Material	Carbon Fiber



**Figure 5:** Recovery Bay CAD Drawing

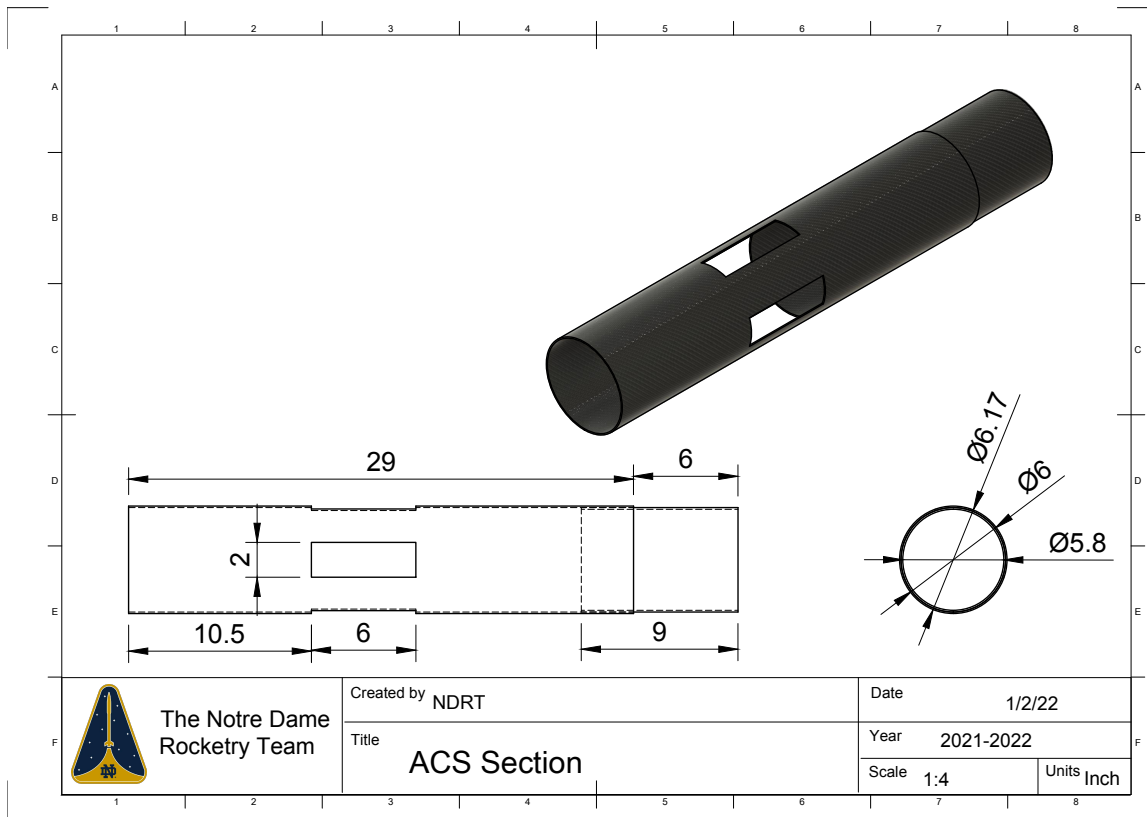
The ACS bay is directly aft of the recovery bay. The purpose of the ACS bay is to house the ACS and the SRM in a configuration that can interface with and separate from the recovery tube and the fin can. Both the ACS and SRM are mounted into the ACS bay via screws inserted from the outside of the tube. The ACS bay will also be made of carbon fiber purchased from PML, chosen because of its high strength and durability and low weight.

This body tube will be purchased at the required diameter and cut to length. ACS flap slots will be machined in-house as well. The aft end of the ACS bay will have a coupler epoxied 3 inches into the tube with an exposed length of 6 inches which interfaces with the fin can. The ACS bay transfers the drag loads from the ACS to the rest of the vehicle. A summary of the important characteristics of the fin can design is provided in Table 7, and a CAD

drawing of the ACS bay is shown in Figure 6.

**Table 7: ACS Bay Specifications**

Parameter	Value
Length (in.)	29
Inner Diameter (in.)	6.00
Outer Diameter (in.)	6.17
Weight (oz.)	43.9
Material	Carbon Fiber
Coupler Length (in.)	9
Coupler Inner Diameter (in.)	5.8
Coupler Outer Diameter (in.)	5.998
Coupler Weight (oz.)	14.9
Coupler Material	Carbon Fiber



**Figure 6: ACS Bay CAD Drawing**

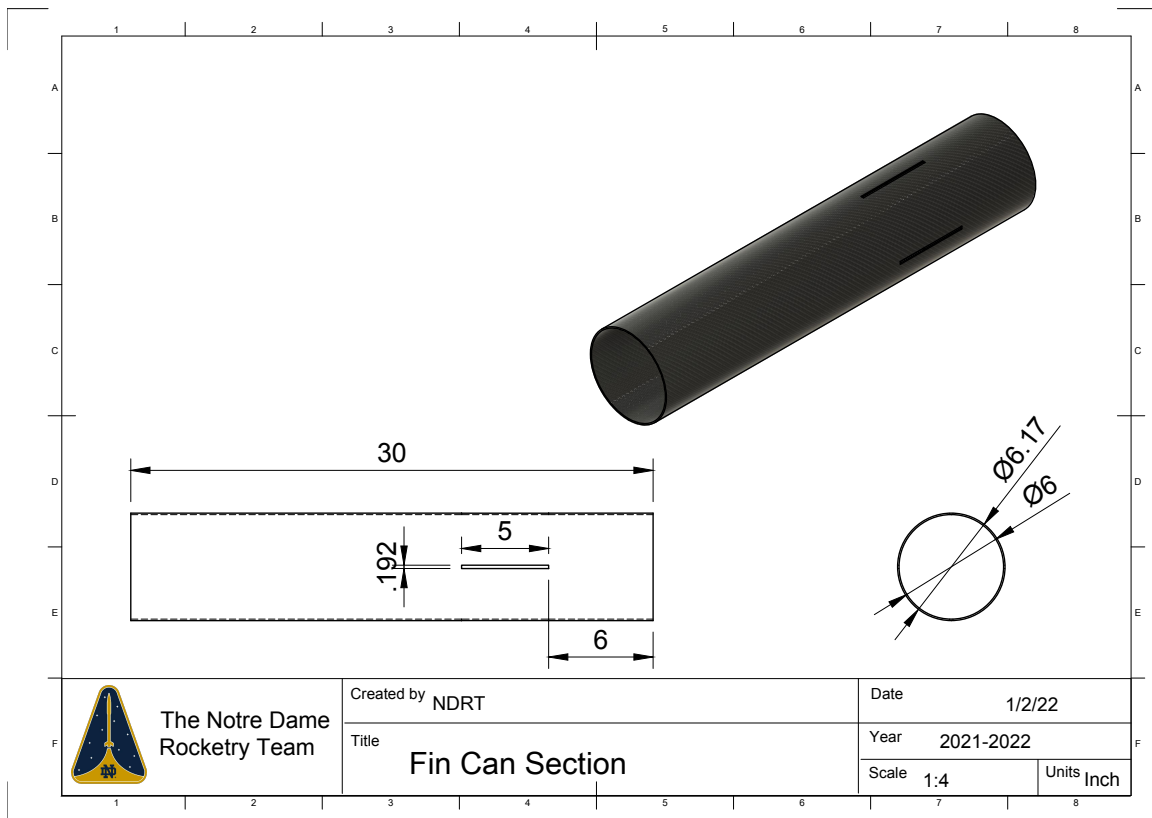
The fin can is the aft-most airframe tube and houses the motor retention system in a configuration that can interface with and separate from the ACS bay. The components of the motor retention system will be epoxied into the fin can. An epoxied bulkhead with an eyebolt will be used to tether the fin can to the ACS bay during recovery.

The fin can will also be made of carbon fiber purchased from PML, chosen because of its high strength, durability and low weight. The body tube will be purchased at the required diameter and cut to 30 inches in length. Fin slots

will be machined in-house. The fin can transfers the thrust loads from the motor retention assembly to the rest of the vehicle. A summary of the important characteristics of the fin can design is provided in Table 8, and a CAD drawing of the fin can is shown in Figure 7.

**Table 8: Fin Can Specifications**

Parameter	Value
Length (in.)	30
Inner Diameter (in.)	6.00
Outer Diameter (in.)	6.17
Weight (oz.)	43.9
Material	Carbon Fiber



**Figure 7: Fin Can CAD Drawing**

### 3.3.3 Camera Shroud

The camera shroud is designed to integrate the chosen camera onto the launch vehicle during flights to record high quality video footage of the launch. The camera shroud is required to securely hold the camera, securely attach to the vehicle, allow access to camera buttons while installed, and cause minimal drag during flight.

The shroud consists of two separate pieces. The first holds the camera and attaches to the payload bay. The camera is inserted from the fore side, and the second piece screws on such that the camera is secured in place. The shroud will be epoxied to the payload bay's outer diameter with the camera facing in the aft direction. The camera is at a 3 degree angle relative to the body tube in order to maximize the field of view when secured. This placement gives the camera visibility of the ACS drag flap actuation and the drogue and main parachute

deployment. All edges of the shroud are rounded in attempt to minimize drag. The camera shroud will be 3D printed from ABS. A drawing of the camera shroud design is shown in Figure 8. CFD was performed and analyzed to ensure that the addition of the camera shroud does not cause excess aerodynamic instability or flow separation (NASA 2.16). The results, shown in Figure 9, suggest that the camera shroud mostly remains in the boundary layer of the vehicle flow and that the separation that is caused reattaches well before the fins or ACS deployment location.

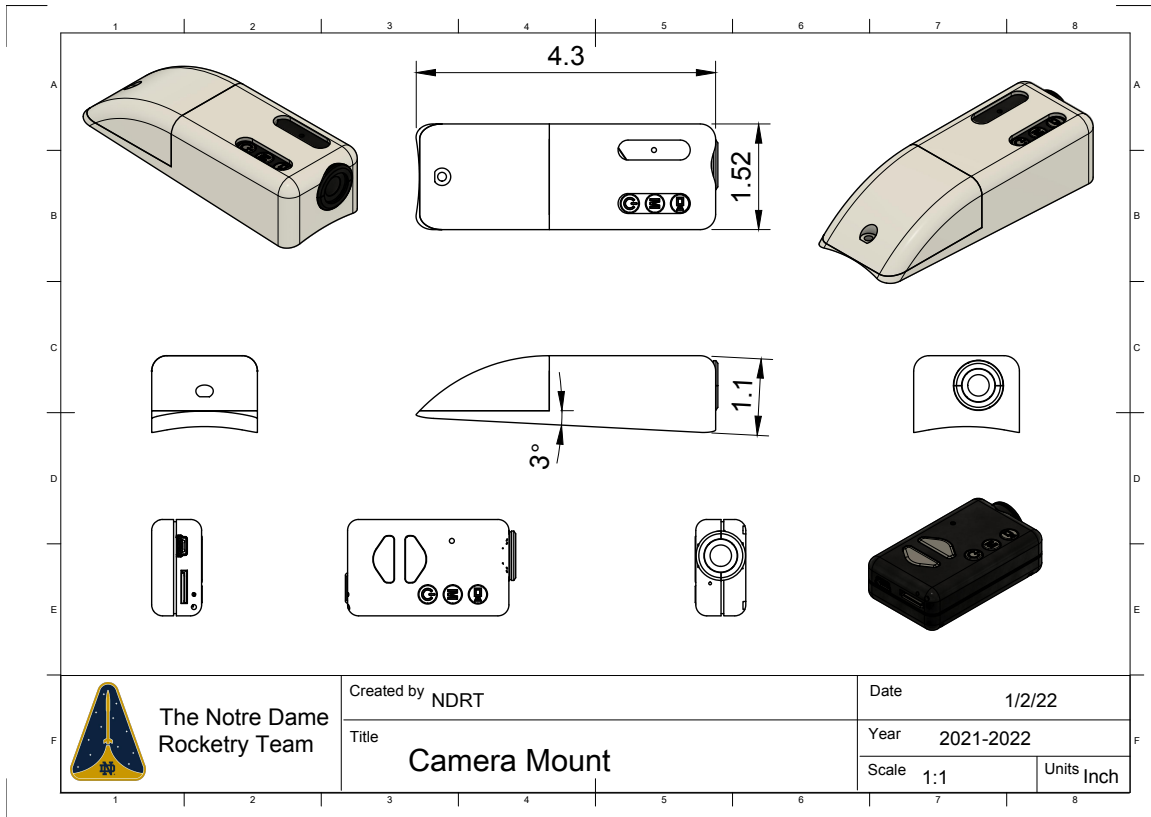


Figure 8: Camera Shroud CAD Drawing



Figure 9: Camera Shroud CFD

The selected camera is the Mobius2 Actioncam. This camera is capable of shooting 1080p video at 60 frames per second with a super wide angle field of view of 130°, with all footage saved onto a removable microSD memory card. The camera weighs approximately 1.587 oz, and is 2.52 in. by 1.40 in. by 0.709 in.

### 3.3.4 Fixed Bulkheads

Two fixed bulkheads will be used to facilitate recovery harness connection points. One bulkhead will be located at the aft end of the payload bay to allow a tether connection to the recovery bay and will also serve to maintain pressure isolation of the LVIS from the main parachute recovery charges. The second bulkhead will be located at the fore side of the fin can to allow a tether connection to the ACS bay. Each bulkhead will be epoxied into the airframe tube.

Each bulkhead will have a 3/8 in. clearance hole for a recovery eyebolt to attach to the tether chords. The bulkheads will be machined out of G10 fiberglass with a 6 in. diameter and a thickness of 0.187 inches. Each bulkhead is designed to be able to withstand the loads required during main parachute deployment. The results of this analysis can be found in Section 5.3. A summary of the important characteristics of the fixed bulkhead assembly is provided in Table 9, and a CAD drawing is shown in Figure 10.

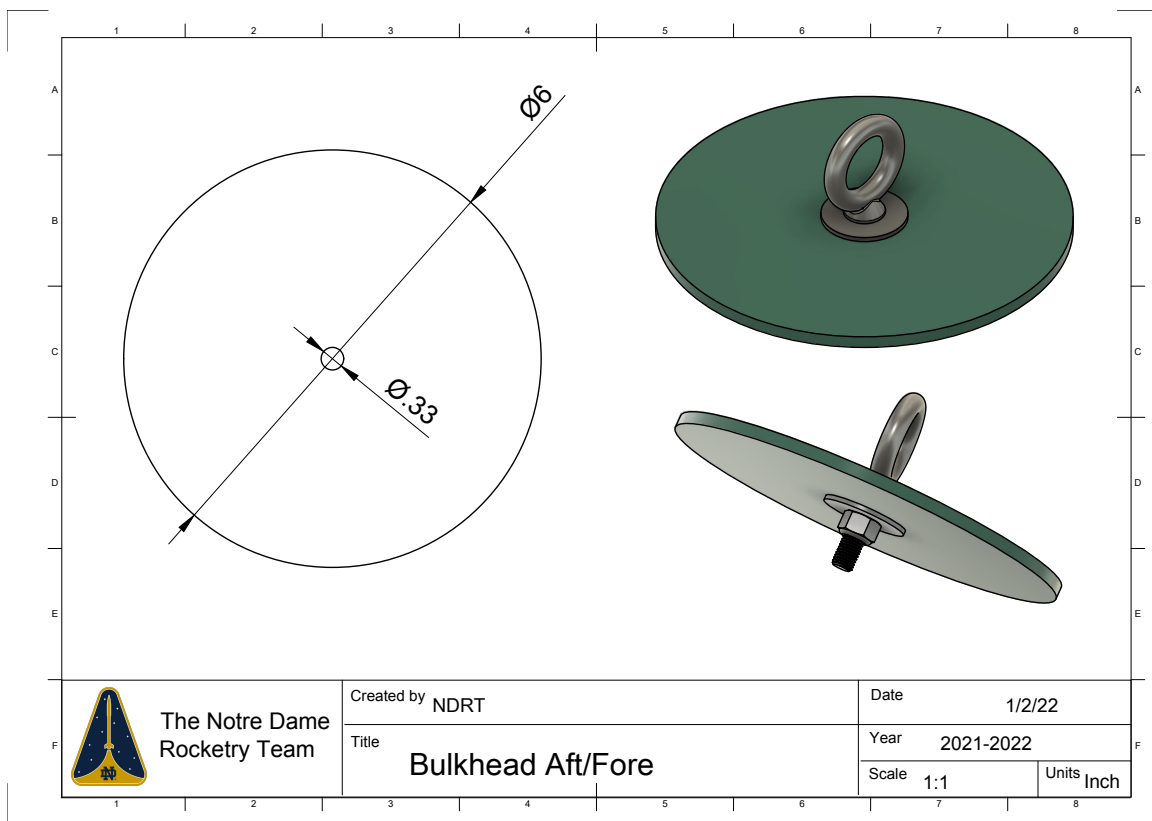


Figure 10: Bulkhead CAD Drawing

**Table 9:** Fixed Bulkhead Specifications

Parameter	Value
Shape	Swept Rectangular
Cross-Section	Airfoil
Root Chord (in.)	6
Tip Chord (in.)	6
Height (in.)	7
Thickness (in.)	6.00
Tab Length (in.)	5
Outer Diameter (in.)	6.17
Material	G10 Fiberglass
Number of Fins	4
Single Fin Weight (oz.)	43.9
Total Fin Weight (oz.)	175.6

### 3.3.5 Fins

Fins are used to control the center of pressure of the vehicle to achieve the desired stability during launch. The main design drivers for the fins were causing a low amount of drag and that the center of lift of the fin's platform shape be far away from the boundary layer on the vehicle's surface. The selected fins for this vehicle have a swept rectangular shape for low drag and a large tip chord. The fins will be made from G10 fiberglass due to its high strength, high durability, and low weight. Fin platform dimensions and the number of fins were then based solely on achieving the desired vehicle static stability margin of 2.75.

The final fin design for the vehicle has a constant chord length of 6.0 in., a height of 7.0 in., and a thickness of 0.187 in. An airfoil shape will be approximated for the fin cross section by rounding the leading edge and chamfering the trailing edge to further reduce the drag for subsonic flight. The fins will have tabs spanning from the fin can tube to the motor mount tube. The tabs will be inserted through slots in the fin can, and the fin will be epoxied at all points of contact. Additionally, epoxy fillets will be applied at the external intersection of the fins and the fin can to provide additional strength and to reduce interference drag. The fins will be machined with a precision CNC water jet. A summary of important parameters in the fin design is provided in Table 10, and a CAD drawing is shown in Figure 11.

A fin flutter analysis was also performed to ensure no damage during flight. The possibility for damage to the fins becomes a genuine concern when the flight speed reaches the fin flutter speed. The fin flutter speed can be calculated from the fin flutter boundary relation in Equation 1:

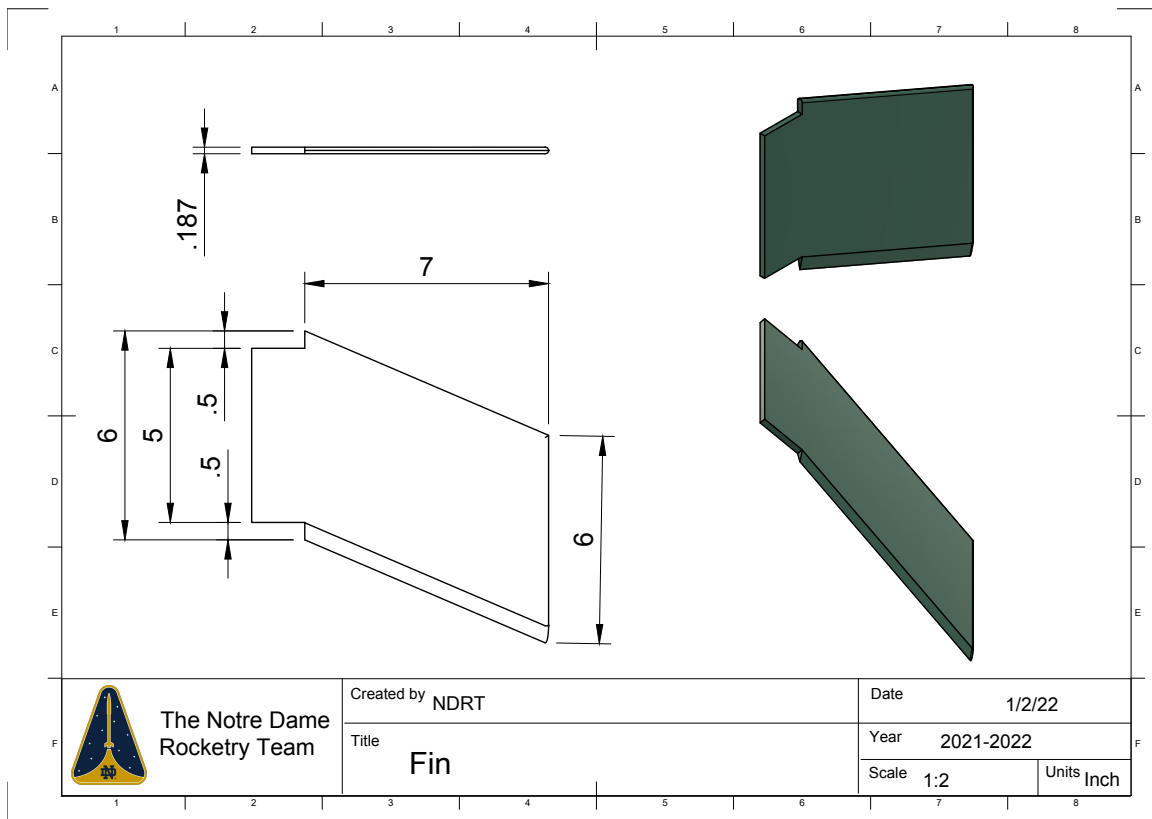
$$v_f = a \sqrt{\frac{G}{2(AR+2)\left(\frac{t}{c_r}\right)^3 \frac{1.337AR^3P(\lambda+1)}{G}}} \quad (1)$$

where  $v_f$  is the fin flutter velocity,  $a$  is the speed of sound,  $G$  is the shear modulus,  $AR$  is the aspect ratio,  $P$  is the pressure,  $\lambda$  is the taper ratio,  $t$  is the fin thickness, and  $c_r$  is the root chord. The value of the fin flutter speed throughout flight using the fin flutter boundary equation was determined to be upwards of 25,000 feet per second. This value is exceedingly far above the maximum flight velocity of about 640 feet per second with a factor of safety of over 39. Thus, the vibrations of the fins pose a negligible threat to the structure.



**Table 10:** Fin Assembly Specifications

Parameter	Value
Shape	Swept Rectangular
Cross-Section	Airfoil
Root Chord (in.)	6
Tip Chord (in.)	6
Height (in.)	7
Thickness (in.)	6.00
Tab Length (in.)	5
Outer Diameter (in.)	6.17
Material	G10 Fiberglass
Number of Fins	4
Single Fin Weight (oz.)	43.9
Total Fin Weight (oz.)	43.9



**Figure 11:** Fin CAD Drawing

### 3.3.6 Motor Retention

The motor retention system consists of the motor mount tube, centering rings, and the retainer. Its purpose is to align the thrust force vector to the center line of the launch vehicle and to keep the motor attached to the vehicle after burnout. The motor mount tube houses the motor and has an internal diameter allowing for a slip fit with the motor. The thrust from the motor is applied to the aft face of the motor mount tube. The motor retainer is an aluminum ring epoxied to the aft end of the motor mount tube to prevent the motor from separating from

sliding out of the motor mount after burnout (NASA 2.23.5). Centering rings are epoxied to the external wall of the motor mount tube and to the interior of the fin can, and transfer the thrust load from the motor mount tube to the airframe. All epoxy joints with the motor mount tube will use J-B Weld due to its heat-resistance and high strength properties. The chosen motor retainer is the Aero Pack 75mm Retainer. The chosen motor retainer is provided in Figure 12.



**Figure 12:** Aero Pack 75mm Motor Retainer

The motor mount tube is made out of carbon fiber due to its high strength and light weight. The tube was purchased from PML and will be cut to length. The centering rings will be machined from G10 fiberglass. Three centering rings will be used, each with the same diameter and a thickness of 0.187 inch. The characteristics of the motor retention assembly is shown in Table 11, and a CAD drawing with dimensions is provided in Figure 13. An analysis of the structural integrity of the motor mount tube and the centering rings during peak thrust can be found in Section 5.3. Note that high-temperature epoxy will be used to attach the centering rings to the motor tube due to their close proximity to the motor, fulfilling LV.5.

**Table 11:** Motor Retention Assembly Specifications

Parameter	Value
Motor mount tube material	Carbon Fiber
Motor mount tube length (in.)	27.0
Motor mount tube inner diameter (in.)	3.00
Motor mount tube outer diameter (in.)	3.112
Motor mount tube weight (in.)	8.37
Number of centering rings	4
Centering ring material	G10 Fiberglass
Centering ring inner diameter (in.)	3.117
Centering ring outer diameter (in.)	5.995
Centering ring thickness (in.)	0.187
Centering ring unit weight (oz.)	5.02
Motor retainer material	Aluminum
Motor retainer weight (oz.)	3.5

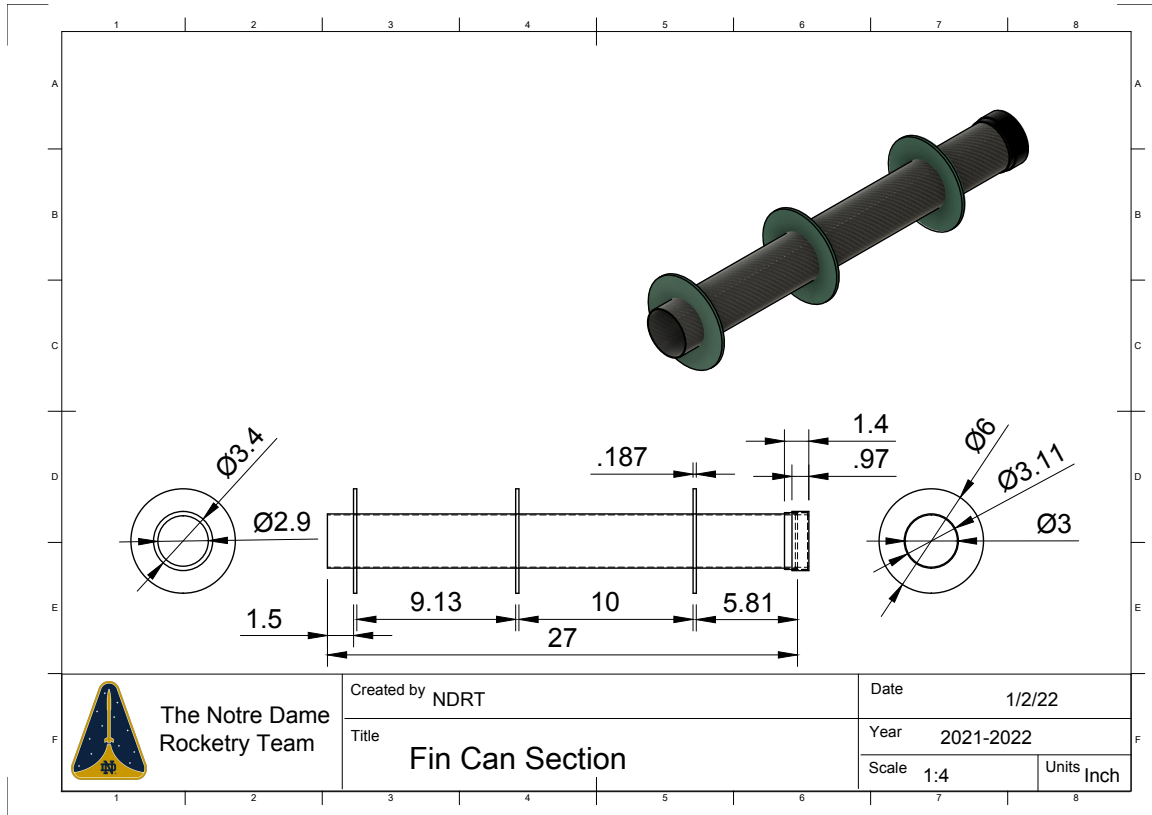


Figure 13: Motor Retention CAD Drawing

### 3.3.7 Tail Cone

A tail cone was added decrease the pressure drag on the launch vehicle during flight. The design requirements for the tail cone were a fore diameter to fit the fin can and an aft diameter of 3.112 in. Decreasing the aft diameter lowers the drag on the launch vehicle by minimizing the low pressure wake area. A 3D-printed ogive tail cone was selected for the launch vehicle because the ogive shape will create a smooth transition between the 6.17 in. diameter of the body tube and the 3 in. diameter of the motor mount tube. A 3 in. transition length was chosen such that the tail cone did not interfere significantly with the centering ring and fin assembly of the motor retention system. Important characteristics of the tail cone are shown in Table 12. Figure 14 displays a CAD drawing of the tail cone.

Table 12: Tail Cone Specifications

Feature	Value
Length (in)	3
Shape	Ogive
Weight (oz)	4.73
Material	3D-printed ABS

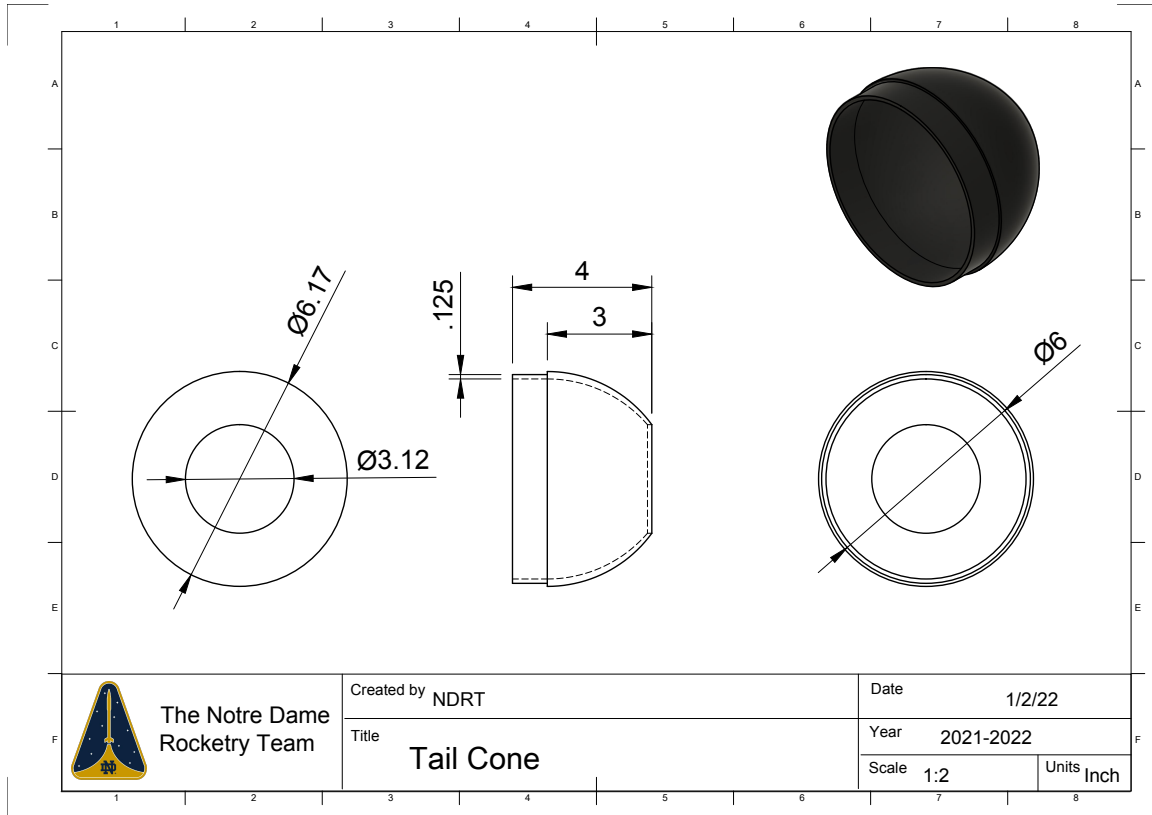


Figure 14: CAD Drawing of 3D-Printed Tail Cone

### 3.4 Launch Vehicle Integrated Design

With all vehicle components designed, sourced, and ready for manufacturing, final mass and volume budgets for all internal payloads were used to create and refine the integrated vehicle design including exact placement for all subsystems and proper fin placement to ensure design stability.

#### 3.4.1 Vehicle Layout and Design Summary

The dimensions of the launch vehicle were selected to optimize apogee and stability and minimize drift while providing enough internal space to house each system. A CAD drawing of the launch vehicle, including dimensions and a list of parts, is shown in Figure 15. Additionally, the material of each component was chosen to reduce weight while maintaining structural strength. The materials that will be used for each component is outlined in Table 13.

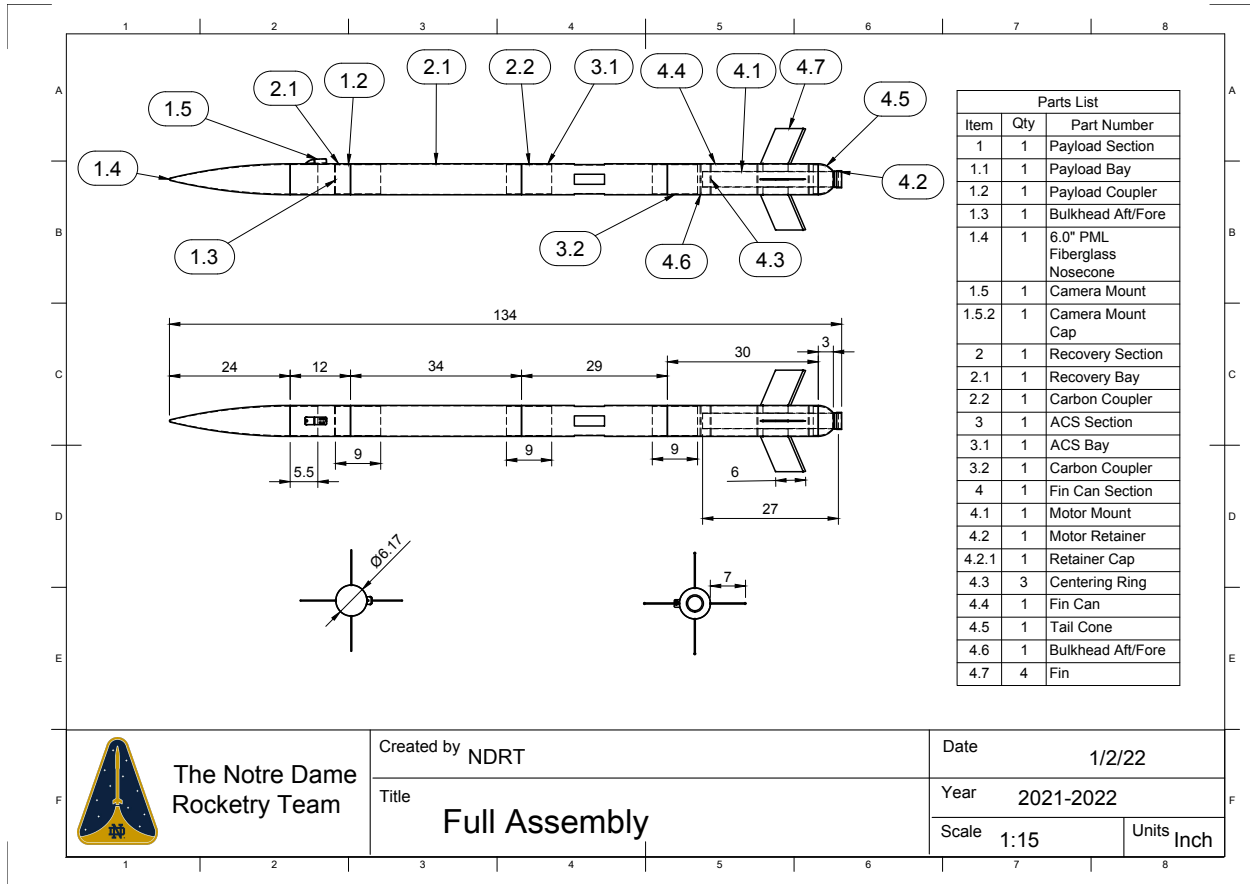
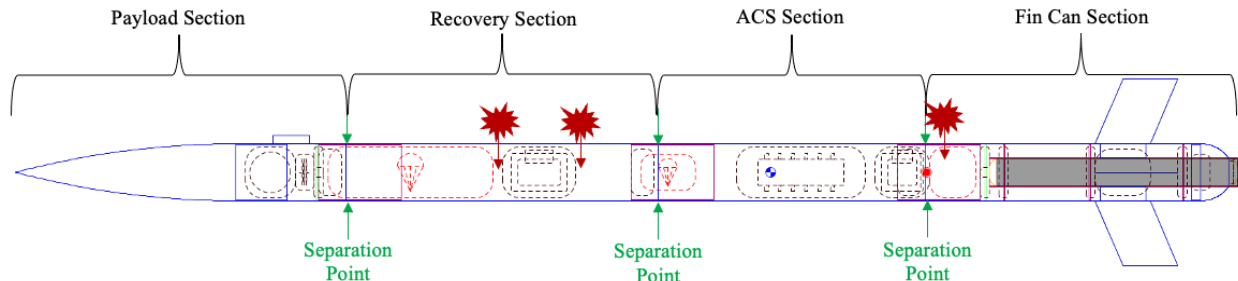


Figure 15: CAD Drawing of the Launch Vehicle Design with Dimensions

Table 13: Summary of Launch Vehicle Component Material

Component	Material
Nose cone	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

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 16, and the distances of these from the tip of the nose cone are shown in Table 14.



**Figure 16:** OpenRocket Diagram with Separation Points and Black Powder Charges

**Table 14:** Distances of Separation Points and Black Powder Locations from Nose Cone 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

### 3.4.2 Detailed Mass Statement

Mass budgets for each system were updated and refined for CDR. NDRT has adopted the mass control method given by AIAA Standard S-120A, titled "Mass Properties Control for Space Systems" to track system mass estimates and budgets throughout the year. Each system gets an allowable mass. Each system tracks estimated component weights beginning at the preliminary design phase, giving a basic mass. Components are given a mass growth percentage depending on their type and design maturity level to estimate the growth of the each system's mass of each system, and is applied to the basic mass estimate. This gives the predicted mass, what the system is expected to be at the end of the design and fabrication process. Mass margin percentage gauges how the predicted mass compares to the allowable mass. All vehicle performance predictions were completed using the predicted mass estimates. Table 15 displays the allowable mass, current basic masses, predicted final masses, mass growth allowances, and margin percentages for each system. The vehicle will be flown with the proper ballast configuration during the full scale flight (NASA 2.19.1.6). Table 16 displays a detailed basic budget for estimate for the launch vehicle vehicle.

**Table 15:** Overall Mass Statement

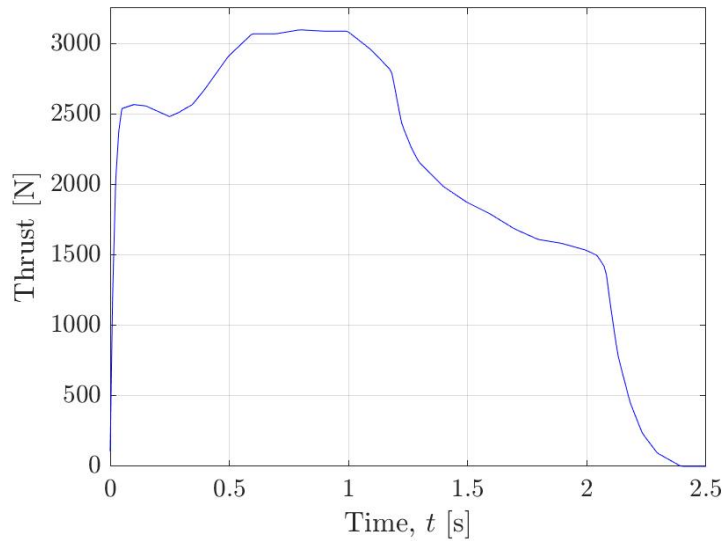
System	Allowable Mass (oz.)	Basic Mass (oz.)	Predicted Mass (oz.)	MGA (%)	Margin (%)
Vehicle	530	518.440	518.440	0.000	2.230
Recovery (PRM)	155	116.051	122.416	5.485	28.077
Recovery (SRM)	60	48.600	52.542	8.111	15.346
Payload	90	48.966	51.808	5.804	77.997
ACS	75	73.035	75.777	3.753	-1.063
Full System	910	805.093	820.982	1.974	11.057

**Table 16:** Detailed Vehicle Basic Mass Estimate

Component	Mass (oz.)
Nosecone	28
Payload Tube	24.3
Payload Bulkhead	6.87
Payload Coupler	20.3
Payload Coupler Epoxy	1.2
Eyebolt Hardware	3
Payload Bulkhead Epoxy	0.3
Camera Mount	2
Recovery Tube	49.7
Recovery Coupler	14.9
Recovery Epoxy	1.2
ACS Tube	42.40
ACS Coupler	14.9
ACS Epoxy	1.2
Fin Can Tube	43.9
Motor Mount Tube	14.9
3 Centering Rings	15.06
Bulkhead	6.87
Bulkhead Epoxy	0.3
Eye Bolt hardware	3
Fins	41
Tail Cone	4.73
Centering Ring Epoxy	1.8
Tail Cone Epoxy	0.4
Motor Retainer Epoxy	0.4
Motor Retainer	3.5
Fin Epoxy	3.6
Motor Casing	79.89
Propellant	88.82
<b>Total</b>	<b>518.44</b>

### 3.4.3 Motor Selection

The team selected the Aerotech L2200G-P motor was selected for both the demonstration and competition ([NASA 2.10.1](#), [NASA 2.19.1.5](#)). Simulations proved it to be the best motor available for the competition, as it had the highest impulse and projected apogee of all commercially available potential motors. Table 17 below provides the motor specifications, and Figure 17 below features a plot of the motor thrust curve, produced with a simulation in OpenRocket. The launch vehicle has a minimum thrust to weight ratio of 9.65 : 1.0 ([NASA 2.15](#)). The launch vehicle will be launched with a 12-volt firing system at both demonstration and competition launches ([NASA 2.8](#)).



**Figure 17:** Motor Thrust Curve of Aerotech L2200G-P Motor

**Table 17:** Aerotech L2200G-P Motor Specifications

Feature	Value
Diameter (in)	2.95
Length (in)	26.80
Loaded Weight (oz)	168.72
Propellant Weight (oz)	88.82
Burnout Weight (oz)	79.90
Impulse (N-s)	5104.00
Average Thrust (N)	2200.00
Maximum Thrust (N)	3114.00
Burn time (s)	2.32
Cost (USD)	322.99

### 3.5 Subscale Flight Results

The team designed, constructed, and successfully launched and recovered a subscale vehicle to critically examine how the full-scale vehicle and subsystems are likely to perform at a fraction of the cost (NASA 2.18). The subscale vehicle was a newly designed and constructed vehicle (NASA 2.18.3). The selected motor for this vehicle was an I-class motor. Five total subscale flights were conducted on November 20, 2021 and December 4, 2021 at the Three Oaks, MI, launch site, some with added LVIS, ACS, and recovery test payloads and some with added static ACS drag flaps.

#### 3.5.1 Subscale Test Priorities and Flight Summary

The primary vehicle test goals for the subscale vehicle were to match the materials, relative dimensions, number of sections, thrust-to-weight ratio, and static stability of the designed full-scale vehicle. This would allow for the team to gain knowledge through experience and engineering analysis to inform the design and manufacturing of the full-scale vehicle. Flight data, including the apogee altitude, was recorded using an altimeter (NASA 2.18.2).



The primary goals for the first launch day on Nov. 20 were to demonstrate a successful flight and to obtain data on the drag effects of ACS drag flaps. Flight 1 included an LVIS test payload, an ACS test payload, and no added ACS flaps. Flight 2 included an LVIS test payload, an ACS test payload, and 60-degree ACS flaps. Flight 1 was successful with no errors. Flight 2 was unsuccessful due a failure of the motor rear charge to separate the vehicle. Flight data was successfully recorded for the first flight only.

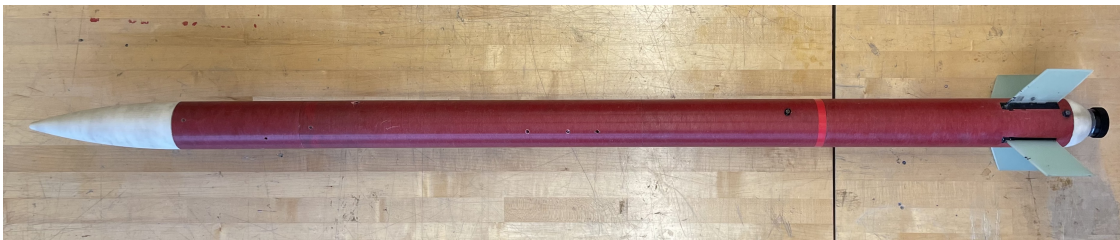
The primary goals for the second launch day on Dec. 4 were to perform recovery articles tests and to again test the effects of added ACS drag flaps. Each of three launches carried two recovery test articles, a combined LVIS/ACS test payload, and ACS static drag flaps. The first flight of the day, Flight 3, was successfully launched and recovered, but no altimeter data was recovered. Flight 4 suffered a failure due to premature vehicle separation caused by added ACS drag flaps, but did successfully record usable altimeter data. Flight 5 again failed due to a failure to separate.

### 3.5.2 Scaling Factor and Dimensions

The subscale vehicle is a 50%-scaled version of the full-scale version to allow ample internal volume for subsystem testing prototypes while remaining simple and cost effective. Each dimension of the subscale launch vehicle was scaled down using the 0.5 scale factor to keep the subscale model proportionally similar to the full-scale model (NASA 2.18.1, NASA 2.18.5). Additionally, the subscale vehicle included all the same section separations as the full-scale vehicle. A comparison of the full-scale and subscale vehicle dimensions is outlined below in Table 18. A CAD drawing of the subscale vehicle is featured below in Figure 19, and a photo of the assembled subscale is shown in Figure 18 below.

**Table 18:** 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%



**Figure 18:** Picture of Fully Assembled Subscale Model

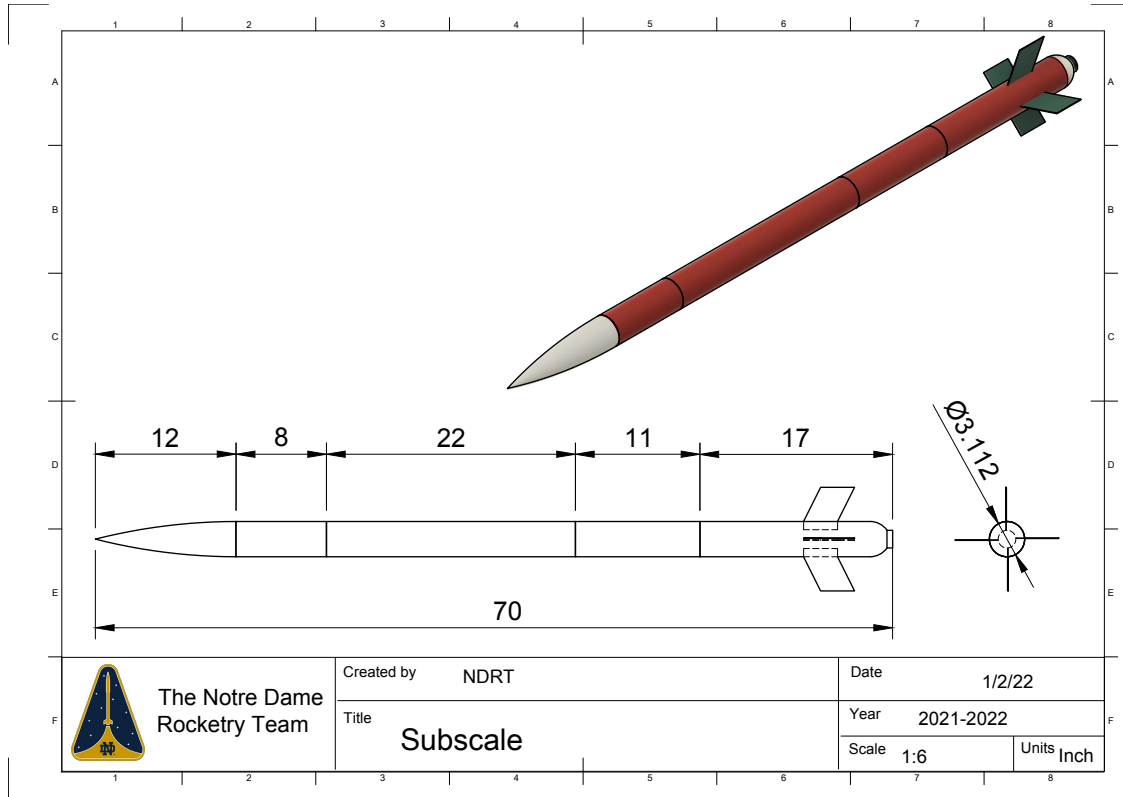


Figure 19: CAD Drawing of Subscale Model with Dimensions

### 3.5.3 Launch Day Conditions

The weather conditions for the subscale launches conducted on November 20th and December 4th are provided in Table 19. All launches were conducted at the Three Oaks, MI, launch site with a 6 degree launch angle and an 8-foot 1010 launch rail .

Table 19: Subscale Launch Day Conditions

Weather Parameter	11/20/2021 Launch Data	12/4/2021 Launch Data
Wind Speed (mph)	13 (no gusts)	15 (gusts up to 22)
Temperature (F)	37	36
Dewpoint (F)	25	30
Atmospheric Pressure (inHg)	30.22	30.25

The weather conditions above were used to perform flight simulations of the subscale launch vehicle. These simulated performance values obtained using these launch day conditions will be evaluated and compared to the actual flight results in Section 3.5.4.

### 3.5.4 Subscale Launch Analysis

The only flight to record successful data for the entire launch and successful recovery was the first flight. This altimeter data is plotted below in Figure 20 (NASA 2.18.4).

The predicted apogee for this flight from OpenRocket with all launch day conditions was 1504 ft, compared to the altimeter recorded apogee of 1498 ft. This result suggests that the approximations used in OpenRocket are

accurate for this flight. The OpenRocket simulation altitude data for the ascent phase of this flight is plotted below along with the altimeter recorded data in Figure 21. A polynomial fit was applied to the flight altimeter data and is also included.

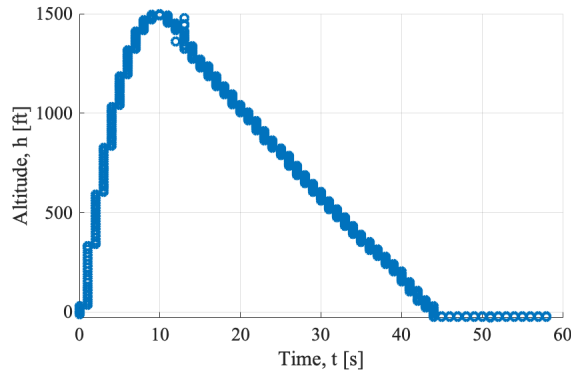


Figure 20: Subscale Test Flight Altimeter Data

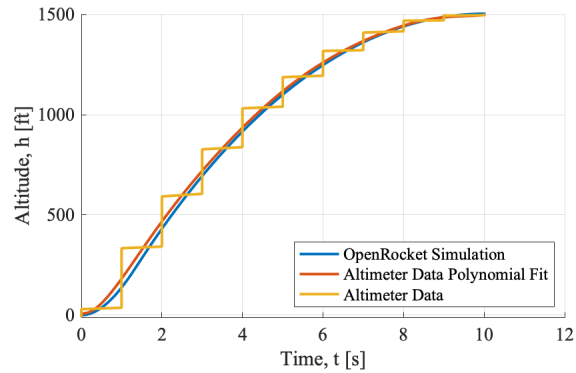


Figure 21: Simulation and Flight Data Acceleration Altitude

Plots of the velocity and acceleration of the subscale launch vehicle for the ascent phase were generated by differentiating the fit curve of the altimeter data and are shown in Figure 22 and Figure 23. This data again matches the simulation data well.

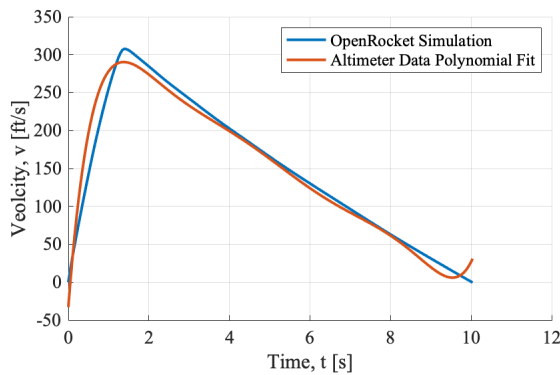


Figure 22: Simulation and Flight Data Velocity

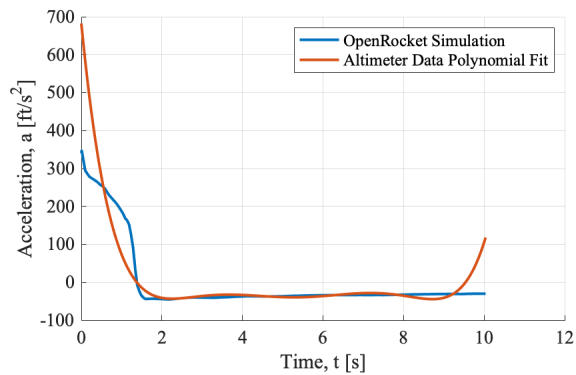


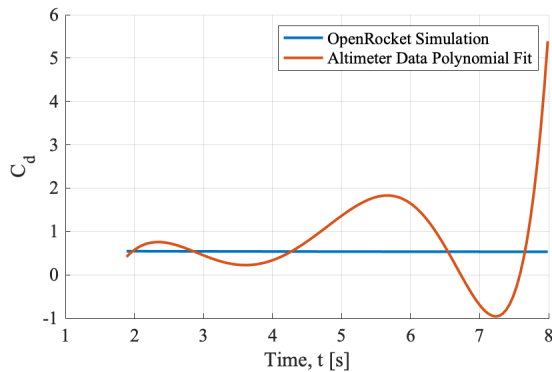
Figure 23: Simulation and Flight Data Acceleration

The equation of motion for the post-burnout coast phase was simplified to Equation 2 to use the subscale launch altimeter data to estimate the drag coefficient on the launch vehicle. The drag force calculated at each point in the flight was then applied to Equation 3 to obtain an estimate of the drag coefficient,  $C_d$ .

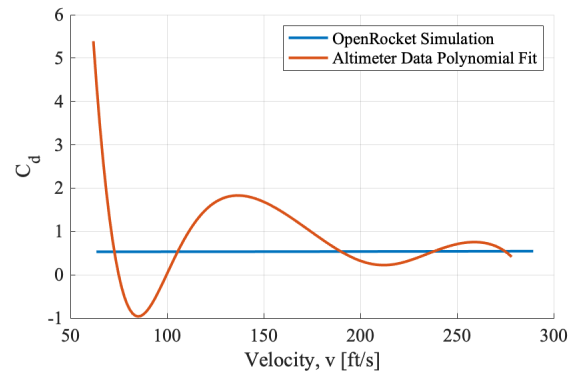
$$F_d = ma - mg \quad (2)$$

$$F_d = \frac{1}{2} \rho C_d V^2 A \quad (3)$$

This calculated drag coefficient for every point in the flight was then plotted against time in Figure 24 and against velocity Figure 25.



**Figure 24:** Calculated  $C_d$  vs Time



**Figure 25:** Calculated  $C_d$  vs Velocity

The calculated drag coefficient oscillates with time and velocity according to the original polynomial approaching the OpenRocket-calculated  $C_d$ . The calculated  $C_d$  at burnout is very close to the simulation  $C_d$  of 0.56. As the coast phase progresses, the calculated  $C_d$  diverges from the simulation  $C_d$ . This divergence is likely due to the fact that the vehicle is cocking into the wind causing a much larger reference area than the cross section of the body tube. This trend is seen again as the calculated approaches the OpenRocket-calculated  $C_d$  at higher velocities which occurred immediately post-burnout. This analysis suggests high confidence in the the OpenRocket  $C_d$  for the vehicle before extreme weather cocking. With this analysis, the team expects the full scale vehicle calculated  $C_d$  to converge to near the OpenRocket-calculated  $C_d$ .

### 3.5.5 Implications for Full Scale Design

The results of the subscale flight tests have a number of implications for the design of the full scale mission. For the vehicle design, the subscale suggested that the design stability of 2.75 was desirable for the aspect ratio of this vehicle. Additionally, through the subscale manufacturing process, the team gained valuable insights on manufacturing methods, tooling abilities, and best practices that will ensure a smooth and successful full-scale construction process. The comparison of the simulation results and the altimeter flight data gave the team high confidence in the simulation results from OpenRocket models. The drag coefficient did not need to be updated because of the similarity between the launch data and the simulated flights. Finally, the subscale flights made the team aware of similar potential issues with the full scale vehicle due to a failure caused by premature separation caused by the added drag of the ACS test flaps. Mitigation for this issue is discussed at greater length in Section 4.3.2.

## 4 Technical Design: Vehicle Recovery System

### 4.1 Mission Statement and Success Criteria

The primary goal of the recovery system is to ensure that every vehicle and payload component is undamaged and ready for reuse after landing (NASA 2.4). In addition, the recovery system will provide means of tracking and logging the flight path of the vehicle. The following criteria will be used to evaluate a successful mission for the recovery system:

- All components of the tethered launch vehicle will land with maximum kinetic energies of 75 ft-lbf (NASA 3.3).

- The launch vehicle will drift no more than 2500 ft in radius from the launch pad (NASA 3.10).
- The launch vehicle will land within 90 s of reaching apogee (NASA 3.11).
- Battery powered altimeters housed within the recovery system will collect official altitude readings as proof of flight (NASA 2.19.1.8).
- 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 (NASA 3.12).

## 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 591 ft AGL will be initiated by the altimeters housed in the Primary Recovery Module (PRM). A third separation event will occur at 520 ft AGL with the sole purpose of reducing the kinetic energy of the remaining 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, and the internal avionics will be armed on the launch pad with keylock switches. 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 Separation and Deployment

The recovery system will employ a staged sequence for parachute deployment (NASA 3.1). Black powder ejection will be used as the separation method for each of the three separation events. This method was chosen over alternative methods, such as mechanical piston ejection or compressed CO<sub>2</sub> ejection, primarily due to the low cost and simplicity of implementation. Motor ejection will not be used as a separation method for any of the separation events (NASA 3.1.3).

### 4.3.1 Separation and Deployment Sequence

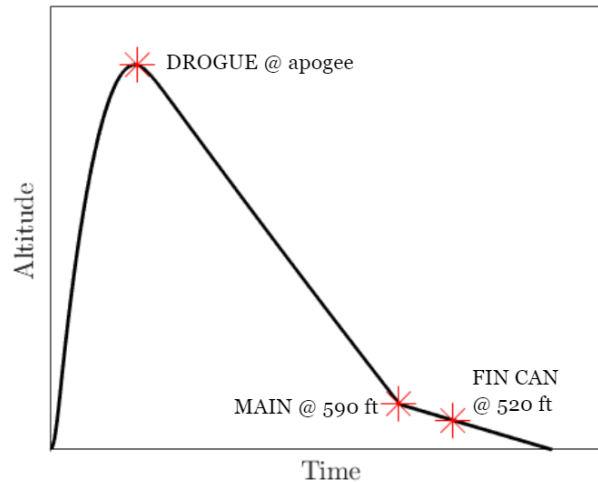
The first separation event will occur at apogee and initiate the deployment of the drogue parachute. The separation point is located between the recovery and ACS bays. The primary ejection charge will be triggered by the altimeter at apogee, and the secondary and tertiary charges will be triggered at 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 591 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 591 ft AGL and the backup charges will be triggered at 0.5 s delays. The lowest possible main deployment altitude can be calculated using the terminal descent velocity under the drogue parachute,  $v_d$ , and the time between subsequent ejections,  $t_{del}$ .

$$h_{\text{lowest}} = h_{\text{primary}} - 2v_d t_{\text{del}} = 591 \text{ ft} - 2(91 \text{ ft/s})(0.5 \text{ s}) = 500 \text{ ft}$$

Therefore, the main parachute will not deploy lower than 500 ft (NASA 3.1.1).

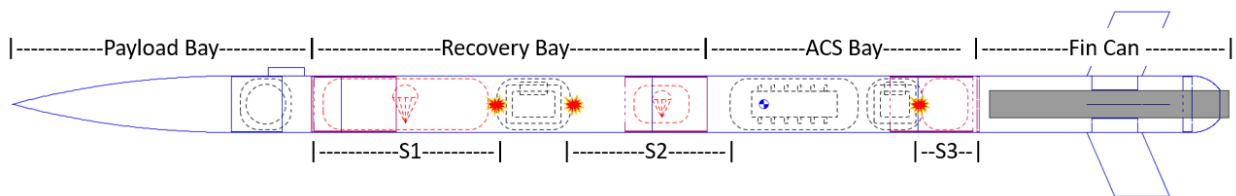
The third separation event will occur at 520 ft AGL and will not initiate the deployment of any parachutes. This event will cause the separation of the fin can from the ACS bay; however, these two sections will remain tethered by a recovery harness. The backup charges will be triggered at 0.5 s intervals so that no ejections occur below 500 ft as with the second separation event. Table 21 in Section 4.3.2 contains a summary of the details of the deployment sequence. Figure 26 shows the sequence of separation events along the launch vehicle's flight path.



**Figure 26:** Separation Events Along Flight Path

#### 4.3.2 Ejection Charge Sizing

Figure 27 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 27:** Launch Vehicle Separation Points

Table 20 lists the dimensions of each of the pressurized sections.

**Table 20:** Dimensions of Pressurization Sections

Section	Length (in)	Cross Sectional Area (in <sup>2</sup> )	Volume (in <sup>3</sup> )
S1	22.312	28.27	630.9
S2	19.5	28.27	551.3
S3	8.5	26.7	226.9

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. This scheme was chosen in consideration of the high drag force produced by the apogee control system flaps on ascent. The shear force required to separate five 4-40 nylon pins exceeds the ACS maximum drag force by a factor of 2 to prevent premature separation. The size of primary ejection charges,  $g_{bp}$ , is given by

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

$$\text{Pressure to Break Shear Pins: } P_{\text{shear}} = \frac{F_{\text{shear}}}{A_{\text{bh}}}$$

$$\text{Moles of Gas Needed: } n_{\text{gas}} = \frac{P_{\text{shear}} L_{\text{sect}} A_{\text{bh}}}{RT}$$

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

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

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

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

where  $\tau_{\text{max}}$  is the shear strength of nylon,  $A_{\text{pin}}$  is the cross-sectional area of one 4-40 pin,  $N_{\text{pins}}$  is the number of pins at each separation point,  $A_{\text{bh}}$  is the bulkhead area,  $L_{\text{sect}}$  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.

Table 21 shows a summary of the separation events, including the ejection charge sizes for the primary, secondary, and tertiary charges. The ejection charge sizes reported include a 1.25 factor of safety to ensure shearing of the nylon pins.

**Table 21:** 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	✓	591 ft	4.5
			545 ft	5
			500 ft	5
Fin Can Separation	SRM		520 ft	2
			510 ft	2.5
			500 ft	2.5

## 4.4 Recovery Devices

Two stages of parachutes will be used to slow the descent of the vehicle and ensure a safe landing. All of the parachutes will be tethered to the vehicle with a shock cord and quicklinks. The sizing of these components is described further in the following sections and in Sections 5.2 - 5.3.

### 4.4.1 Main Parachute Assembly

The main parachute is used during the final stage of the vehicle's descent to slow the separated vehicle sections to a safe kinetic energy of less than 75 ft-lbf (NASA 3.3). A minimum drag parameter  $C_d A$  can be obtained for sizing the main parachute using the section masses given in Table 22.

**Table 22:** 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

The value for  $(C_d A)_{\min}$  is given by

$$(C_d A)_{\min} = \frac{2m_{\text{tot}}g}{\rho \sqrt{\frac{2KE_{\max}}{m_{\max}}}} = 110.1 \text{ ft}^2$$

where  $m_{\text{tot}}$  is the total vehicle mass after burnout,  $KE_{\max}$  is the kinetic energy given by NASA Requirement 3.3, and  $m_{\max}$  is the mass of the heaviest section. This parameter was used to select appropriate parachutes for the trade study performed for PDR. The parachute selection was reexamined with the most updated mass estimates, and the selected parachute was still the best option when weighing cost, packing volume, and weight. The parameters of the main parachute are listed in Table 23. The parachute will be packed in a Nomex deployment bag during launch, which also serves as additional parachute protection from ejection gases and debris. The main parachute will be guided out of the deployment bag by a pilot parachute after the main separation event. The parameters of the pilot chute are also shown in Table 23.

**Table 23:** Main and Pilot Parachute Parameters

Parameter	Main	Pilot
Brand	Rocketman	FruityChutes
Shape	Parabolic	Classic Elliptical
Canopy Material	1.1 oz Ripstop Nylon	1.1 oz Ripstop Nylon
Shroud Lines Material	200 lb Nylon	220 lb Nylon
No. Shroud Lines	4	8
$C_d$	0.97	1.6
Diameter (ft)	12	2
Weight (oz)	17	2.2
Packing Volume (in <sup>3</sup> )	138.2	12.2

A recovery harness will be used to tether the main parachute to the launch vehicle. The specifications of this harness are shown in Table 24.

**Table 24:** Main Recovery Harness Parameters

Parameter	Value
Brand	Rocketman
Material	Braided Kevlar
Width (in)	0.200
Length (ft)	40
No. Loops	3
Breaking Strength (lbs)	2520
Weight (oz)	4.5

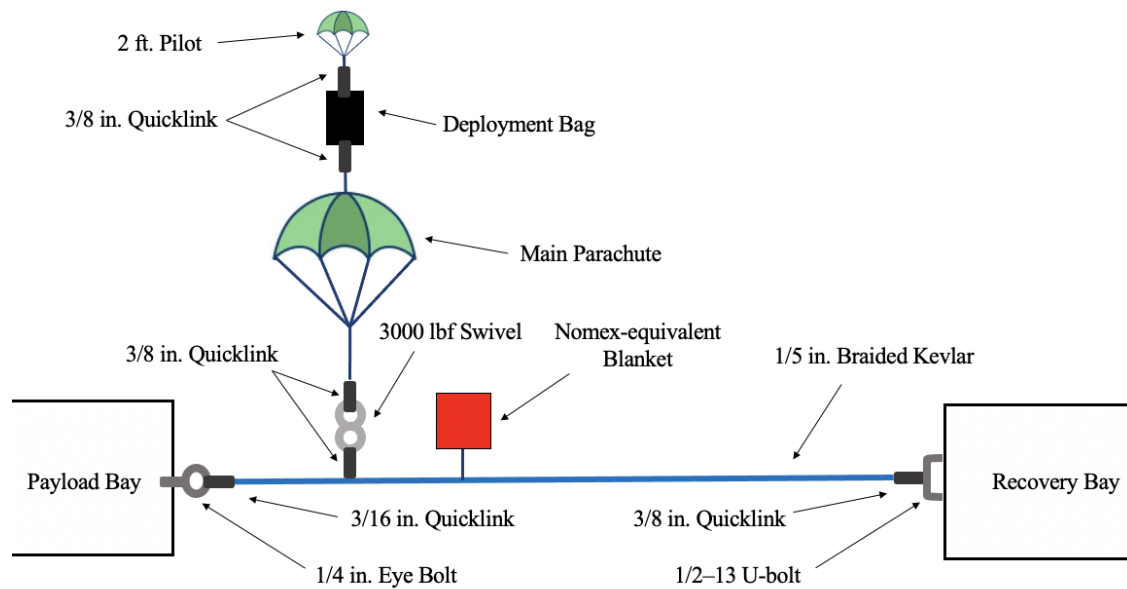


The recovery harness and parachutes will be wrapped in a Nomex blanket, satisfying NDRT Requirement R.2. The parameters of the parachute protector are listed in Table 25.

**Table 25:** Main Parachute Protector Parameters

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

The parachutes, deployment bag, parachute protector, and recovery harness will be attached using quicklinks of various sizes. Figure 28 shows the quicklink parameters and locations in the full parachute assembly.



**Figure 28:** Main Parachute Assembly

The structural verification of these components is detailed in Section 5.3.

#### 4.4.2 Drogue Parachute Assembly

The drogue parachute is used during the first stage of the vehicle’s descent to minimize high accelerations at main parachute deployment while also remaining within the descent time and drift requirements (NASA 3.10, NASA 3.11). Maximum values for the drogue parachute drag parameter can be obtained from these requirements, the terminal descent velocity under the main parachute, the main deployment altitude, and the expected apogee. The value for  $(C_d A)_{max}$  derived from both the descent time and drift radius requirements are

given by

$$\text{Descent Time : } (C_d A)_{\max} = \frac{2m_{\text{tot}}g}{\rho \left( \frac{h_{\text{apo}} - h_{\text{main}}}{t_{\text{max}} - \frac{h_{\text{main}}}{v_{\text{main}}}} \right)^2} = 6.31 \text{ ft}^2$$

$$\text{Drift Radius : } (C_d A)_{\max} = \frac{2m_{\text{tot}}g}{\rho \left( \frac{(h_{\text{apo}} - h_{\text{main}})v_{\text{wind}}}{d_{\text{max}} - v_{\text{wind}} \frac{h_{\text{main}}}{v_{\text{main}}}} \right)^2} = 5.32 \text{ ft}^2$$

$$(C_d A)_{\max} = 5.32 \text{ ft}^2$$

where  $m_{\text{tot}}$  is the total vehicle mass after burnout,  $h_{\text{apo}}$  is the expected apogee,  $h_{\text{main}}$  is the main deployment altitude,  $v_{\text{main}}$  is the terminal descent velocity under the main parachute,  $v_{\text{wind}}$  is the highest expected wind speed,  $t_{\text{max}}$  is the maximum allowed descent time given by NASA Requirement 3.11, and  $d_{\text{max}}$  is the maximum allowed drift radius given by NASA Requirement 3.10. No absolute minimum drag parameter could be determined for the drogue parachute since there is not a hard limit on the maximum acceleration or maximum load at main deployment. However, a soft force limitation was set at 1000 lbs to make sizing flight hardware easier. A soft limit for  $(C_d A)_{\min}$  was obtained from this limitation:

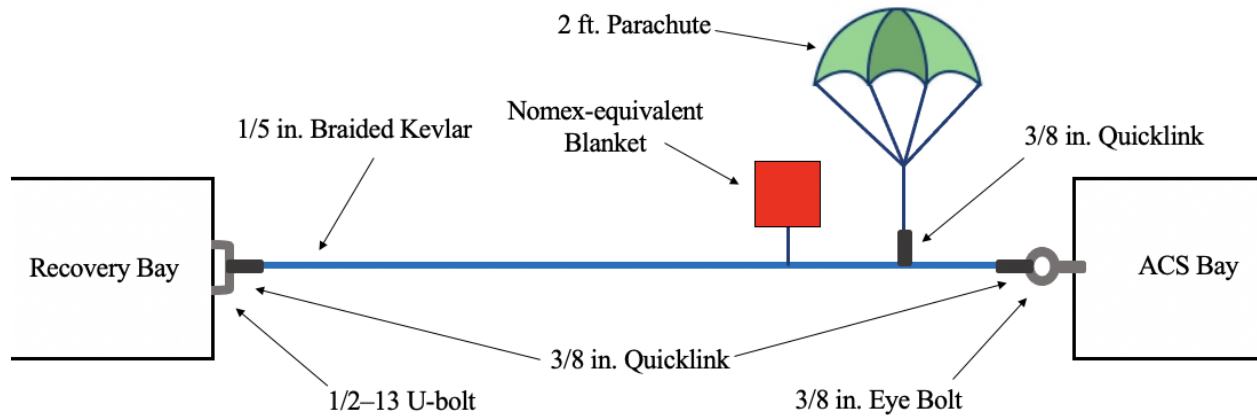
$$(C_d A)_{\min} = \frac{mg(C_d A)_{\text{main}}}{F_{\max}} = 4.61 \text{ ft}^2$$

where  $(C_d A)_{\text{main}}$  is the drag parameter for the main parachute and  $F_{\max}$  is the soft force limitation. These parameter were used to select appropriate parachutes and size a streamer for the trade study performed at the preliminary design stage. These selections were reexamined with the most updated mass estimates, weighing cost, packing volume, drag parameter, and weight at the critical design stage. The results of an experiment assessing the drift reducing properties of the streamer showed that the streamer did not provide any discernible reduction in drift, and thus the "drift reduction" weight was removed from the trade study. The details of this experiment can be found in Appendix A, and the parameters of the selected drogue parachute are listed in Table 26.

**Table 26:** Drogue Parachute Parameters

Parameter	Value
Brand	Rocketman
Shape	Elliptical
Canopy Material	1.1 oz Ripstop Nylon
Shroud Lines Material	250 lb Nylon
No. Shroud Lines	8
$C_d$	1.6
Diameter (ft)	2
Weight (oz)	2.1
Packing Volume (in <sup>3</sup> )	12.16

A recovery harness will be used to tether the drogue parachute to the launch vehicle. The specifications of this harness are shown in Table 27.



**Figure 29:** Drogue Parachute Assembly

**Table 27:** Drogue Recovery Harness Parameters

Parameter	Value
Brand	Rocketman
Material	Braided Kevlar
Width (in)	0.200
Length (ft)	20
No. Loops	3
Breaking Strength (lbs)	2520
Weight (oz)	2.26

The recovery harness and parachutes will be wrapped in a Nomex-equivalent flame-retardant blanket, satisfying NDRT Requirement R.2. This method of parachute protection was chosen for the low weight and cost, simplicity, and effectiveness. The parameters of the parachute protector are listed in Table 28.

**Table 28:** Drogue Parachute Protector Parameters

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

The parachutes, parachute protector, and recovery harness will be attached using quicklinks of various sizes. Figure 29 shows the quicklink parameters and locations in the full parachute assembly. The structural verification of these components is detailed in Section 5.3.

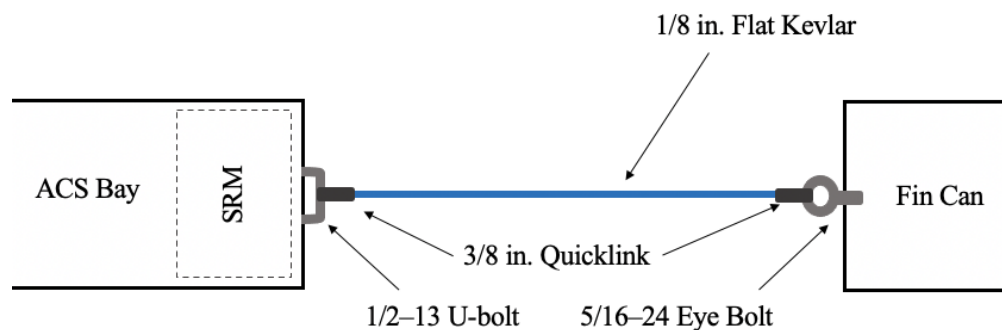
#### 4.4.3 Fin Can Separation Assembly

A recovery harness will keep the fin can and the ACS bay tethered together after separation at 400 ft AGL. No parachute will be deployed during this separation event. Table 29 lists the specifications for the chosen Rocketman Braided Kevlar Recovery Y-Harness.

**Table 29:** Fin Can Recovery Harness Parameters

Parameter	Value
Brand	OneBadHawk
Material	Kevlar
Width (in)	3/8"
Length (ft)	15
No. Loops	2
Breaking Strength (lbs)	1800

The recovery harness will be attached to the vehicle on either end with quicklinks. Figure 30 shows the details of the recovery hardware for the fin can harness assembly. The structural verification of each component is assessed in Section 5.3.

**Figure 30:** Fin Can Harness Assembly

## 4.5 Primary and Secondary Recovery Modules

The parachute assemblies will be tethered to the airframe via the recovery modules, the PRM, and the SRM. The PRM serves as the structural interface for both the main and drogue parachute assemblies to the launch vehicle as well as the housing for the corresponding altimeters and energetics for those separation and deployment events. The SRM provides the same function for the fin can separation event. Both recovery modules share the same basic architecture featuring two carbon-fiber bulkheads which enclose an altimeter mounting sled, switch board assembly, and minimally load bearing aluminum standoffs. The fore bulkhead of the SRM does not house any structural elements or charge wells since it only initiates one separation event on the aft side.

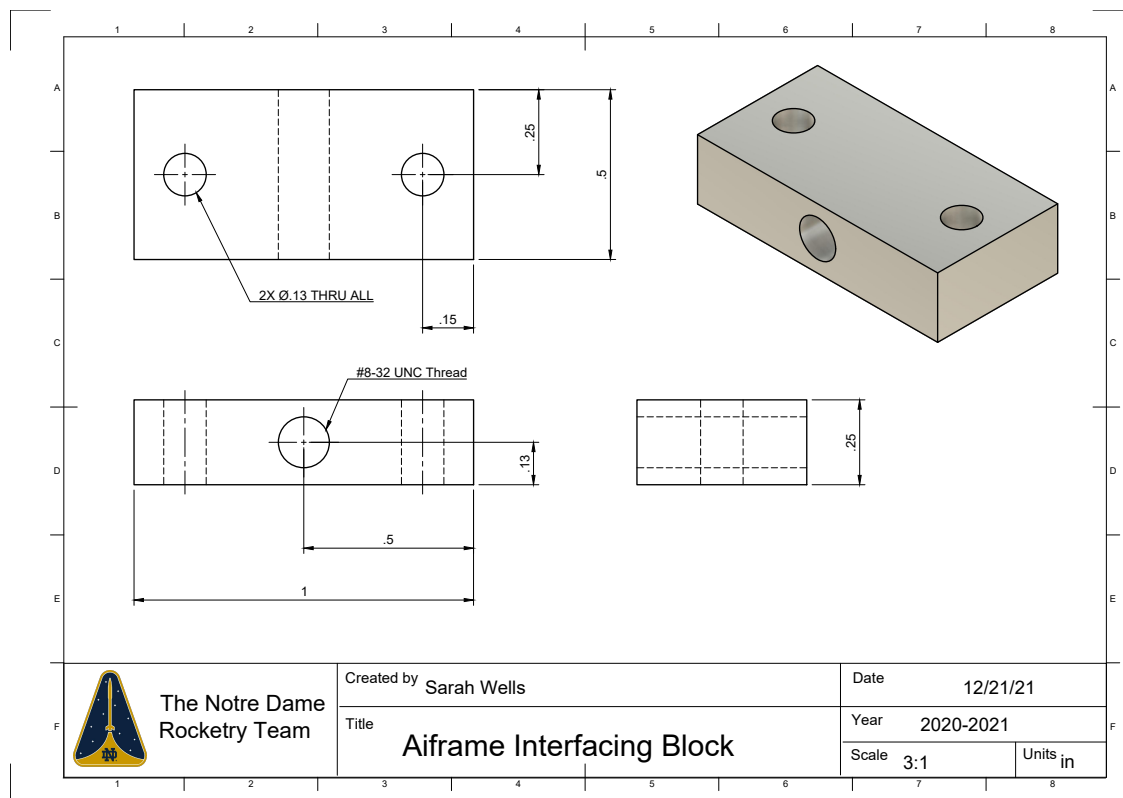
### 4.5.1 Primary Structural Elements

The primary load path of the drag force from the parachutes travels through the parachute and harness assemblies to the recovery module via 1/2"-13 U-bolts. The U-bolts will be affixed to 1/8" carbon fiber bulkheads with washers and lock-nuts. The properties of the U-bolt are shown in Table 30.

**Table 30:** U-bolt Parameters

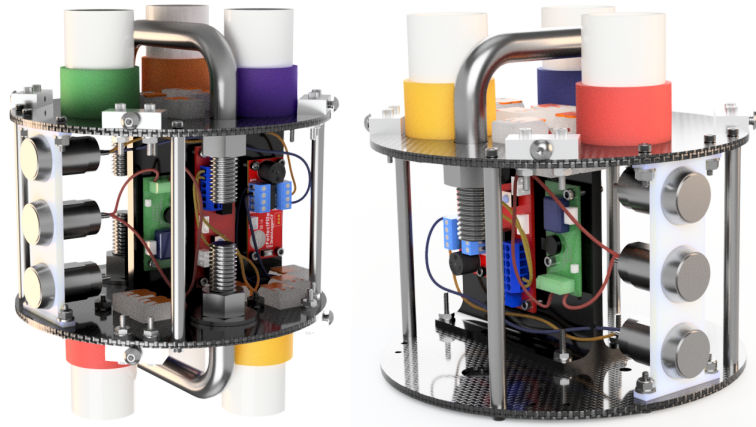
Parameter	Value
Brand	McMaster Carr
Material	Zinc Plated Steel
Thread	1/2"-13
Breaking Strength (lbs)	2000

The bulkhead material was changed from Garolite G-10 to carbon-fiber due to its RF shielding properties. The launch vehicle airframe is constructed from carbon-fiber, meaning that choosing carbon-fiber for the bulkhead material allowed for complete RF blockage of the recovery module's interior. This simplified possible shielding designs for the altimeters. A trade study was conducted with carbon-fiber and Garolite-G10, weighing the simplicity and ease of manufacturing and assembly of the carbon-fiber bulkhead design against the lower cost of the Garolite-G10 bulkhead configuration. The carbon-fiber bulkhead design ultimately won the trade study and was selected as the bulkhead material. The bulkhead thickness for both the SRM and PRM was determined using FEA, which is further detailed in Section 5.3. The load passes through the bulkhead to four airframe interfacing block, pictured in Figure 31. These blocks will be machined from 6061 Aluminum (NASA 2.23.10).



**Figure 31:** Airframe Interfacing Blocks

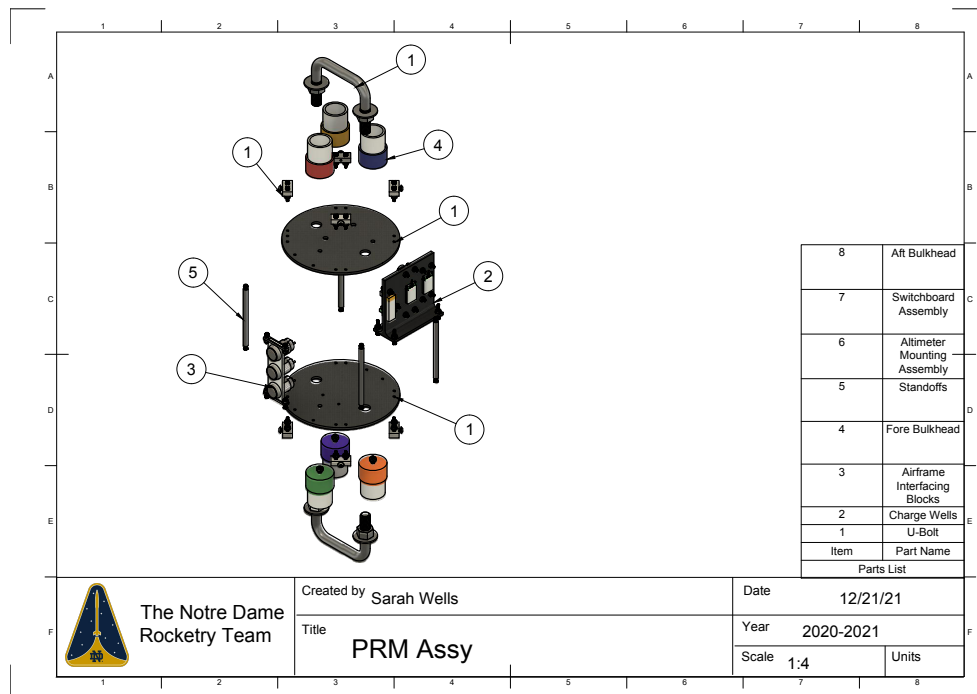
The airframe interfacing blocks are affixed to the bulkhead with a set of two 4-40 screws and to the airframe with 8-32 screws. The integration of the PRM and SRM modules are shown in Figures 32, 33, and 34. The structural verification of each of these components is detailed in Section 5.3.



(a) PRM

(b) SRM

**Figure 32: Recovery Module Assemblies**



**Figure 33: PRM Exploded View**

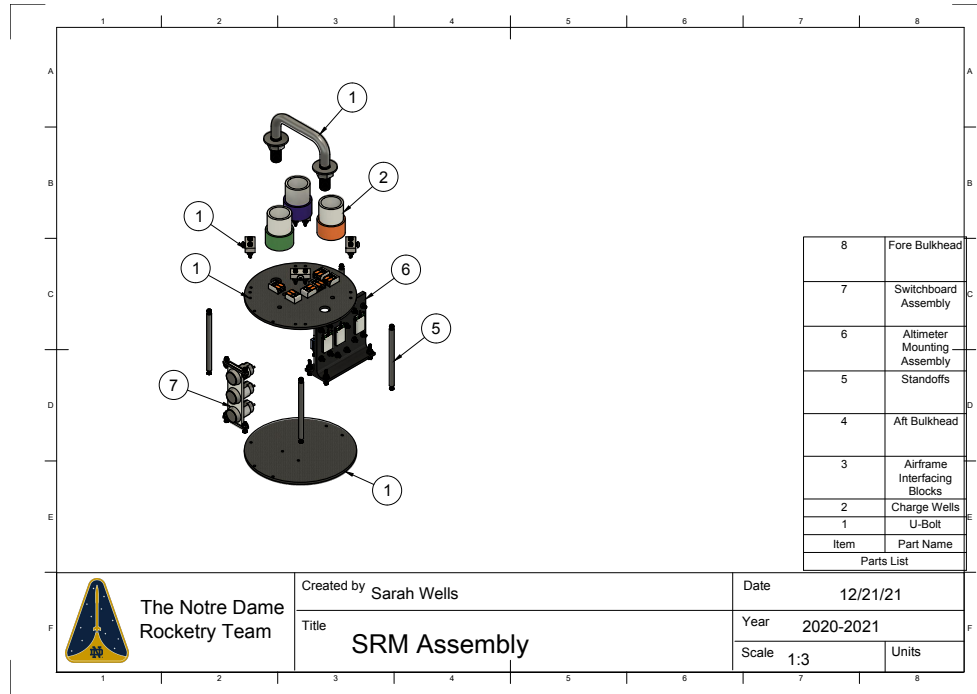
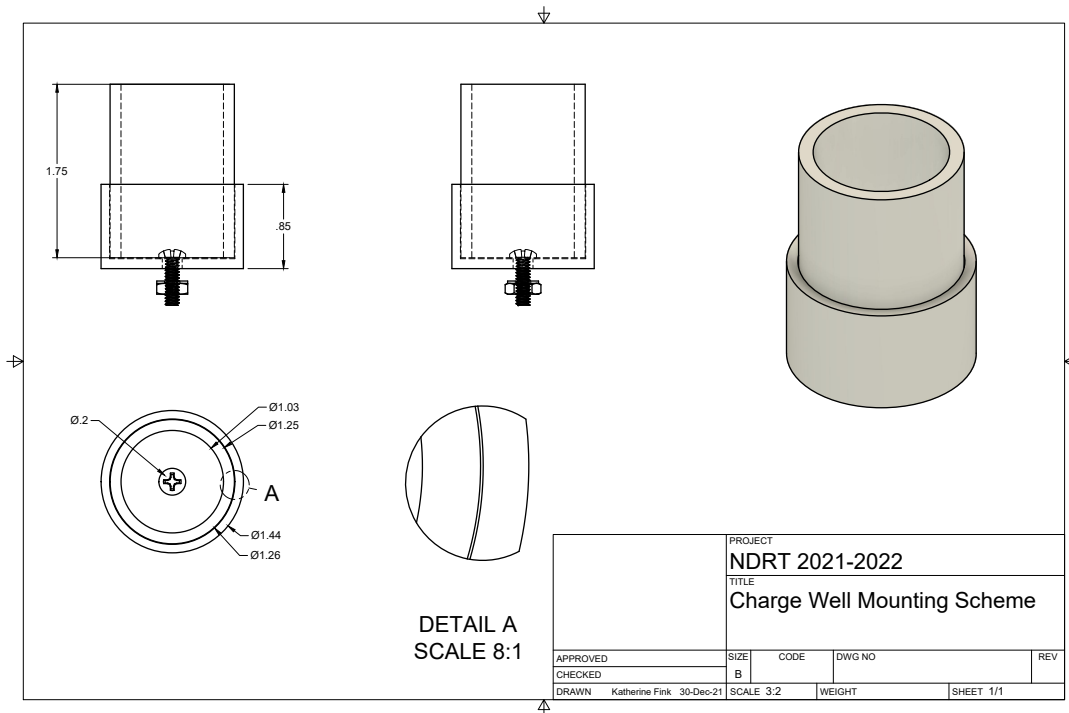


Figure 34: SRM Exploded View

#### 4.5.2 Secondary Structures

The PRM and SRM are also comprised of various minimally load bearing components in addition to the primary structural elements described in Section 4.5.1. Charge well assemblies, shown in Figure 35, will be mounted on the outer faces of the three bulkheads at the separation points to house the energetics. The PRM will house six charge wells and the SRM will house three to accommodate for the single separation event. The charge wells will be connected to the bulkhead using 3D printed end caps bolted directly into the bulkhead and fixed in place with washers and nuts. The PVC charge wells will be connected to the 3D printed end caps using JB Weld epoxy. In past years, the PVC charge wells were attached directly to the bulkhead using epoxy. This connection often failed with the charge wells and epoxy popping loose during the ejection event. Using end caps with JB Weld epoxy allows for more surface area on which the epoxy can act which will maintain the connection during the separation event. Furthermore, JB Weld epoxy has a high temperature rating and will maintain its strength during the high temperatures at separation (R.5).



**Figure 35: Charge Well Assembly**

Three minimally load bearing aluminum standoffs will be used to connect the bulkheads and enclose the altimeter mounting board and switchboard. Both the altimeter mounting board and switchboard will be 3D printed with ABS plastic. Both boards will have a flanged base attached to the aft bulkhead with screws. The top of the altimeter mounting board facing the fore bulkhead is free while the top of the switchboard will be stabilized with a mounting jib that is screwed into the fore bulkhead. The switches are much heavier than the altimeters and will require extra structural support for stabilization. All attachments to the bulkheads will be with 4-40 machine screws. In past years, epoxy was used to connect structural jigs and mounting boards to the bulkheads but this attachment method was difficult to manufacture and assemble. The use of standardized screws for all connections allows for a simple assembly and disassembly of both recovery modules. The altimeter mounting board and switchboard are shown in Figures 36 and 37 respectively. All electrical component details can be found in Section 4.6.



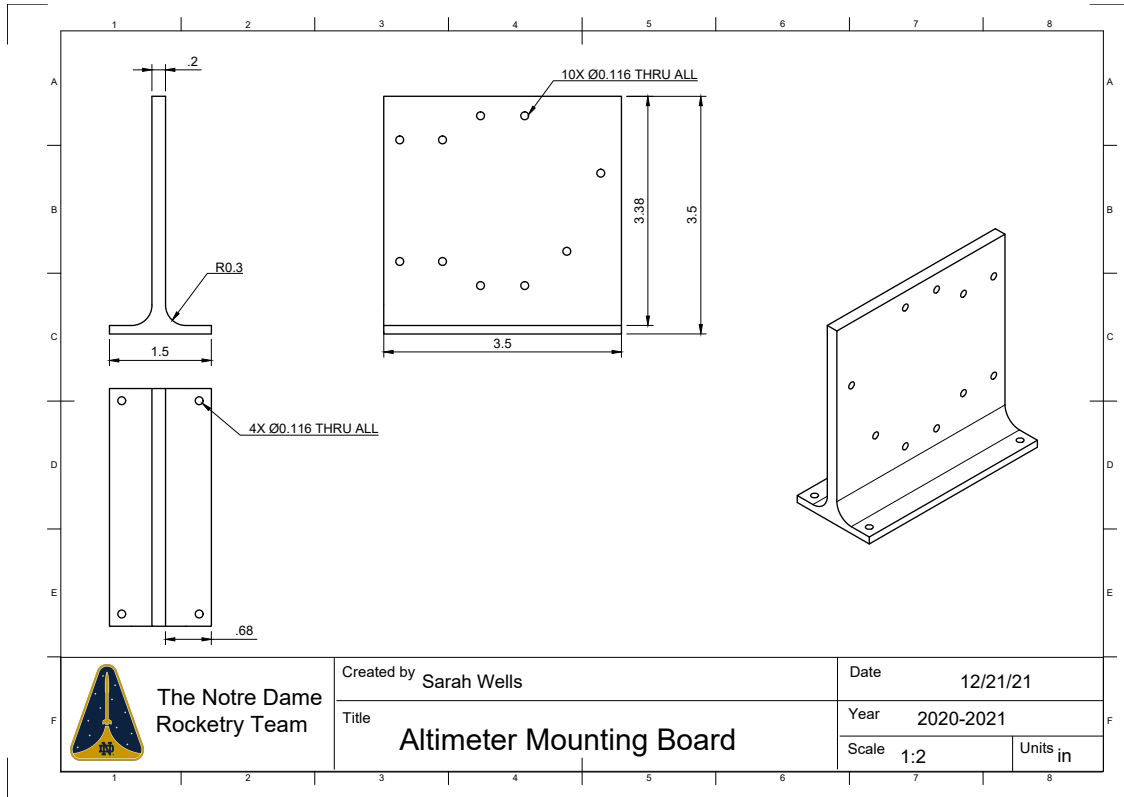


Figure 36: Altimeter Mounting Board

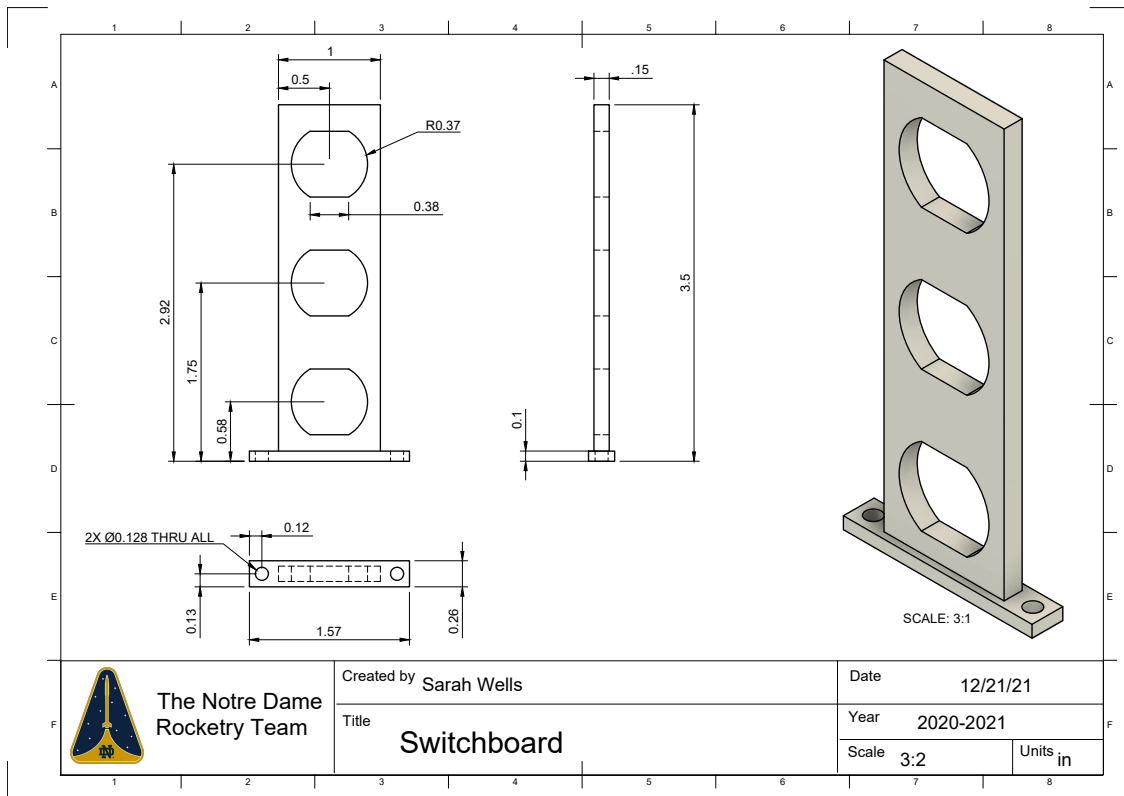


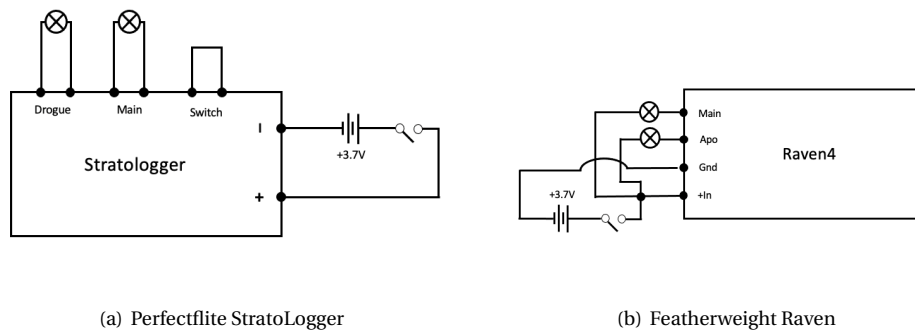
Figure 37: Switchboard

## 4.6 Electronics

The avionics of the recovery system are housed entirely between the bulkheads of the PRM and the SRM, aside from the ejection charges. The recovery circuitry is thus completely independent of the payload electronics (NASA 3.8). Each electrical component will also be able to operate during standard day conditions between 0 and 100°F (NDRT R.3). The electrical design of the recovery system is detailed in the following sections.

### 4.6.1 Altimeters

The recovery system uses a total of six commercially available altimeters between the two recovery modules, with three altimeters in each module. The use of three altimeters ensures an independently redundant system to maximize safety (NASA 3.4, R.6). Five of the altimeters, the Featherweight Raven4, two Stratologger SL100s, and two Stratologger CFs, were in the team's inventory and were selected due to their reliability and low cost. One Stratologger CF was selected as a new altimeter due to its low cost, compact size, and minimized weight. The system has even greater redundancy by using dissimilar altimeters for each separation event (NDRT R.6). Each of the altimeters will be wired to a dedicated switch, battery, e-match using direct electrical connections (NASA 3.5). The electrical schematics for the altimeters are shown in Figure 38. The charge wells and wires on the PRM and SRM will be color coordinated so that the correct wires will be connected to the right altimeters and charge wells, which will remove confusion and ease assembly on launch day. The properties of each selected altimeter are listed in Table 31.



**Figure 38:** Recovery Electrical Schematics

**Table 31:** 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

The altimeters housed within the SRM and PRM will be mounted on altimeter mounting boards by means of size 4-40 standoffs, 3 mm thick. These standoffs ensure that the altimeters are not pressed directly against the mounting board. The altimeters will also be protected from any on-board electronic devices that may adversely affect it during flight (NASA 3.13). The recovery altimeters are located in a physical compartment from all RF

transmitting and wave producing devices (NASA 3.13.1). The altimeters will also be shielded from electromagnetic interference by the carbon-fiber bulkheads and airframe which block RF radiation and magnetic waves (NASA 3.13.2), NASA 3.13.3, NASA 3.13.4).

The Stratologger CF and Stratologger SL100 altimeters will be powered by Tattu 1S Lithium Polymer batteries with specifications in Table 32 (NASA 3.5). The Featherweight Raven4 will be powered by an E-Flite 1S Lithium Polymer battery with specifications also in Table 32. The current consumption of each altimeter can be found in Table 31. The battery was chosen to satisfy the battery requirements listed in the altimeter manuals and due to its low cost and weight. The battery life was calculated using

$$\text{Battery Life} = \frac{C}{c_{Avg}} \quad (4)$$

where the battery life is calculated in hours,  $C$  is the capacity of the battery in mAh and  $c_{Avg}$  is the average current consumption of the altimeter in mA. It was determined that the battery life for the chosen battery connected to the Stratologger altimeters was 9.72 days and 30 hours for the battery connected to the Raven, validating the battery choice and satisfying NASA 2.7. Batteries will also be brightly colored and marked as dangerous and protected, satisfying NASA 2.22.

**Table 32:** 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

#### 4.6.2 GPS

A GPS transmitter will be mounted on the bulkhead separating the payload and recovery bays to verify the results of the payload mission and to fulfill NASA 3.12. Mounting will be further discussed in Section 6.4. The Featherweight GPS Tracker was chosen due to its accuracy and reliability as well as its ease of use. The GPS connects to an iPhone which shows real time altitude and data location, allowing for ease of data collection during and after flight. The GPS will be fully functional on launch day and be able to accurately track the location of the landed launch vehicle (NASA 3.12.1, NASA 3.12.2). The GPS will also be tested as described in RT.4 to verify its accuracy.

The GPS tracker will be powered by a 1S Lithium Polymer battery with specifications shown in Table 33 (NASA 3.5). The battery was chosen to fulfill the current and voltage requirements listed in the GPS manual which are a recommended voltage range of 3.4V to 4.5V and at least a 150 mAh capacity. The battery must also be able to accommodate the GPS tracker which consumes 50 mA when not transmitting and 90 mA when transmitting. The battery will power the GPS tracker for five hours of continual use according to the Featherweight GPS Tracker Manual, validating the battery choice for the GPS tracker and NASA 2.7.

**Table 33:** Lithium Polymer 1S Battery Specifications

Battery Parameters	Value
Capacity (mAh)	400
Voltage (V)	3.7
Constant Discharge Rate (C)	25

### 4.6.3 Other Electronics

The altimeters in both the SRM and PRM will be armed on the launch pad using keyed rotary switches (NASA 3.6). The keyed rotary switches were chosen as the arming mechanism due to their simplicity, rigidity, and clarity of state. The switches will be placed on the same side of the launch vehicle's exterior to ensure an easy and expedited arming procedure on launch day. The switch mounting mechanism is discussed further in Section 4.5. The keyed rotary switches are also low profile and have proven to remain unaffected by in-flight forces with past launches (NASA 3.7).

## 4.7 Mass Statement

The components are listed with their respective masses in Table 34 for the PRM, and 35 for the SRM. Moreover, the component maturity and type, the basic mass estimate and mass growth allowance percentage for each component, the total system basic mass, and the total system predicted mass are listed.

**Table 34:** Recovery (PRM) Mass Breakdown

Component Name	Maturity	Component Type	Basic Mass Estimate	MGA %	Predicted Mass
Main Parachute	5	PRIM	22.65	2	23.103
Main Recovery Harness	2	PRIM	8.25	15	9.4875
Main Quicklinks	5	PRIM	12.9	2	13.158
Main Deployment Bag	5	SEC	4	3	4.12
Main Pilot Chute	5	SEC	2.1	3	2.163
Main Parachute Protector	5	PRIM	4.6	2	4.692
Drogue Parachute	3	PRIM	2.1	10	2.31
Drogue Recovery Harness	2	PRIM	8.25	15	9.4875
Drogue Quicklinks	5	PRIM	2.2	2	2.244
Drogue Parachute Protector	5	PRIM	1	2	1.02
Bulkhead	3	PRIM	5.52	10	6.07
Airframe Interfacing Block	4	PRIM	1.555456	4	1.61767424
AIB 4-40 Screws	5	SEC	0.585728	3	0.60329984
AIB 4-40 Washers	5	SEC	0.219648	3	0.22623744
AIB 4-40 Locknuts	4	SEC	0.292864	6	0.31043584
AIB 8-32 Screws	5	PRIM	0.439296	2	0.44808192
1/2-13 U-bolt	4	PRIM	14.25792	4	14.8282368

**Table 34:** LVIS Mass Breakdown (continued)

Component Name	Maturity	Component Type	Basic Mass Estimate	MGA %	Predicted Mass
U-bolt 1/2-13 Washers	4	PRIM	1.391104	4	1.44674816
U-bolt 1/2-13 Locknuts	4	PRIM	2.324608	4	2.41759232
Charge Well	4	SEC	0.211446	6	0.22413276
Charge Well End Cap	4	SEC	1.592574	6	1.68812844
CW 4-40 Screw	5	SEC	0.219648	3	0.22623744
CW 4-40 Washer	5	SEC	0.082368	3	0.08483904
CW 4-40 Locknut	4	SEC	0.109824	6	0.11641344
WAGO Connectors	5	ELEC	2.5392	3	2.615376
3.5" 4-40 Standoff	4	SEC	3.075072	6	3.25957632
Standoff 4-40 Screws	5	SEC	0.219648	3	0.22623744
Altimeter Mountng Board	4	SEC	1.917464	6	2.03251184
4-40 Mounting Screw	5	SEC	0.512512	3	0.52788736
4-40 Mounting Washer	5	SEC	0.192192	3	0.19795776
4-40 Mounting Locknut	4	SEC	0.256256	6	0.27163136
PCB 4-40 Standoff	4	SEC	0.00613	6	0.0064978
Stratologger SL100	5	SENS	0.45	2	0.459
Stratologger CF	5	SENS	0.38	2	0.3876
Raven4	5	SENS	0.2328	2	0.237456
2S Lipo	5	BAT	2.186	2	2.22972
1s 165mAh Lipo	5	BAT	0.0987	2	0.100674
Keyed Switch	5	ELEC	4.8	3	4.944
Mounting Board	4	SEC	0.218228	6	0.23132168
Mounting Jig	4	SEC	0.023294	6	0.02469164
4-40 Screws	5	SEC	0.146432	3	0.15082496
4-40 Washers	5	SEC	0.054912	3	0.05655936
4-40 Locknuts	4	SEC	0.073216	6	0.07760896
Black Powder	1	PRIM	1.06	22	1.2932
Ematches	5	ELEC	0.01	3	0.0103
Wiring	1	WIRE	0.05	75	0.0875
Epoxy	1	SEC	0.5	28	0.64

**Table 34:** LVIS Mass Breakdown (continued)

Component Name	Maturity	Component Type	Basic Mass Estimate	MGA %	Predicted Mass
Clay	1	SEC	0.2	28	0.256
<b>Total</b>			<b>116.05134</b>		<b>122.4156702</b>

**Table 35:** Recovery (SRM) Mass Breakdown

Component Name	Maturity	Component Type	Basic Mass Estimate	MGA %	Predicted Mass
Recovery Harness	2	PRIM	8.25	15	9.4875
Quicklinks	2	PRIM	5.16	15	5.93
Parachute Protector	5	PRIM	1.00	2	1.02
Bulkhead	3	PRIM	5.52	10	6.07
Airframe Interfacing Block	4	PRIM	0.78	4	0.81
AIB 4-40 Screws	5	SEC	0.29	3	0.30
AIB 4-40 Washers	5	SEC	0.11	3	0.11
AIB 4-40 Locknuts	4	SEC	0.15	6	0.16
AIB 8-32 Screws	5	PRIM	0.22	2	0.22
1/2-13 U-bolt	4	PRIM	7.13	4	7.41
U-bolt 1/2-13 Washers	4	PRIM	0.70	4	0.72
U-bolt 1/2-13 Locknuts	4	PRIM	1.16	4	1.21
Charge Well	4	SEC	0.11	6	0.11
Charge Well End Cap	4	SEC	0.80	6	0.84
CW 4-40 Screw	5	SEC	0.11	3	0.11
CW 4-40 Washer	5	SEC	0.04	3	0.04
CW 4-40 Locknut	4	SEC	0.05	6	0.06
WAGO Connectors	5	SEC	1.27	3	1.31
3.5" 4-40 Standoff	4	SEC	3.08	6	3.26
Standoff 4-40 Screws	5	SEC	0.22	3	0.23
Altimeter Mountng Board	4	SEC	1.92	6	2.03
4-40 Mounting Screw	5	SEC	0.512512	3	0.52788736
4-40 Mounting Washer	5	SEC	0.192192	3	0.19795776

**Table 35:** LVIS Mass Breakdown (continued)

Component Name	Maturity	Component Type	Basic Mass Estimate	MGA %	Predicted Mass
4-40 Mounting Locknut	4	SEC	0.256256	6	0.27163136
PCB 4-40 Standoff	4	SEC	0.00613	6	0.0064978
Stratologger SL100	5	SENS	0.45	2	0.459
Stratologger CF	5	SENS	0.38	2	0.3876
Raven4	5	SENS	0.2328	2	0.237456
2S Lipo	5	BAT	2.186	2	2.22972
1s 165mAh Lipo	5	BAT	0.0987	2	0.100674
Keyed Switch	5	ELEC	4.8	3	4.944
Mounting Board	4	SEC	0.218228	6	0.23132168
Mounting Jig	4	SEC	0.02	6	0.02
4-40 Screws	5	SEC	0.15	3	0.15
4-40 Washers	5	SEC	0.05	3	0.06
4-40 Locknuts	4	SEC	0.07	6	0.08
Black Powder	1	PRIM	0.27	22	0.32
Ematches	5	ELEC	0.01	3	0.01
Wiring	1	WIRE	0.05	75	0.09
Epoxy	1	SEC	0.50	28	0.64
Clay	1	SEC	0.10	28	0.13
<b>Total</b>			<b>48.60</b>		<b>52.54</b>

## 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.

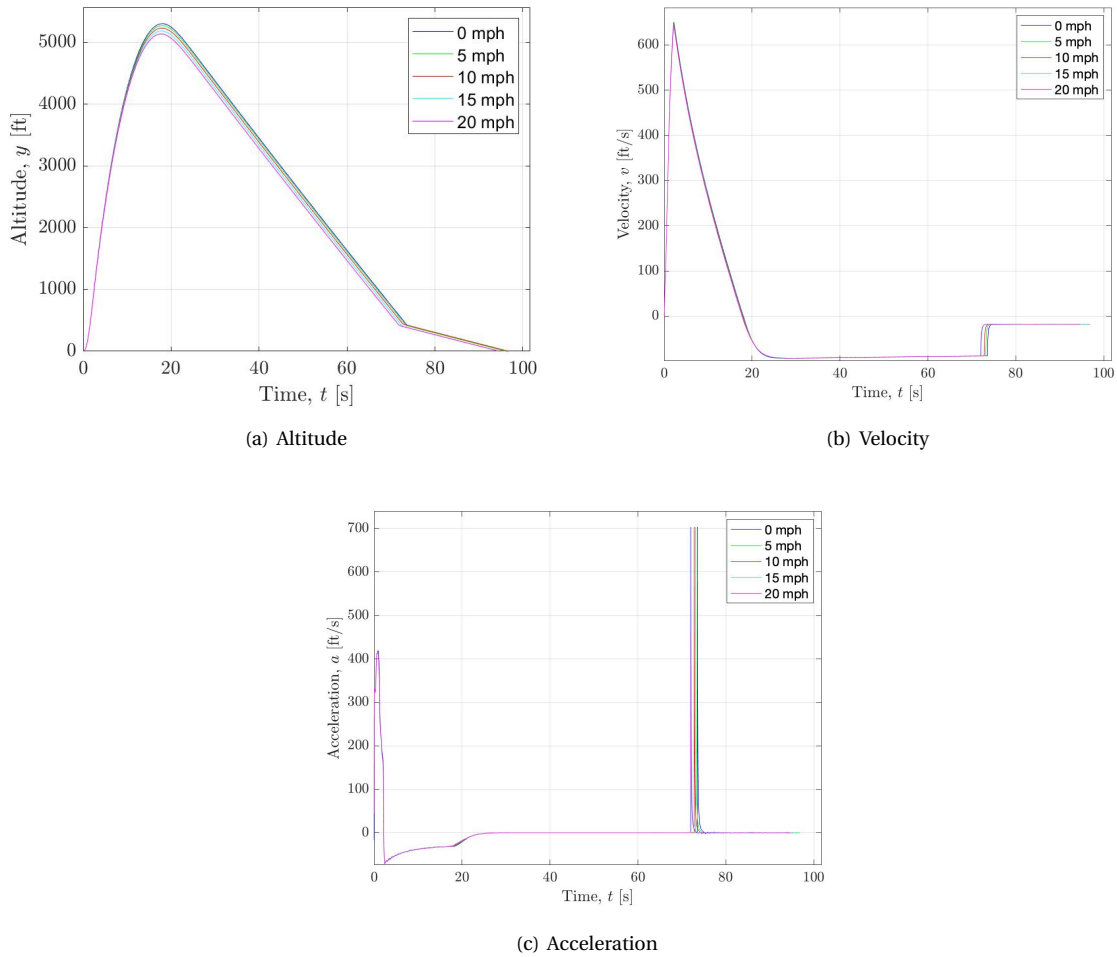
### 5.1.1 Simulation Results

The team conducted a series of flight simulations using detailed vehicle models in OpenRocket to predict a range of flight profiles within the possible launch rail cant angles of 5 - 10° and wind speeds of 0 - 20 mph. The results of those simulations are provided in Table 36, Table 37, and Table 38, which include the velocity off the rod (ft/s), apogee altitude (ft), max velocity (ft/s), and max acceleration (ft/s<sup>2</sup>) of the launch vehicle for varying wind speeds. All predicted apogees are above the NDRT target apogee of 4800, fulfilling IV.1. The accompanying flight profiles for the three tables above are provided in Figure 39, Figure 40, and Figure 41.

**Table 36:** 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 <sup>2</sup> )
0	89.2	5304	653	421
5	89.8	5270	653	420
10	89.8	5230	652	420
15	89.8	5196	652	420
20	89.8	5143	651	420

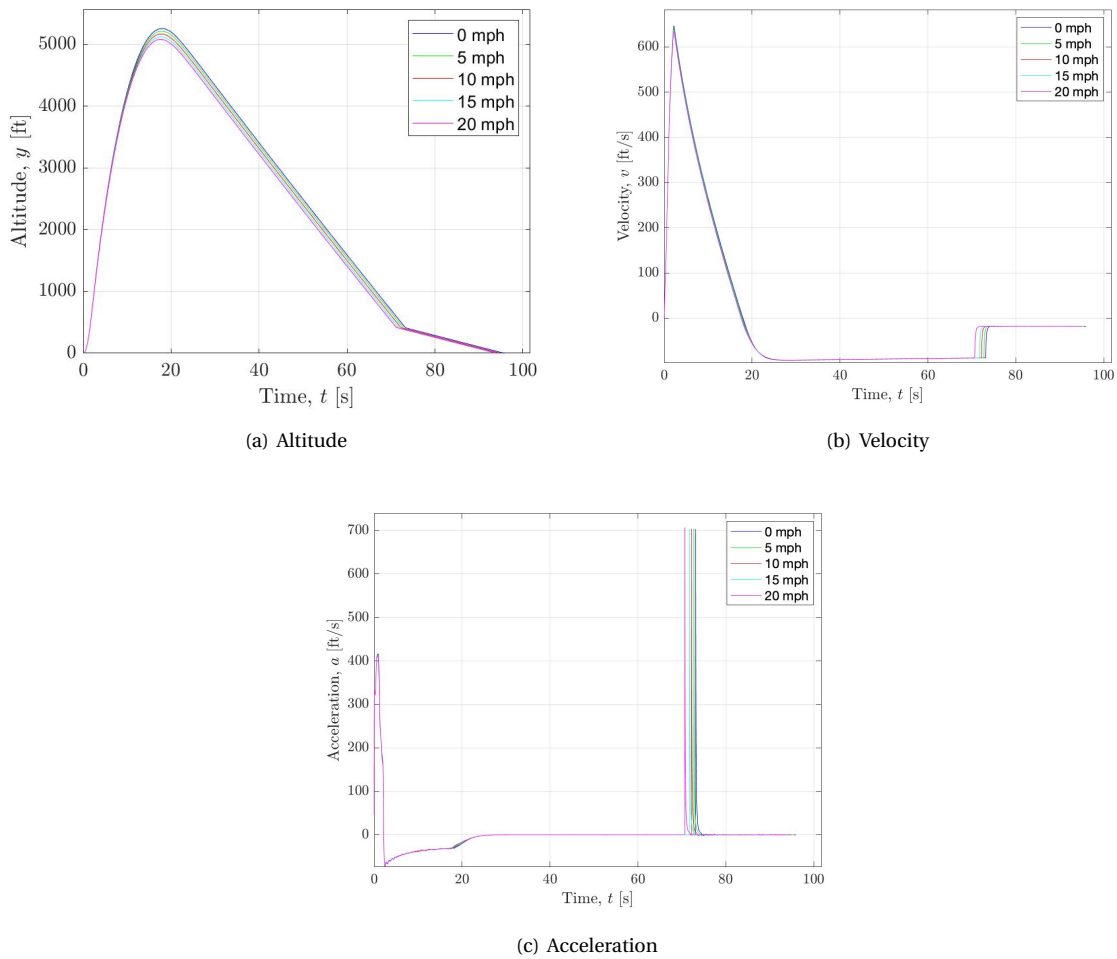




**Figure 39:** Flight Profiles from OpenRocket Simulations for Launch Angle of 5°

**Table 37:** OpenRocket Simulation Critical Values for Launch Angle of 7°

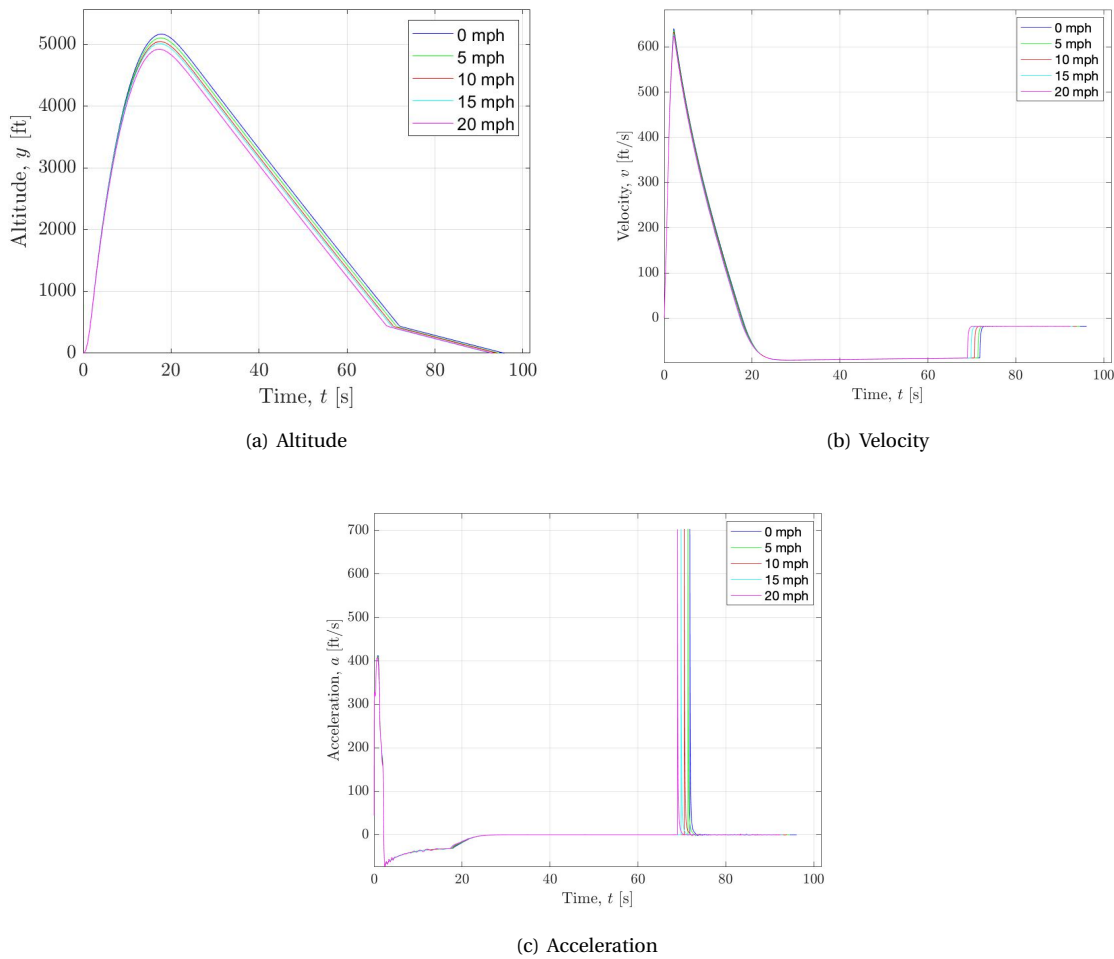
Average Wind Speed (mph)	Velocity off Rod (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s <sup>2</sup> )
0	89.8	5258	653	420
5	89.8	5214	653	420
10	89.8	5161	652	420
15	89.8	5109	652	421
20	89.8	5051	651	421



**Figure 40:** Flight Profiles from OpenRocket Simulations for Launch Angle of 7°

**Table 38:** 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 <sup>2</sup> )
0	89.9	5167	654	420
5	89.9	5110	654	420
10	89.9	5058	653	421
15	89.9	4984	652	421
20	89.9	4939	651	421



**Figure 41:** Flight Profiles from OpenRocket Simulations for Launch Angle of 10°

A model of the launch vehicle was also generated in RockSim, and the same setup conditions were applied to cross-verify the validity of the OpenRocket simulations provided above. The results of the RockSim simulations are provided in Table 39, Table 40, and 41.

**Table 39:** 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 <sup>2</sup> )
0	88.87	5748	661.8	423.5
5	88.87	5771	661.6	423.4
10	88.87	5783	661.24	423.4
15	88.87	5785	660.7	423.4
20	88.87	5779	660.1	423.5

**Table 40:** 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 <sup>2</sup> )
0	88.87	5700	662.0	423.7
5	88.87	5733	661.8	423.5
10	88.87	5756	661.4	423.4
15	88.87	5768	660.9	423.4
20	88.87	5772	660.2	423.4

**Table 41:** 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 <sup>2</sup> )
0	89.19	5599	662.6	424.0
5	89.19	5648	662.3	423.7
10	89.19	5686	661.8	423.5
15	89.19	5713	661.2	423.4
20	89.19	5730	660.5	423.4

The RockSim model overestimates the apogee compared to OpenRocket, similarly to the PDR simulation findings. The OpenRocket simulation results are used as the primary source of simulation data based on the results from the subscale flight analysis and simulation. Full-scale vehicle flight data will be used to further assess the accuracy of each simulation method. The maximum Mach number achieved by the launch vehicle throughout all simulations is 0.57, fulfilling [NASA 2.23.6](#).

### 5.1.2 Target Apogee

The target apogee, as set in the PDR, is 4800 ft ([NASA 2.2](#)). The worst case apogee scenario is that the vehicle is on a trajectory to an apogee less than the target apogee such that the ACS system is completely unable to affect apogee. For this reason, the OpenRocket simulations were considered acceptable at a range of 5304 to 4924 feet for the allowable launch angles and wind speeds which will allow the ACS to activate and reduce the apogee to the target ([NASA 2.1](#)). The amount of ballast in the full configuration will be varied according to launch conditions to give ensure that the predicted trajectory apogee can be reduced to the target apogee within the capabilities of the ACS. This amount of ballast will not exceed 10% of the total unballasted weight of the rocket ([NASA 2.23.7](#)). The full-scale test flight will be flown in the fully ballasted configuration such that the team is able to use any range of ballast less than this limit. ([NASA 2.19.1.6](#)). The performance of the launch vehicle and recovery system will be verified with the mission performance predictions after the full-scale demonstration flight ([NASA 2.19.1.2](#)). Because the ballast can be configured, the team is confident that motor selection will not have to be reconsidered after the CDR deadline ([NASA 2.10.2](#)).

### 5.1.3 Stability

A stability margin value of 2.75 was chosen based on literature values for pencil-like rockets, with this stability value being desirable for rockets with a large length to diameter ratio. The launch vehicle has a height to diameter ratio of 21.7:1.

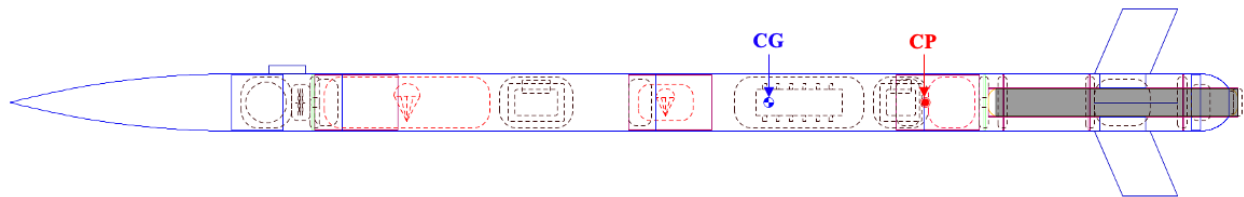
The static stability measured in the OpenRocket and Rocksim models was 2.75 calibers. The center of pressure (CP) is 99.1 in. aft of the tip of the nose cone, and the center of gravity (CG) is 82.2 in. aft of the tip of the nose cone, as simulated in OpenRocket. These locations are labelled on the diagram in Figure 42. The static stability is calculated using the following equation:

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

where  $S$  is the static stability,  $C_P$  is the distance from the tip of the nose cone to the center of pressure,  $C_G$  is the distance between the tip of the nose cone to the center of gravity, and  $D_{outer}$  is the outer diameter of the launch vehicle. The outer diameter used in this calculation is 6.17 in. The off-rail stability as measured by OpenRocket was 2.79 calibers, with an off-rail velocity of 89.8 ft/s (NASA 2.14). Throughout flight, the motor burn will move the CG forward thus increasing stability. Additionally, the hinge point for the ACS flaps is located 2.25 inches aft of the burnout CG (NASA 2.16). This ensures that the deployment of ACS flaps will not decrease stability during flight. A summary of the important stability parameters is included below in Table 42.

**Table 42:** Summary of Important Stability Parameters

CG location (in.)	CP location (in.)	Static stability margin (cal.)	Off-rail stability (cal.)	Off-rail velocity (ft/s)
82.2	99.1	2.75	2.79	89.8



**Figure 42:** Vehicle Diagram with CP and CG Locations

## 5.2 Flight Descent Analysis

The vehicle descent is modeled using OpenRocket and hand calculations in a MATLAB script `simplifiedescent.m`. The OpenRocket flight simulator was described in detail in Section 5.1. The MATLAB script, printed in Appendix B, estimates the kinetic energy at landing, descent time, and drift radius at main deployment from the following input parameters:

- parachute dimensions and drag coefficients
- apogee (using the highest predicted from OpenRocket)
- deployment altitude of main parachute
- the weight of each section of the rocket
- wind velocity (using the maximum of 20mph)

The hand calculations considerably simplify the in-flight dynamics by making several assumptions:

- instantaneous parachute opening and velocity change
- no variation in wind speed or direction with altitude or position
- apogee is reached directly above the launch pad
- shock cords are rigid
- the drogue parachute contributes to the main descent

The hand calculations use the parachute parameters and vehicle mass to determine descent rates:

$$\text{Main Descent: } v_{\text{main}} = \sqrt{\frac{2m_{\text{tot}}g}{\rho(C_d A)_{\text{main}}}} = 18.4 \text{ ft/s}$$

$$\text{Drogue Descent: } v_{\text{drogue}} = \sqrt{\frac{2m_{\text{tot}}g}{\rho(C_d A)_{\text{drogue}}}} = 91.2 \text{ ft/s}$$

The average descent rates given by OpenRocket are:

$$\text{Main Descent: } v_{\text{main}} = 18.3 \text{ ft/s}$$

$$\text{Drogue Descent: } v_{\text{drogue}} = 88.2 \text{ ft/s}$$

The hand calculations of `simplifiedescent.m` generally predict higher drift and descent time compared to the OpenRocket. This is mainly due to the assumption of instantaneous velocity change at main deployment. Variations in drift and descent time are caused by stochastic effects in the turbulence model used by OpenRocket. All reported results from OpenRocket are the average of at least five performed simulations to account for variations in each OpenRocket simulation and ensure precise predictions.

### 5.2.1 Kinetic Energy

The kinetic energy at landing was calculated from the main vehicle descent rate for each simulation:

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

The calculated kinetic energies at landing for each vehicle section are given in Table 43.

**Table 43:** Kinetic Energy of Vehicle Sections at Landing

Section	OpenRocket K.E. (ft-lb)	MATLAB K.E. (ft-lb)
Payload Bay	44.6	45.0
Recovery Bay	37.9	38.2
ACS Bay	55.4	55.9
Fin Can	71.4	71.9

The values from OpenRocket and the hand calculations are within 1% of each other, which instills confidence in the results of both simulations and in the design itself. Each of these kinetic energies reported is under the required 75 ft-lb set by NASA 3.3 with a mass margin of 4.2% for the heaviest section.

### 5.2.2 Descent Time

The descent times from hand calculations were obtained from the following equations:

$$\text{Main Descent: } T_{\text{main}} = h_{\text{main}} / v_{\text{main}} = 32.2 \text{ s}$$

$$\text{Drogue Descent: } T_{\text{drogue}} = (h_{\text{apo}} - h_{\text{main}}) / v_{\text{drogue}} = 51.6 \text{ s}$$

$$\text{Total: } T_{\text{tot}} = T_{\text{main}} + T_{\text{drogue}} = 83.8 \text{ s}$$

The descent time from OpenRocket was determined by subtracting the time to apogee from the total flight time. The maximum expected descent times are shown in Table 44.

**Table 44:** Descent Time from Apogee

	OpenRocket (s)	MATLAB (s)
Descent Time	78.8	83.8

The 6% difference in descent times is due to the differences between drogue descent velocity and the variations in model construction discussed in Section 5.2. Both sets of calculations verify that the descent time will be within the required 90 s set by NASA 3.11.

### 5.2.3 Drift Radius

The predicted drift radii from hand calculations were obtained from the following equation:

$$D = T_{\text{tot}} v_{\text{wind}}$$

The drift radii from OpenRocket were determined by taking the absolute value of the lateral distance traveled between apogee and landing. The expected drift radii for different wind speeds are shown in Table 45.

**Table 45:** Drift Radius

Wind Speed (mph)	MATLAB (ft)	OpenRocket (ft)
0	0	0
5	614.7	498.7
10	1229.4	1009.8
15	1844.2	1532.3
20	2458.9	2077.8

The difference between the predictions from OpenRocket and the hand calculations increase with increasing wind speed. Similar to the descent rate, the difference in drift radii is due in part to the differences between drogue descent velocity. However, the majority of the difference is likely due to the turbulence model used in OpenRocket, as the turbulence model has a greater affect as the velocity increases. Both sets of calculations verify that the drift radius will be within the required 2500 ft set by NASA 3.10. The maximum expected drift for the launch vehicle is 2456.5 ft (NASA 4.2.1.1).

## 5.3 Structural Analysis

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. The main methods used in performing this structural analysis were hand calculations and FEA. Hand calculations were used for most of the components, especially those commercially available with guaranteed force ratings. FEA was used for the in-house components such as bulkheads, centering rings, and body tubes, as simple hand calculations were not available for those more complicated geometries and loading scenarios.

All FEA was performed using ANSYS Mechanical Static Simulation. A static simulation was used to reduce the complexity and time of the simulation process, while maintaining conservative estimates for loading. Performing the simulation in this way ensures that the design will be able to withstand even the most extreme loading scenarios (LV.1). Mesh convergence studies were conducted for each component, ensuring the most accurate simulation possible once all loading conditions were applied to the simulations.

### 5.3.1 Peak Thrust

At the maximum thrust, the force transmitted to the vehicle is 700 lbf. Finite Element Analysis was used to examine the resultant stress from this loading on the vehicle components. The results of the FEA for the motor mount, centering rings, the ACS bay, and the Recovery bay are shown in Figures 44 - 43.

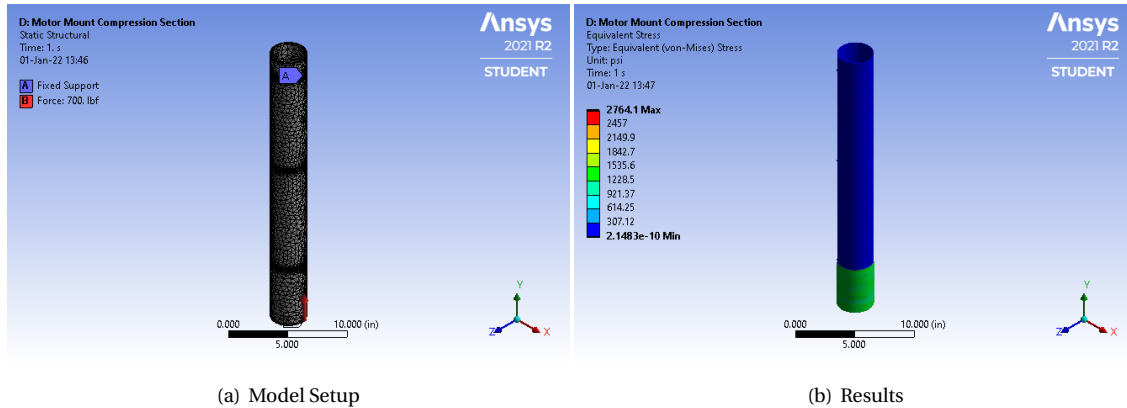


Figure 43: Motor Mount FEA

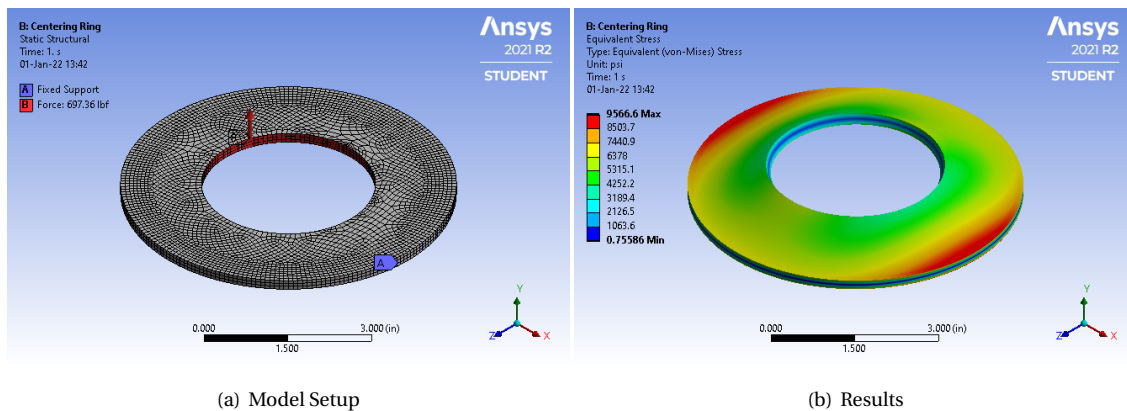


Figure 44: Centering Ring FEA

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.



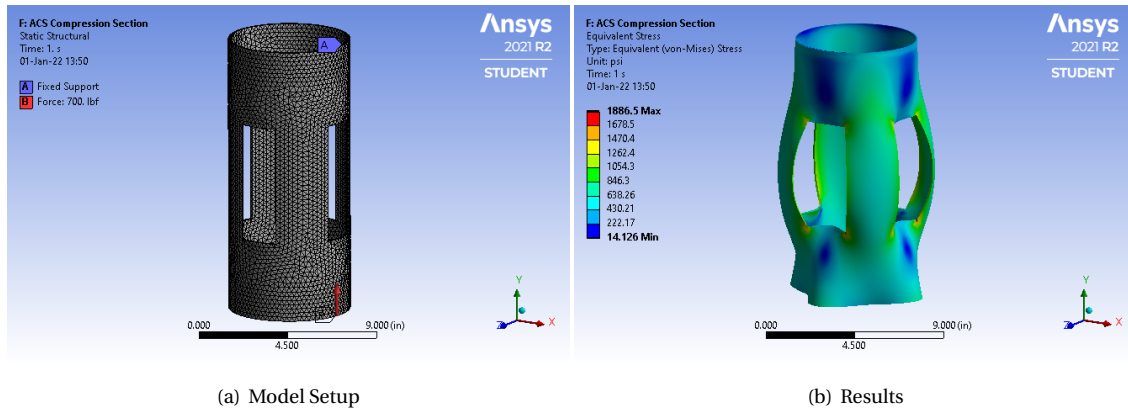


Figure 45: ACS Bay FEA

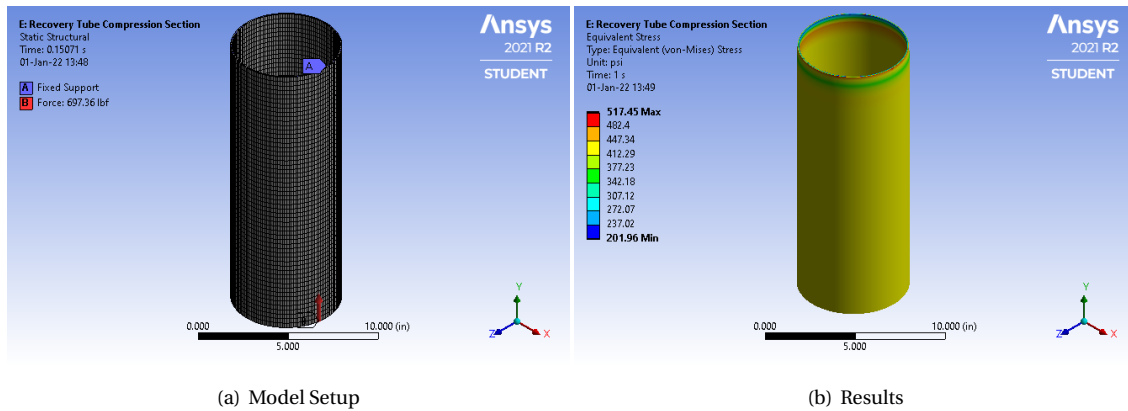


Figure 46: Recovery Bay FEA

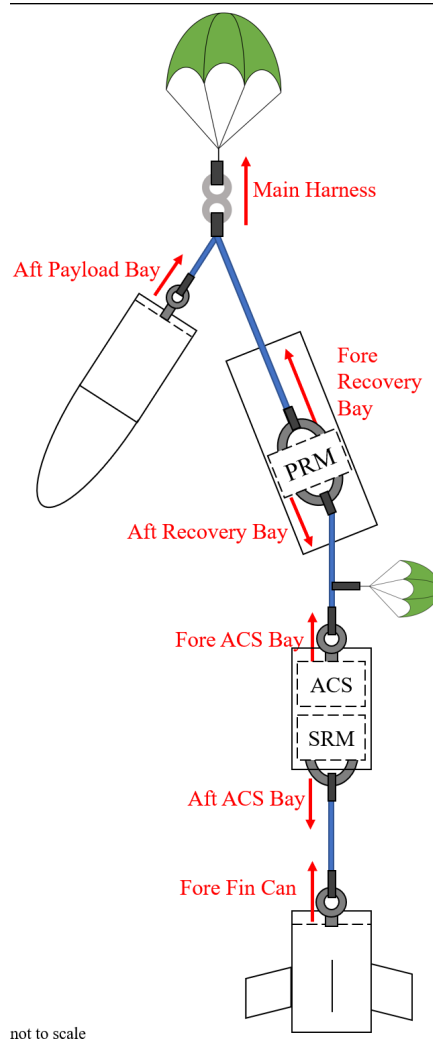
The resultant stresses were then used to determine the factor of safety for each component, shown in Table 46. Each of these factors of safety are greater than 2, satisfying NDRT LV.2.

Table 46: 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

### 5.3.2 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 47 shows the free body diagram of forces on the different vehicle components.



**Figure 47:** 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:

$$\Sigma F = ma = D - W$$

where  $W$  is the weight of the entire vehicle and  $D$  is the drag on the main parachute, given by

$$D = \frac{1}{2} \rho (C_d A)_{\text{main}} v_{\text{drogue}}^2$$

where  $(C_d A)_{\text{main}}$  is the drag parameter of the main parachute travelling at the terminal velocity of the drogue parachute  $v_{\text{drogue}}$ , given by

$$v_{\text{drogue}} = \sqrt{\frac{2mg}{\rho(C_d A)_{\text{drogue}}}} = 91.22 \text{ft/s}$$

The lift on the vehicle is assumed to be negligible. The normalized acceleration  $\bar{a}$  is then given by

$$\bar{a} = \frac{\frac{1}{2} \rho (C_d A)_{\text{main}} v_{\text{drogue}}^2}{mg} - 1 = 23.64g$$

The force experienced by each of the vehicle sections can be calculated by multiplying the acceleration by the mass of the supported sections, shown in Table 47. The forces on each of the major sections are given in Table 48.

**Table 47:** 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 48:** Forces on Launch Vehicle Sections at Main Deployment

Location	Force [lbs]
Main Recovery Harness	991.1
Aft Payload Bay	211.3
Fore Recovery Bay	779.8
Aft Recovery Bay	600.4
Fore ACS Bay	600.4
Aft ACS Bay	337.9
Fore Fin Can	337.9

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 using

$$FOS = \frac{S}{F}$$

where  $S$  is the breaking strength of the hardware in lbs and  $F$  is the force on the hardware due to the deployment of the main parachute in lbs. The calculated factors of safety can be seen in Table 49.

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

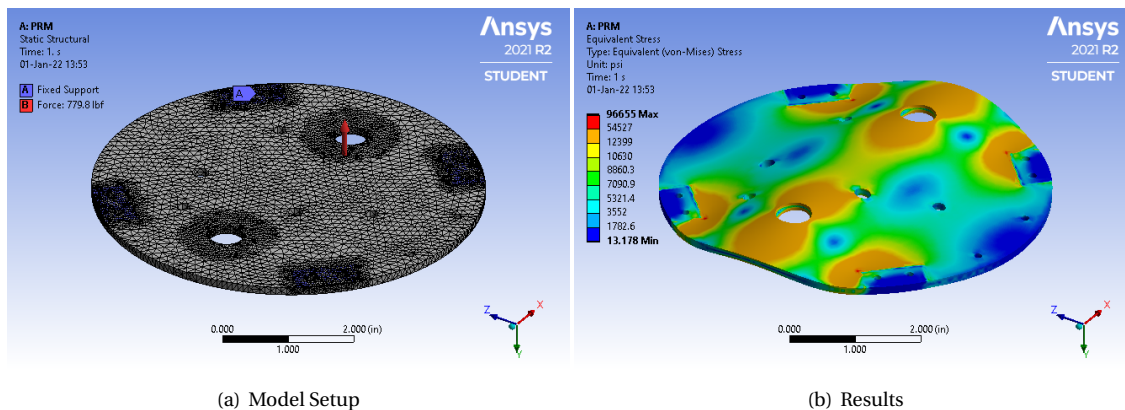
$$FOS = \frac{\tau_{max} \frac{\pi}{4} D^2}{\frac{1}{n} F_{main}} = 4.17$$

where  $\tau_{max}$  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. The loading on each bulkhead was simulated using the area of each washer that transmits the load from the U-Bolt to the bulkhead and the areas of the four airframe interfacing blocks on the top face of the bulkheads. Figures 48-51 show the

**Table 49:** Attachment Hardware Factors of Safety at Main Deployment

Hardware	Location	Load (lbs)	Breaking Strength (lbs)	FOS
Drogue Harness	Drogue Harness	600.4	2520	4.30
3/8 in. Quicklink	Aft Recovery Tube	600.4	2200	3.75
3/8 in. Quicklink	Fore ACS Bay	600.4	2200	3.75
3/8 in. Quicklink	Drogue Chute	600.4	2200	3.75
U-bolt	Aft Recovery Tube	600.4	2000	3.41
3/8 in. Eye Bolt	Fore ACS Bay	600.4	3100	5.28
Main Harness	Main Harness	991.1	2520	2.60
3/8 in. Quicklink	Main Chute	991.1	2200	2.27
3/8 in. Quicklink	Pilot Chute	991.1	2200	2.27
3/16 in. Quicklink	Aft Payload Bay	211.3	500	2.37
3/8 in. Quicklink	Fore Recovery Tube	779.8	2200	2.89
1/4 in. Eye Bolt	Aft Payload Bay	211.3	500	2.37
U-bolt	Fore Recovery Tube	779.8	2000	2.63
Swivel	Main Chute	991.1	3000	3.09
Fin Can Harness	Fin Can Harness	337.9	2520	4.30
3/8 in. Quicklink	Aft ACS Bay	337.9	2200	6.51
3/8 in. Quicklink	Fore Fin Can	337.9	2200	6.51
5/16"-24 Eye Bolt	Fore Fin Can	337.9	2000	6.06

model setup, loading scenario, final mesh, and results for the FEA. Table 50 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, verifying R.1, LV.2, and LVIS.2.



**Figure 48:** PRM Bulkhead FEA

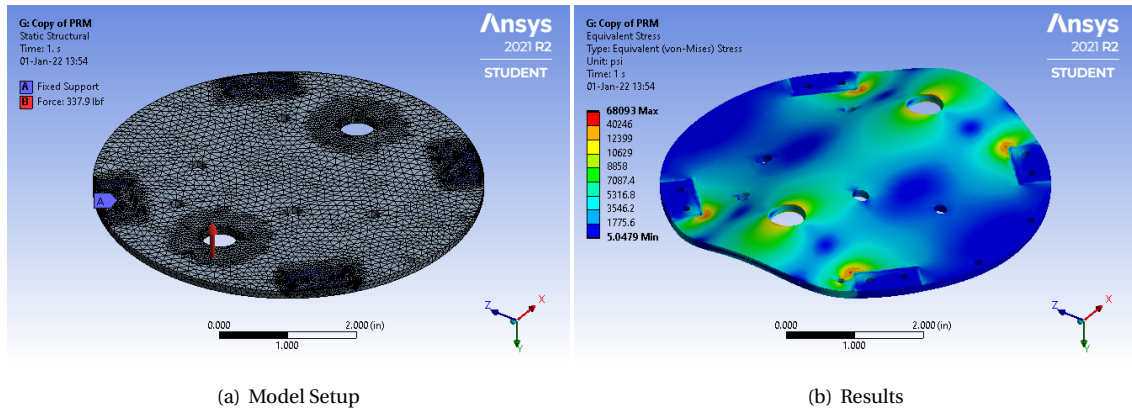


Figure 49: SRM Bulkhead FEA

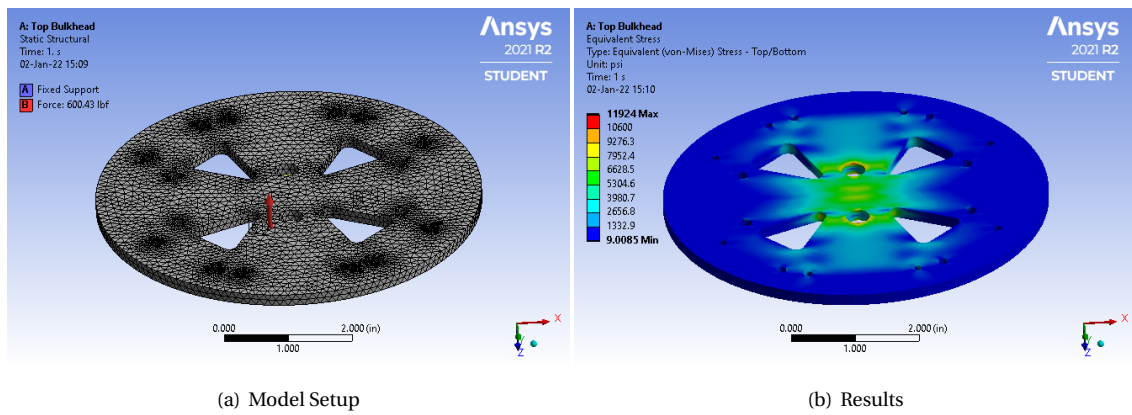


Figure 50: ACS Bay Bulkhead FEA

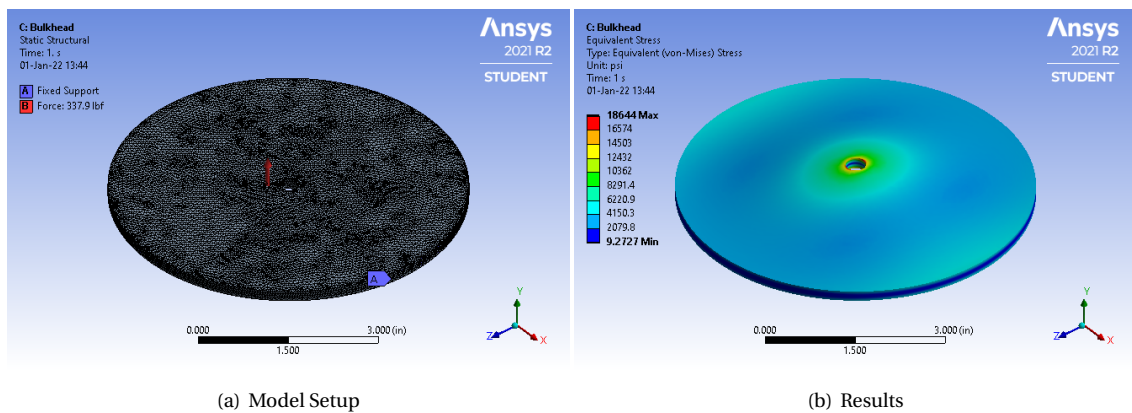


Figure 51: Payload Bay/Fin Can Bulkhead FEA

Table 50: 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: Launch Vehicle Identification System

### 6.1 Design of Payload Equipment

The team presented three design alternatives in PDR, including an inertial navigation system, UAV computer imaging system, and a glider computer imaging system. A trade study conducted on the criteria of mechanical simplicity, accuracy, precision, computational simplicity, and cost effectiveness demonstrated that the inertial navigation system was the best design choice of the options presented.

### 6.2 System Level Design Overview

The design is an inertial navigation system called LVIS. LVIS features mechanical, software, and electrical subsystems, and it is rigidly fixed to the launch vehicle. LVIS will not deploy a payload during descent nor use energetics ([NASA 4.3.1](#), [NASA 4.3.3](#)). LVIS does not feature an unmanned aircraft system ([NASA 4.3.4](#), [NASA 4.3.5](#), [NASA 4.3.6](#)). After the launch vehicle lands, it uses an algorithm to process the acquired flight data to identify the grid square it is in and translates this number to a ground station. LVIS does not interface with the Apogee Control System or Recovery system ([NASA 3.8](#)). LVIS does not utilize external hardware or software outside of the launch vehicle and the ground station ([NASA 4.2.5](#))

### 6.3 Mission Success Criteria

The follow criteria will be used to evaluate the success of the payload system ([NASA 4.1](#)):

- The payload system correctly identifies and transmits the grid square in which the rocket lands and depicts the launch rail in the gridded image.
- The payload system collects relevant data throughout the entire flight and processes it through a sensor fusion algorithm to complete the task of identifying and transmitting the grid square after landing ([NASA 2.19.1.8](#)).
- 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 operates in variable conditions and temperatures such that the electronics are fully functional.

### 6.4 Mechanical Component Level Design

The LVIS mechanical design consists of a tiered bulkhead design, with two fiberglass bulkheads on the fore and aft sides of a third bulkhead made of hardwood plywood. Each bulkhead is attached to the others by four aluminum hexagonal standoffs. The frame's design is made to fit in the launch vehicle's nose cone and nose cone shoulder and it is attached to the vehicle with bolts which screw onto two sets of four retention blocks, one set on each fiberglass bulkhead, from the outside of the vehicle frame.

The middle bulkhead, onto which the sensors will be attached, is made of plywood because of its ease of manufacturing, ease of mounting sensors, low cost, and desirable loss factor, meaning it dampens vibrations.

Additionally, rubber washers at this bulkhead’s attachment points to the standoffs and the sensors assist in minimizing the transmission of vibrations from the LVIS and launch vehicle onto the sensors and thus maximizing their accuracy by minimizing signal noise.

Fiberglass was chosen for the material of the top and bottom bulkheads because of its strength. The transmission antenna is mounted on the fiberglass bulkheads, as well as the main battery pack, as the strength of this bulkhead is optimal for the heavier weight of these components. Each of the bulkheads has a hole in the center through which wires will be passed. A full CAD rendering is shown in Figure 53, and a drawing of the assembly is shown in Figure 52.

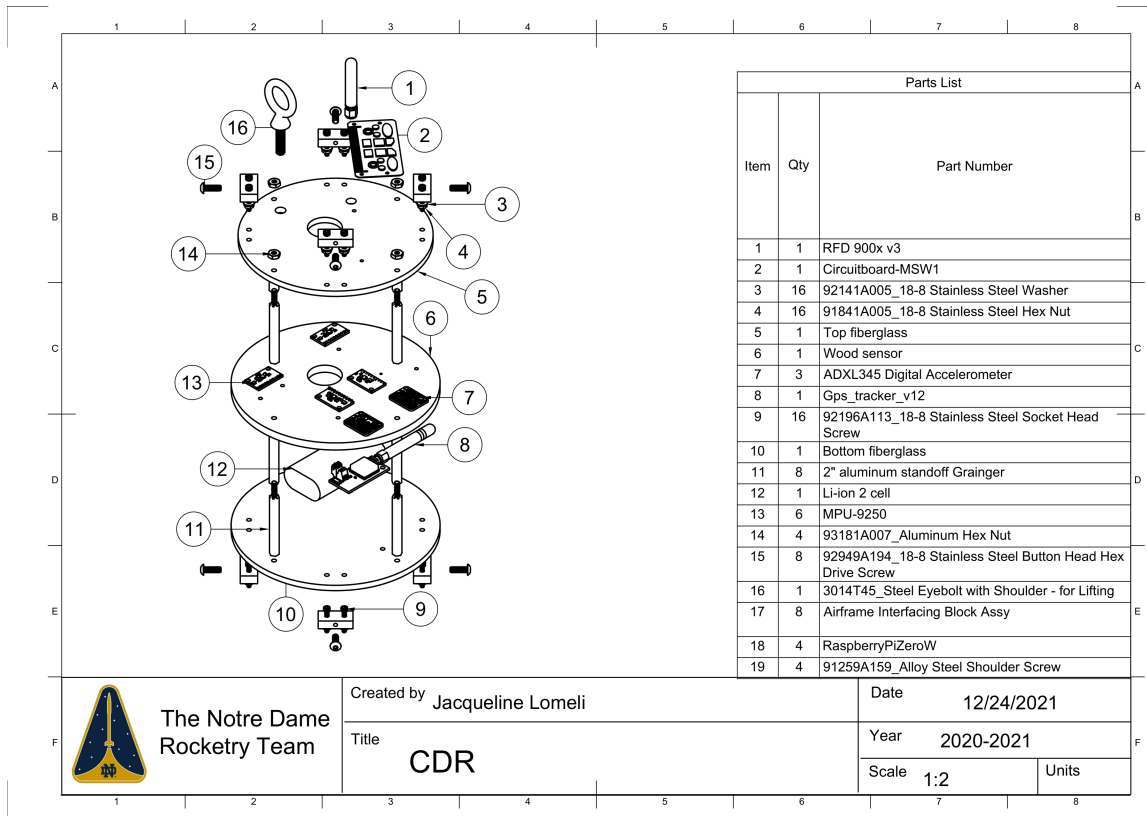


Figure 52: LVIS Assembly Drawing

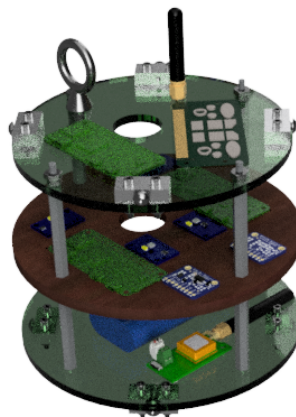


Figure 53: LVIS Render



## 6.5 Electrical Component Level Design

The electrical design for the LVIS consists of three microcontroller subunits, each with two separate IMUs, a HiG accelerometer, and a microcontroller. The subunits are then integrated via a main microcontroller which controls data processing and transmission. A battery-powered power delivery printed circuit board will supply voltage and current for the electrical components as PCB's provide improved connections and increased mechanical stability. The following sections detail the sensors, batteries, and wireless transmission, as well as their integration.

### 6.5.1 Sensors

The Inertial Navigation System is made up of two Inertial Measurement Units (IMUs) and a HiG accelerometer. The IMUs will determine the motion of the launch vehicle at any given moment and the orientation of the launch vehicle while on the launch pad by providing acceleration, rotation, and magnetic field measurements with the end goal of determining the touchdown location of the vehicle. Two different IMUs were chosen for redundancy and to reduce the signal to noise ratio and therefore improve the accuracy ([NDRT LVIS.1](#)). The selected IMUs are shown in Figure 54. Both IMUs were chosen for their sampling rate and sensitivity. As clarified after PDR, the magnetometers will not be used during the launch vehicle's trajectory. They will only be utilized while the launch vehicle is on the launch pad to calibrate the sensors.

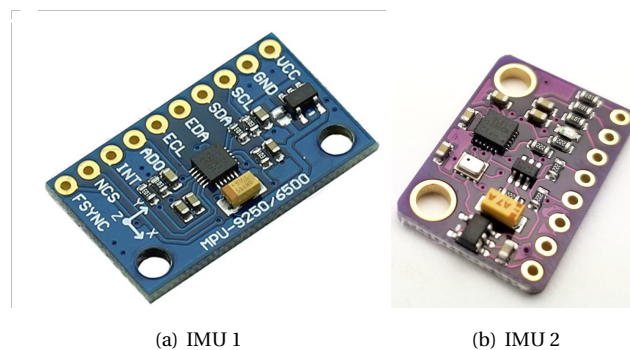


Figure 54: LVIS IMUs

The HiG accelerometer ensures that the acceleration is recorded accurately during the high force points of the vehicle's trajectory, such as main parachute deployment. LVIS will use a DFRobot Gravity 12C chosen for its cost effectiveness, widespread availability, and accuracy, in addition to recording high-g acceleration ([LVIS.6](#)). This accelerometer is shown in Figure 55.

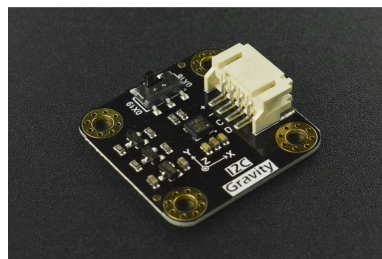


Figure 55: LVIS HiG Accelerometer



### 6.5.2 Wireless Transmission

The wireless transmission system of the LVIS will transmit the grid square where the launch vehicle lands to the ground station. It will consist of a custom PCB integrating the power and radio circuitry shown in Figure 56. Identical boards will be used for both the LVIS and ground station, enabling simpler assembly and repair processes. The radio transmission system will consist of a microcontroller and a radio transceiver communicating over SPI. The microcontroller interfaces with the INS over UART on the LVIS side and with the host laptop over UART on the ground station side. The transceiver will have an external antenna located in the nose cone of the launch vehicle. A dipole and patch antennas are currently planned for the wireless transmission system.

The 915 MHz ISM band was selected for the purpose of maximizing transmission range. The transceiver will interface with the microcontroller over SPI. It will transmit at or less than the maximum of 250 mW (2.23.8). A transceiver with frequency modulation is preferred for the purpose of improving reliability at long range and to mitigate interference (2.23.9). The system will accept data from a processor onboard the launch vehicle and transmit it to a ground station located up to half a mile away. The system will be deemed successful if the ground station receives the coordinates computed by the launch vehicle's onboard processor following a successful flight. The payload bay will be fiberglass, allowing radio frequency (RF) signals to pass through the body tube. The payload transceiver will interface with the locating system to receive the grid square upon landing and the ground station transceiver will output the location to a terminal.

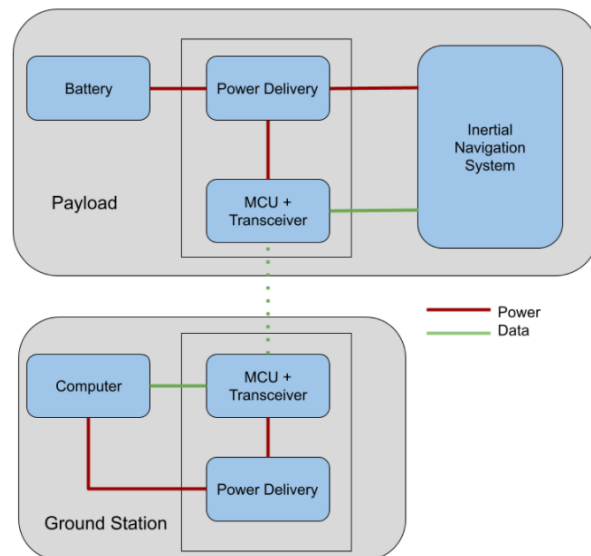


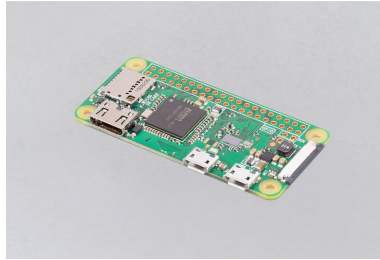
Figure 56: LVIS Wireless Transmission Diagram

### 6.5.3 Microcontroller

The Raspberry Pi 0W was chosen for its small size, sufficient processing capabilities, minimal power use, and availability at a low cost. Its high processing capability is due to the 1 GHz single-core CPU and a footprint of 1950 mm<sup>2</sup>. Moreover, the voltage inputs for the microcontroller are easily achieved. The Raspberry Pi allows data storage through a MicroSD card and allows the team to upload programs to achieve its purpose.

The purpose of the microcontrollers is twofold. There are three subunit microcontrollers that achieve the first purpose of computing displacements. They receive data from the IMUs and accelerometers, filter incoming data,

compute displacements, and send the resultant information. The second purpose of the main microcontroller unit is to transmit the final location of the payload to a ground station. It achieves this goal by taking the computed displacements from the subunits, determining if there is an outlier, and averaging the displacements. The Raspberry Pi 0W microcontroller is shown in figure 57.



**Figure 57:** LVIS Microcontroller: Raspberry Pi 0W

#### 6.5.4 Battery

The battery must contain enough energy to power the entire system for at least two hours of idle time on the launch pad followed by a complete successful flight and transmission, and the components must survive the high acceleration expected during a successful flight. The team chose an Adafruit Lithium Ion Battery Pack, shown in Figure 58, which consists of two 18650 sized cells, to power the LVIS. The LVIS consists of a central Raspberry Pi 0W as well as three other Raspberry Pi 0Ws, each of which is connected to a sensor array. This battery was chosen because it can supply 7.4 V, a voltage that is high enough to be regulated down to 5 V and 3.3 V and low enough to minimize power consumed by a voltage regulator. The 5 V supply will be needed to power each of the Pis and will be achieved by using a 5 V Boost Regulator. The 3 V supply will be required to power the sensors and will be achieved through the use of a R 3.3 V LDO Regulator. This system is further described in the next section. Furthermore, this pack provides a total maximum capacity of 4400 mAh which will ensure a sufficiently long lifespan even in the case of time delays during launch. The battery will also be brightly colored and marked as dangerous and protected, satisfying [NASA 2.22](#).



**Figure 58:** LVIS Adafruit Lithium Ion Battery Pack

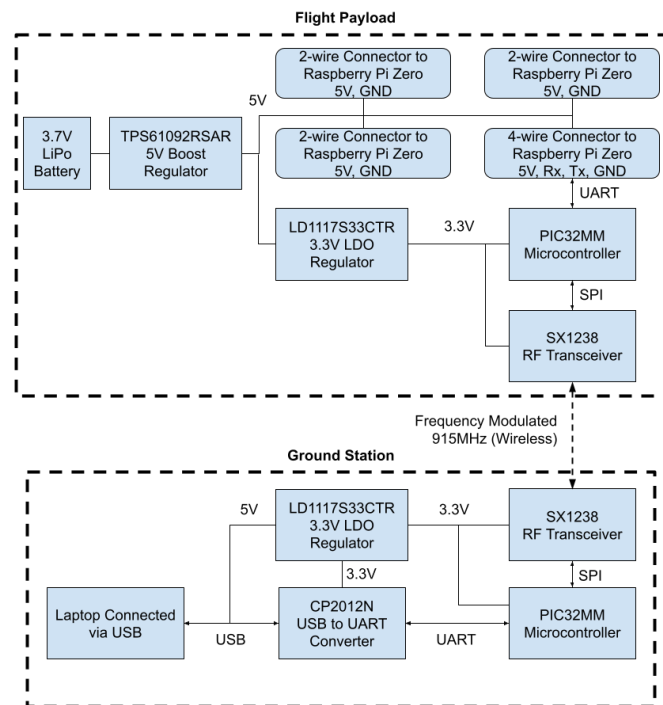
#### 6.5.5 Power Distribution

A power distribution PCB shown in Figure 59 will be designed to properly accommodate the different voltage requirements to properly power the components of LVIS. Moreover, the PCB will incorporate the wireless transmission as described in the previous section. Boost converters will be used to regulate the battery voltage up to 5 V, providing power to the Raspberry Pis. Parts will be selected which allow for a maximum current draw of  $500 \text{ mA} + 500 \text{ mA} \times$  the number of Raspberry Pis which is currently four. A low dropout (LDO) regulator will regulate 5 V to 3.3 V, providing power to the microcontroller and transceiver. The 3.3 V rail will draw very low

current for the majority of the time. Current will peak during transmission for a relatively short time. An LDO is a simple and cheap solution as it requires a small number of external components and the low-noise output voltage of a linear regulator is ideal when supplying voltage to sensor modules as it has noise countermeasures. The PCB components are listed in Table 51.

**Table 51: LVIS PCB Components**

Part Name	Manufacturer	Description
SX1238IMLTRT	Semtech	RF Transceiver
PIC32MM0032GPL	Microchip	Microcontroller
LD1117S33CTR	STMicroelectronics	LDO to power microcontroller
TPS61092RSAR	Texas Instruments	High-current 5 V boost regulator
AS1325-BSTT-50	AMS	5 V boost regulator
CP2102N-A02	Silicon Labs	UART-to-USB adapter



**Figure 59: LVIS PCB Block Diagram**

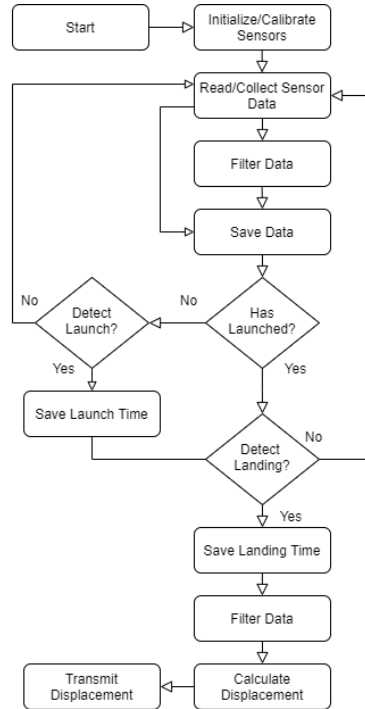
## 6.6 Software

The following sections will detail the procedure 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, as well as an overall testing plan.

### 6.6.1 Overall Control Flow

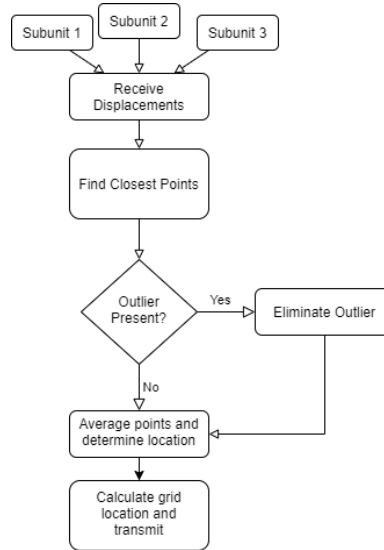
The control flow demonstrates the process that the software and code will follow to acquire and process data from LVIS. This process incorporates data filtration and software testing portions in order to test and

demonstrate a functional design. The control flow for LVIS is shown in Figure 60.



**Figure 60:** LVIS Control Flow Diagram

There are three subunit microcontrollers on LVIS that follow the same program. The program will begin by calibrating each sensor and collecting data during flight to filter with the Kalman filter. Additionally, it will save an unfiltered copy to analyze and aid in the calculation of the displacement. Through the data collected from the sensors, such as velocity, acceleration, and altitude readings, which will be filtered with minimal noise, the landing will be able to be determined. Once landing is established, data collection will stop and the program will transition to using a Gauss-Newton filter for the data. The Gauss-Newton filtered data will be used to calculate the overall displacement of the payload bay, specifically, with data collected between the launch and landing timestamps. This location will then be sent to the primary microcontroller for final calculations as seen in Figure 61.



**Figure 61:** LVIS Control Flow Diagram for Final Calculations

### 6.6.2 Data Filters

The sensor data to be received by LVIS will be passed through filtering both in real time during flight and after the vehicle has landed. The goal of this filtering will be to filter out process and measurement noise in order to have a more accurate measurement of the state of the launch vehicle at a certain time. The current choices that the team has for mid-flight filtering and post-flight filtering are the Kalman Filter and the Gauss-Newton Filter.

The Kalman filter is effective for mid-flight data filtering and “true” measurement estimation in its speed and memory efficiency: all the data that are needed to estimate a current state of the system are the raw measurement for the current state from the sensors and the estimate of the previous state of the system.

A one-dimensional iteration of the Kalman filter works as the following: at any  $n^{th}$  stage, the filter predicts the  $(n + 1)^{th}$  stage based on expectations as well as uncertainty and then it moves to that  $(n + 1)^{th}$  stage and adjusts measurement values according to the value of the filter’s extrapolation. The exact algorithm is detailed below for any measured state value  $x$ :

$$\hat{x}_{n,n} = n, \hat{n} - 1 + K_n(z_n - \hat{x}_{n,n-1})$$

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

The first aforementioned equation depicts an updating of the filter’s extrapolation of the  $n^{th}$  state based on measurements and the second depicts the extrapolation of the  $(n + 1)^{th}$  state, where in this case, as the time steps are miniscule, the  $(n + 1)^{th}$  state is approximated to be equal to the  $n^{th}$  state. In the equations, the value  $K_n$  is the Kalman gain for the  $n^{th}$  state. Its value for an iteration is calculated through the equations:

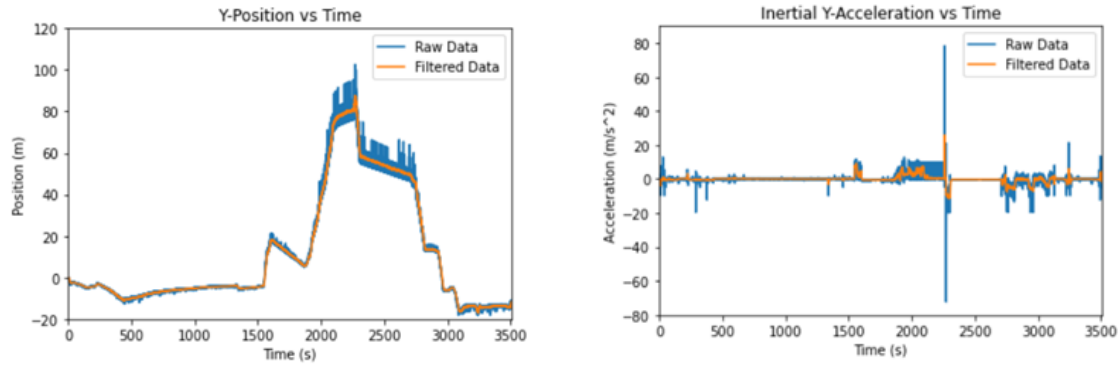
$$K_n = \frac{p_{n,n-1}}{p_{n,n-1} + r}$$

$$p_{n,n} = (1 - K_n)p_{n,n-1}$$

$$p_{n+1,n} = p_{n,n} + q$$

where  $p$  is the estimated uncertainty for a given state, which is also recalculated each iteration based on the expressions aforementioned. This uncertainty is initialized to a hyperparameter known as the initial state uncertainty. The values  $r$  and  $q$  are also hyperparameters for the filter, being the measurement uncertainty and

process noise variance, respectively. The filter is experimentally optimized by adjusting the hyperparameters and observing which set of hyperparameters yield the most effective filter. Figure 62 demonstrates the effectiveness of the Kalman filter in de-noising data.



**Figure 62:** Kalman Filtered Data from Subscale Flight

Post flight, the raw data collected will be passed through a Gauss-Newton filter, which, in principle, works by locally linearizing a nonlinear system and assuming a random Gaussian vector associated with the measurement of that system as noise. The nonlinear system and the measurement and processing of that system are shown via the two nonlinear differential equations:

$$\begin{aligned}x'(t) &= F(x(t)) \\ y(t) &= G(x(t)) + v(t)\end{aligned}$$

where  $F$  and  $G$  are nonlinear functions of the state vector  $x(t)$ ,  $y(t)$  is the measurement vector of that system, and  $v(t)$  is a random Gaussian vector. From the infinitely many trajectories based on the measurements of the system, the filter will try to identify one trajectory  $\hat{x}(t)$  which is characterized by the expression:

$$x(t) = \hat{x}(t) + \delta x(t)$$

where  $\delta x(t)$  is known as the perturbation vector, a vector of time-dependent functions with relatively small magnitudes. This  $\hat{x}(t)$  vector is close in value to  $x(t)$  and is an approximate solution to the aforementioned differential equation. This perturbation vector is characterized by the differential equation:

$$(\delta x(t))' = A(\hat{x}(t))\delta x(t)$$

where  $A(\hat{x}(t))$  is a sensitivity matrix defined as:

$$A(\hat{x}(t)) = \frac{\delta F(x(t))}{\delta(x(t))}$$

The differential equation for the perturbation vector is linear such that it has a transition equation:

$$\delta x(t + \zeta) = \Phi(t_n + \zeta, t_n, \hat{x})\delta x(t)$$

in which  $\Phi(t_n + \zeta, t_n, \hat{x})$  is a transition matrix from time  $t_n$  to  $t_n + \zeta$ , incremented by  $\zeta$ . This transition matrix in turn is also characterized by another differential equation:

$$\frac{\delta}{\delta \zeta} \Phi(t_n + \zeta, t_n, \hat{x}) = A(\hat{x}(t + \zeta))\Phi(t_n + \zeta, t_n, \hat{x})$$

where

$$\Phi(t_n, t_n, \hat{x}) = I$$

in which  $I$  is the identity matrix. Given these differential equations, one can numerically integrate for the transition matrix in order to solve for the approximate true state of the system  $\hat{x}(t)$ . This procedure yields the true perturbation vector; however, in the case of data filtering, one is interested in the observation perturbation vector. Assume that noise free observation  $\hat{y}(t_n)$  is defined as

$$\hat{y}(t_n) = G(\hat{x}(t_n))$$

so that subtracting  $\hat{y}(t_n)$  from the actual observation yields the perturbation vector

$$\delta y(t_n) = y(t_n) - \hat{y}(t_n).$$

The observation perturbation vector can be shown to be related to the true state perturbation vector via the observation sensitivity equation:

$$\delta y(t_n) = M(\hat{x}(t_n))\delta x(t_n) + v_n.$$

$M(\hat{x}(t_n))$  is the Jacobian matrix of  $G$  evaluated at  $\hat{x}(t_n)$ :

$$M(\hat{x}(t_n)) = \frac{\delta F(x(t_n))}{\delta(x(t_n))}.$$

Now consider a series of  $L + 1$  measurements with times  $t_{n-L}, t_{n-L+1}, \dots, t_n$  with a series of observation perturbations  $\delta y(t_{n-L}), \dots, \delta y(t_n)$  arranged in a vector. The observation sensitivity equation can be rewritten in vector form as

$$\delta \mathbf{Y}(t_n) = \mathbf{M}_n + \mathbf{V}_n$$

where the element of these vectors are

$$\begin{bmatrix} \delta y(t_n) \\ \delta y(t_{n-1}) \\ \vdots \\ \delta y(t_{n-L}) \end{bmatrix} = \begin{bmatrix} M(\hat{x}(t_n))\delta x(t_n) \\ M(\hat{x}(t_{n-1}))\delta x(t_{n-1}) \\ \vdots \\ M(\hat{x}(t_{n-L}))\delta x(t_{n-L}) \end{bmatrix} + \begin{bmatrix} v_n \\ v_{n-1} \\ \vdots \\ v_{n-L} \end{bmatrix}.$$

Using the transformation equation for the state perturbation vector  $\delta x(t + \zeta) = \Phi(t_n + \zeta, t_n, \hat{x})\delta x(t)$ , the vector  $\mathbf{T}_n$  can be defined as

$$\mathbf{T}_n = \begin{bmatrix} M(\hat{x}(t_n)) \\ M(\hat{x}(t_{n-1}))\Phi(t_{n-1}, t_n, \hat{x}) \\ \vdots \\ M(\hat{x}(t_{n-L}))\Phi(t_{n-L}, t_n, \hat{x}) \end{bmatrix}.$$

so that the equation for  $\delta \mathbf{Y}(t_n)$  can be rewritten as

$$\delta \mathbf{Y}(t_n) = \mathbf{T}_n \delta x(t_n) + \mathbf{V}_n$$

Using these relations, one obtains the solution  $\delta \hat{x}_{t_n}$  that solves the observation sensitivity equation using minimum variance estimation:

$$\delta \hat{x}(t_n) = (\mathbf{T}_n^T \mathbf{R}_n^{-1} \mathbf{T}_n)^{-1} \mathbf{T}_n^T \mathbf{R}_n^{-1} \delta \mathbf{Y}(t_n)$$

with covariance matrix

$$\mathbf{S}_n = (\mathbf{T}_n^T \mathbf{R}_n^{-1} \mathbf{T}_n)^{-1}$$

and where  $\mathbf{R}_n^{-1}$  is the least squares matrix, a block diagonal weight matrix. Through this computation, one can estimate the state of the system through local linearization and minimum variance estimation with the Gauss-Newton method. The method can become very computationally and memory heavy as the vectors and matrices in the algorithm become very large. Its strong accuracy as well as the less need for immediate data filtering for post-flight analysis make the Gauss-Newton method an effective candidate for post-flight data-filtering before the data is passed through LVIS's inertial algorithm.

### 6.6.3 Software Testing

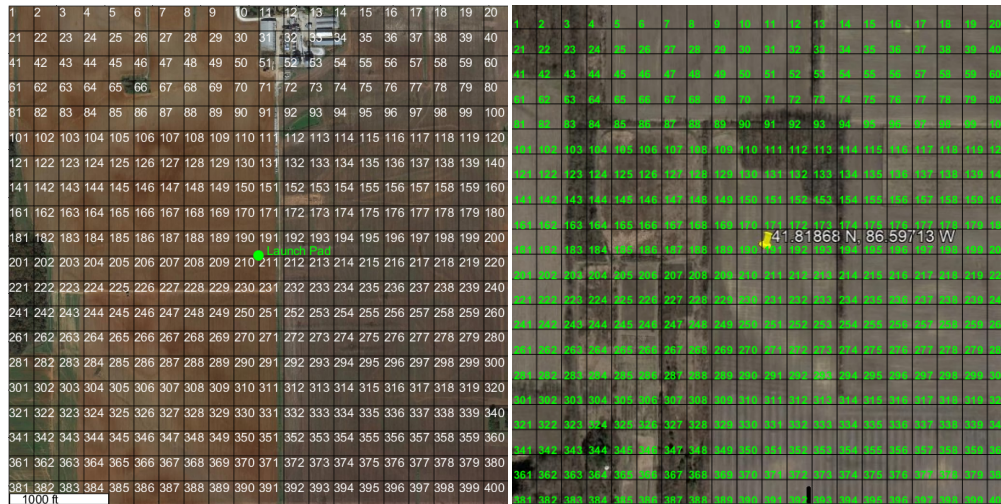
The team has various tests planned to ensure that the software system performs as expected. These include unit testing on numerous sections of the code and ensuring that sensor outputs match the expected results. Such testing has already begun and will continue until the competition flight in April to ensure the best functioning system possible. The integrated software system is and will be tested via test launches, both subscale and full scale. The subscale launch on December 4 provided the team with data from one of the microcontroller subunits consisting of 2 IMUs, 1 HiG accelerometer, and a Raspberry Pi 0W. The software system's location output will be tested against the GPS coordinates of the vehicle's actual location recorded for each of the three test flights. Additionally, the data collected will be run through the mid-flight Kalman filter and the post-flight Gauss Newton filter to ensure that faulty data or noise is not affecting the results. These tests will allow for the continued refinement of the code until the first full scale demonstration, where the full system will then be implemented. The testing will then shift to successfully integrating the three microcontroller subunit outputs into the most accurate single output. Legacy data from previous years could also be utilized for additional testing if necessary, since last year's ACS also consisted of IMUs with nine degrees of freedom. A detailed explanation of the various LVIS tests is provided in Section 9.1.3.

## 6.7 Imaging

Figure 63 provides a gridded image with a scale of the Huntsville Launch Field (NASA 4.2.2). It was created by inputting the coordinates of the Huntsville Launch Field given by NASA through the Student Launch FAQ into Google Earth to provide a satellite image. Forming a radius of 2500 ft from the coordinates of 34°53'43.6"N, 86°37'01.2"W, the image was saved and then transferred into MATLAB (NASA 4.2.1). The entire launch field measures 5000 ft by 5000 ft (NASA 4.2.2.2). Once in MATLAB, the image was overlaid with a grid and labeled with numbers 1 to 400 (NASA 4.2.2.5). Each grid box is square in shape, measures 250 ft by 250 ft, and is uniform in size (NASA 4.2.2.1, NASA 4.2.2.3, NASA 4.2.2.4). Google Earth was chosen to provide the image of the launch field as it is the highest quality source that the team has access to (NASA 4.2.4). The location of the launch pad is marked on Figure 63 (NASA 4.2.4.1). The same procedure was followed for the home launch field for the team in Three Oaks Michigan. The launch pad has the coordinates of 41.81868"N, 86.59713"W and a radius of 2500 ft was established for the image.

These images will aid in completing the mission of identifying the launch vehicle's grid upon landing. More specifically, the image of the home launch field will be used with the appropriate subscale data, the vehicle demonstration flight, and finally, the payload demonstration flight. With the launch rail coordinates, the information collected throughout the flight, and the flight algorithm, the computed final landing can be verified with the the final landing coordinates from the GPS on the respective grid. GPS will not be used in any part of the payload mission and is only present on the launch vehicle to verify its final location (NASA 4.2.3, NASA 4.2.3.1). This GPS verification data will be included in PLAR (NASA 4.2.3.2)





(a) Huntsville Field

(b) Three Oaks Field

**Figure 63:** Gridded Launch Field Images

## 6.8 Vehicle Integration

The team decided to use retention blocks, interfaced with the upper and lower payload bulkheads, that attach to the interior wall of the launch vehicle body to integrate the LVIS with the main launch vehicle. These bulkheads are made of fiberglass, in contrast to the interior bulkhead, which is made of wood, 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 threaded holes for screws: two smaller 4-40 screws attach the block to the bulkhead and an 8-32 screw attaches to the launch vehicle tube. Figure 64 shows the dimensions of the retention blocks and how they interface with the assembly. In the event that a payload mass simulator needs to be flown, the simulator will interface with these mounting blocks (NASA 2.19.1.3.2).

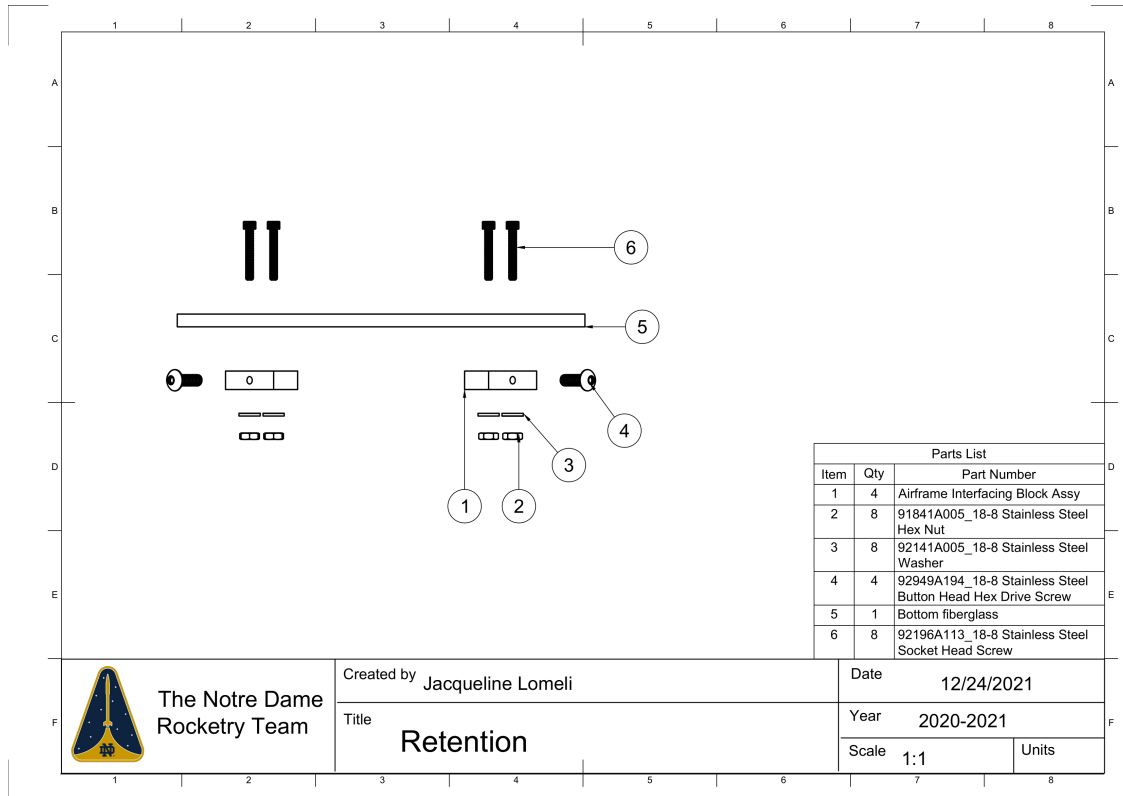


Figure 64: Retention System

Four blocks are being used on each bulkhead to retain the LVIS to the full scale vehicle for redundancy and added safety, while the subscale launch vehicle only used two aluminum blocks on each bulkhead. Additionally, while the subscale design positioned the payload entirely in the main rocket body, in the full scale design, the payload has been moved slightly forward to overlap with the 5.5 in. shoulder of the nosecone to save space.

### 6.9 Comprehensive Mass Statement

The components are listed with their respective masses in Table 52 (NASA 2.19.1.3.1). Moreover, the component maturity and type, the basic mass estimate and mass growth allowance percentage for each component, the total system basic mass, and the total system predicted mass are listed.

Table 52: LVIS Mass Breakdown

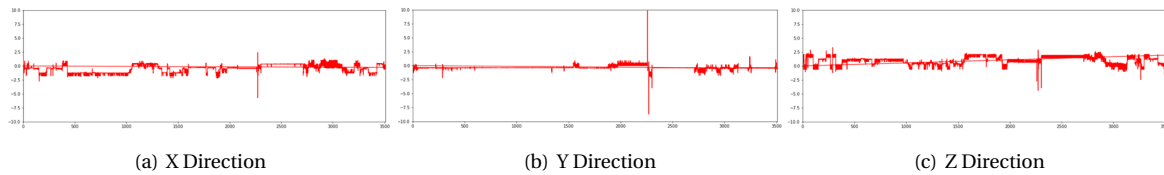
Component Name	Maturity	Component Type	Basic Mass Estimate	MGA %	Predicted Mass
Raspberry Pi 0W	5	SENS	1.4	2	1.428
Lithium Ion Battery Pack - 3.7 V 4400 mAh	5	BAT	3.2	2	3.264
HiLetgo MPU 9250	5	SENS	0.29	2	0.29
9-Axis Inertial Navigation Module	5	SENS	0.1	2	0.1

**Table 52:** LVIS Mass Breakdown (continued)

Component Name	Maturity	Component Type	Basic Mass Estimate	MGA %	Predicted Mass
Wood Sensor Bulkheads	4	PRIM	2.53	4	2.63
Eyebolt	5	SEC	1.63	3	1.6789
Aluminum Retention Blocks	4	PRIM	2.36	10	2.6
Threaded Hex Standoff	4	PRIM	9.37	4	9.74
DFRobot Gravity I2C H3LIS200D	5	SENS	0.23	2	0.230
Wiring	3	WIRE	3	18	3.54
Fiberglass Retention Bulkheads	4	PRIM	12.6	4	13.1
Power Board	3	ELEC	1.5	14	1.71
Screws/Nuts	3	PRIM	3.4	10	3.74
Antenna	3	ELEC	0.4	14	.46
Rubber Vibration Dampening Balls	4	SEC	0.05	6	0.053
Retention Screws	4	PRIM	0.44	4	0.458
Recovery GPS + Antenna	5	ELEC	0.5	3	0.515
GPS Battery	5	BAT	1	2	1.02
CW 4-40 Screw	5	SEC	0.220	3	0.226
CW 4-40 Washer	5	SEC	0.082	3	0.085
CW 4-40 Locknut	4	SEC	0.110	6	0.116
Al Hex Nut (4)	4	SEC	0.144	6	0.15264
<b>Total</b>			<b>48.97</b>		<b>51.81</b>

## 6.10 Subscale

The methods of data filtering to be used by the team require the initialization of values for hyperparameters, such as measurement uncertainty, and a certain set of hyperparameters may yield a more accurate estimate for the true state of the system over another set of hyperparameters. The collected data during the first subscale flight seen in Figure 65 helps in establishing these parameters. Running the collected data through different versions of a data filtering algorithm allows the team to calibrate towards the most accurate iteration of a filter that is possible.



**Figure 65:** Collected Subscale Data from Flight 1

The insights from the subscale data will also allow the team to calibrate the LVIS sensor suites and adjust resolution and bias in order to optimize accurate data collecting on the part of the sensors.

## 7 Technical Design: Apogee Control System

### 7.1 Mission Statement and Success Criteria

The objective of the Apogee Control System (ACS) is to assist the launch vehicle in reaching the target apogee of 4800 feet while increasing the regularity with which the launch vehicle reaches a uniform apogee. This will be accomplished by adding a controlled drag force onto the launch vehicle. The ACS is made up of a series of sensors and supporting equipment that allow data collection and then prompt the launch vehicle to release four drag tabs from their initial position and employ to reduce overall velocity. The ACS utilizes an altimeter, accelerometer, IMU, and a power relay to determine the correct extension and angle for the drag tabs. The launch vehicle will engage the drag tabs at burnout and will utilize them until apogee is met. Any changes in position will act in accordance with a PID control law. The drag tabs will return to their original position inside the launch vehicle once apogee is reached and remain there for the remainder of the flight.

#### 7.1.1 Mission Success Criteria

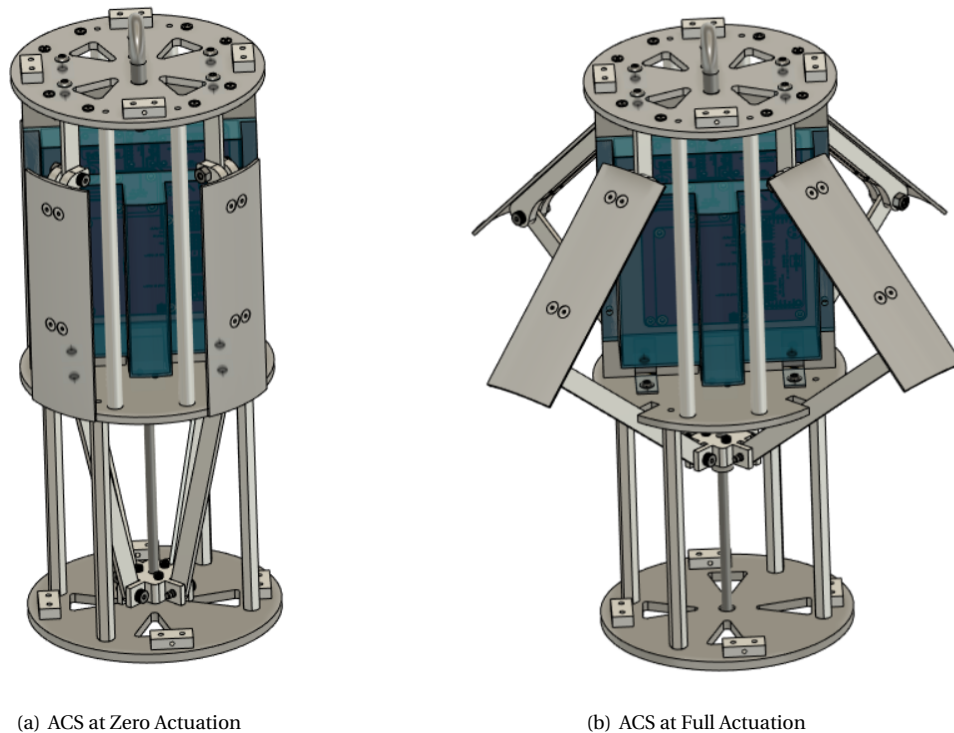
The ACS must alter the apogee of the launch vehicle so that it achieves an apogee of 4800 feet without jeopardizing its safety or successful flight to be considered. In doing so, the ACS must achieve the following:

- The induced drag will cause the launch vehicle to achieve apogee within  $\pm 30$  feet of the target apogee of 4800 feet.
- The drag tabs will not cause destabilization to the launch vehicle during or after deployment.
- The ACS drag tabs correctly respond to the velocity, acceleration, and position of the launch vehicle during flight.
- The ACS will not interfere with the performance of other critical systems of the launch vehicle.
- Appropriate and complete data over the entire flight can be recorded for post-flight analysis.
- The ACS tabs will only actuate after burnout of the launch vehicle has been achieved.
- After apogee, the drag tabs will retract and remain retracted for the remainder of the flight.

### 7.2 Mechanical Design

The mechanism of the Apogee Control System consists of a leadscrew assembly connected to a flaps integral to the body tube of the launch vehicle. The leadscrew is rotated by a HSR-M9382TH continuous servo motor housed in the motor bulkhead. The leadscrew runs through the central hub, made of aluminum, which hinges to the

aluminum pusher arms such that as the leadscrew rotates, the central hub will move vertically and cause the pusher arms to actuate the drag flaps in or out. The pusher arms connect to aluminum plates which are fastened to the backs of the 3D-printed resin flaps with carbon fibers inlaid for added strength. The aluminum plates then connect to the aluminum hinges on the upper bulkhead so that the plates, not the drag tabs, bear most of the load due to actuating the mechanism. The mechanism fully open and fully closed is shown below in Figure 66.



**Figure 66:** Integrated Apogee Control System

### 7.2.1 Changes Made Since PDR

Several mechanism design changes were made since PDR to improve the performance and stability of ACS. The most significant change is the addition of the central bulkhead so that the sensor sled can be located below the top bulkhead. This allows the lead screw and pusher arms to be longer, which increases the moment induced by the pusher arms on the drag tabs for a given load and increases the drag tabs' angle of displacement for a given angle of rotation of the lead screw. This results in less stress on the central hub and pusher arms and allows the drag tabs to be actuated faster, so the drag can be increased or decreased more quickly if necessary. In addition, this configuration eliminates the possibility of the mechanism reaching close to a dead position, which could lock up the mechanism and prevent movement. Furthermore, the size of drag tabs was reduced to lower stresses in the mechanism caused by drag and improve the load-bearing ability of the body tube by reducing the amount of material removed to give space for the drag tabs. This change does lower the amount of drag produced by ACS for a given drag tab angle, but the system is still capable of inducing far more drag than would be necessary, and the previous design's tabs were unnecessarily long for the purposes of the mechanism. Lastly, aluminum plates were added to the backs of the carbon-fiber drag tabs. The plates are connected to the top hinges and pusher arms, bearing the majority of in-flight loads and reducing the stress felt by the drag tabs.

### 7.2.2 Drag Flaps

The control surfaces of the system, referred to as drag flaps, are a set of four surfaces designed to have the same curvature as the body tube and 3D printed out of resin inlay with carbon fiber. They are not primary structural members, as they are each supported by two aluminum columns, known as flap support arms, which will transmit the load from the lead screw to the flaps. As such, the drag flaps were designed to be lightweight and to facilitate easy printing, with the intention that they are a safe fail component that can be easily swapped if damaged. A drawing of the completed drag flaps is given in Figure 67.

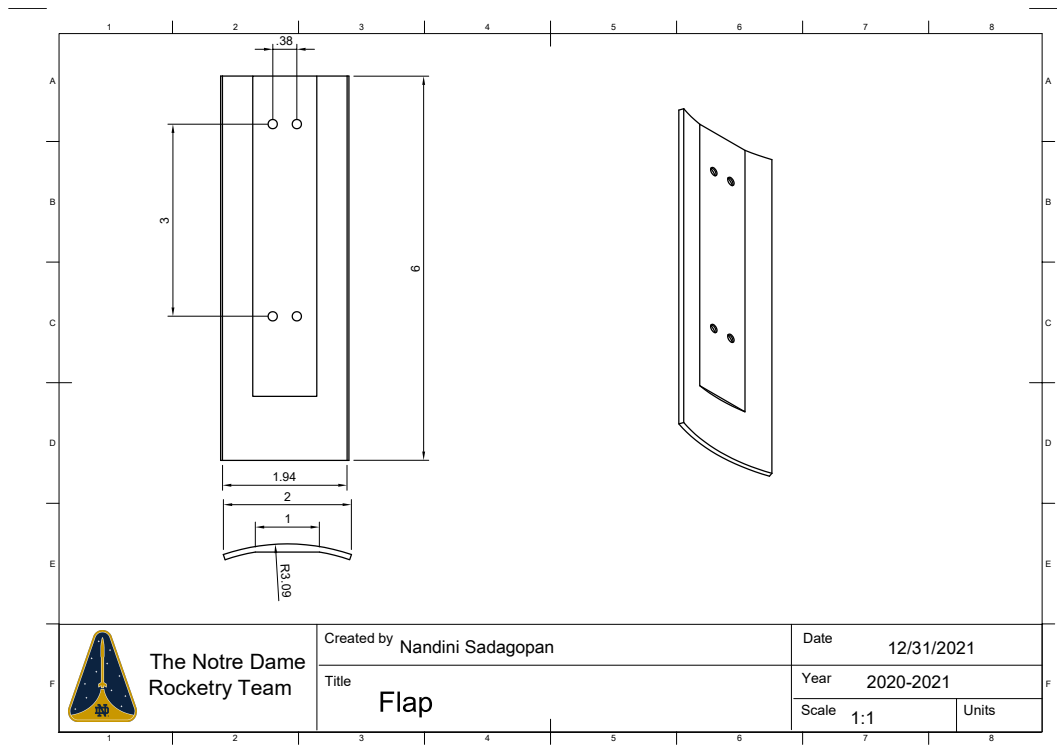
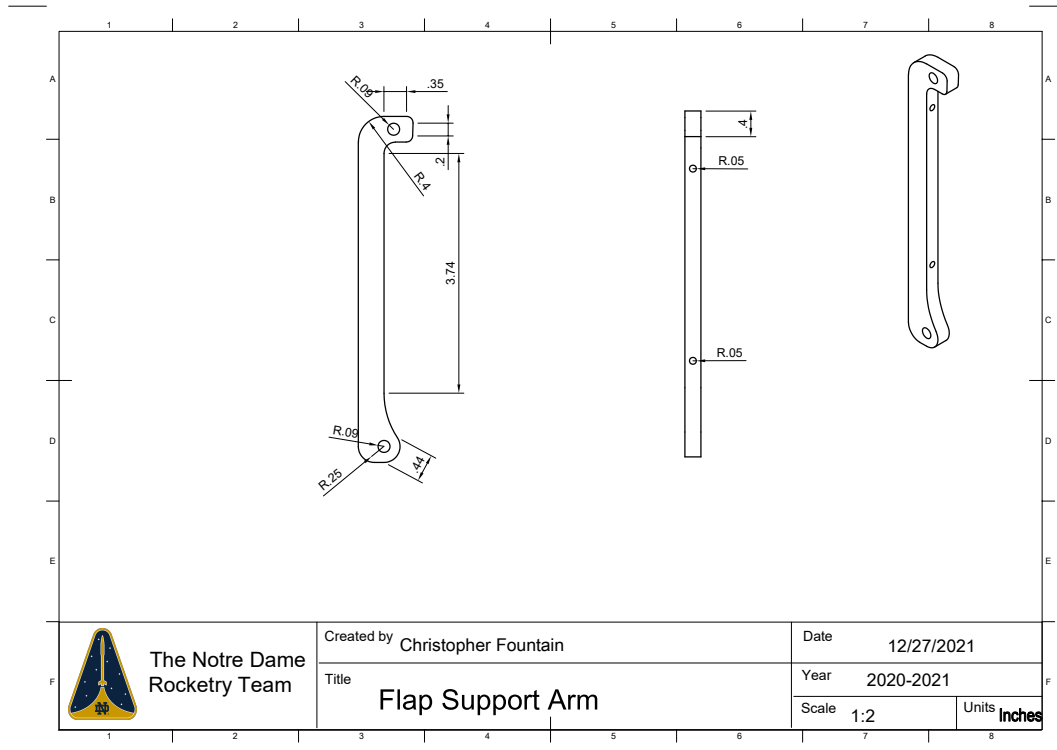


Figure 67: As Designed Drag Flaps

The drag flaps interface with the flap support using four countersunk screws. In order for the flaps to lay flush with the body tube when assembled, the flaps will be transported disassembled from the main structure of the ACS and screwed after ACS is integrated into the launch vehicle.

### 7.2.3 Flap Support Arms

The flap support arms are structural support members that interface with the drag flaps in order to transmit loads from the pusher arms. Additionally, the flap support arms interface with the hinges at the top of the mechanism for ease of integration with the ACS mechanism. The main design drivers of these supports were to maintain a relatively lightweight but rigid structure, and to ensure ease of manufacturing. As such, these supports will be manufactured out of aluminum bar stock using a CNC mill (NASA 2.23.10). After the profile is milled, the piece will be turned and holes will be drilled and tapped for interfacing between the flap supports and the drag flaps. Additional through holes will be milled for hinge connection points. A drawing of the designed flap support arm is given in Figure 68.



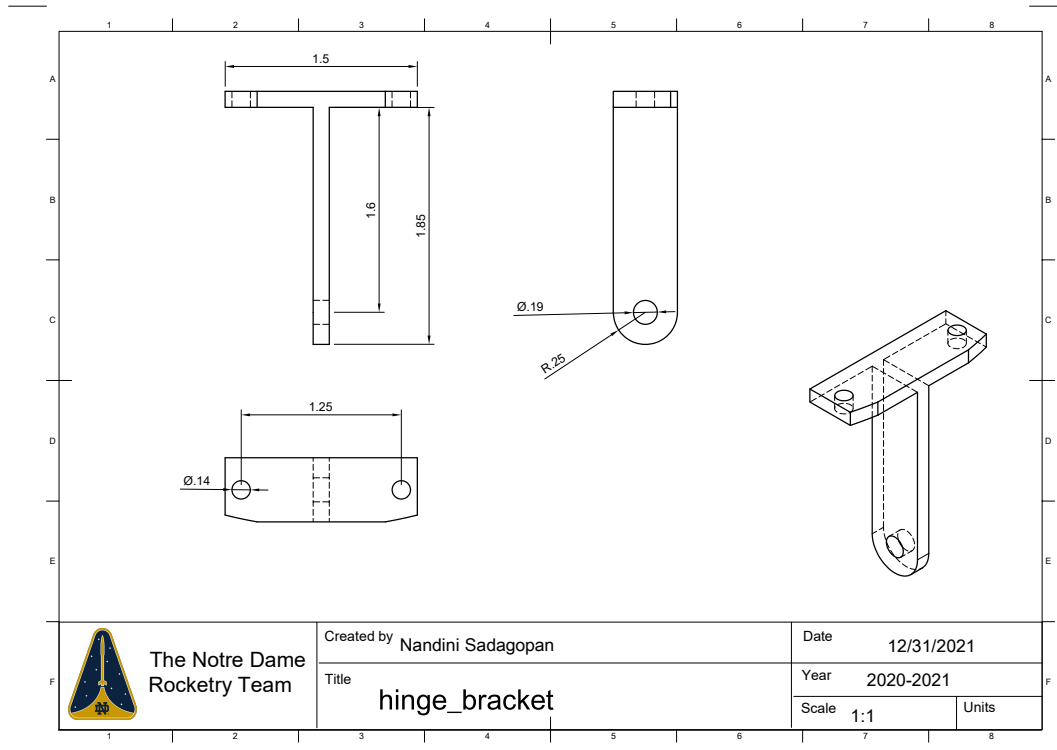
**Figure 68:** As Designed Flap Support Arms

The flap support arms will be connected to the hinges and pusher arms using shoulder screws and locknuts, allowing for relatively low friction rotation of the flap assembly without danger of the connection point loosening over time.

Finite element analysis was performed in order to ensure compliance with a factor of safety requirement of 2 because the flap support arms are load bearing. The results of all finite analysis for the ACS mechanism load bearing members is found in Section 7.2.9, Load Path Analysis.

#### 7.2.4 Bulkhead Hinges

The bulkhead hinges interface the flap support arms with the top bulkhead, constraining the drag flaps to only rotational motion. As the hinges are load bearing, and transmit a portion of the drag load to the fore bulkhead, they will be fabricated out of aluminum bar stock using a two stage CNC milling process, which will first machine the profile of the component before machining the through holes for the shoulder screws. A drawing of the designed bulkhead hinges is given in Figure 69.



**Figure 69:** As Designed Bulkhead Hinges

The hinges will be affixed to the fore bulkhead with 4-40 screws and locknuts, allowing for a secure connection and load transfer from the hinge through the bulkhead to the body tube.

### 7.2.5 Pusher Arms

The pusher arms connect the central hub to the flap support arms, transforming the translational motion of the central hub on the lead screw into rotational motion of the drag flap about the bulkhead hinge. They are primary structural members, as they have to support the moment induced by drag on the flaps at any angle of actuation of the mechanism. As such, the pusher arms were designed primarily for strength without being prohibitively heavy. They will be manufactured out of aluminum bar stock using a one step CNC milling process. A drawing of the designed pusher arm is given in Figure 70.



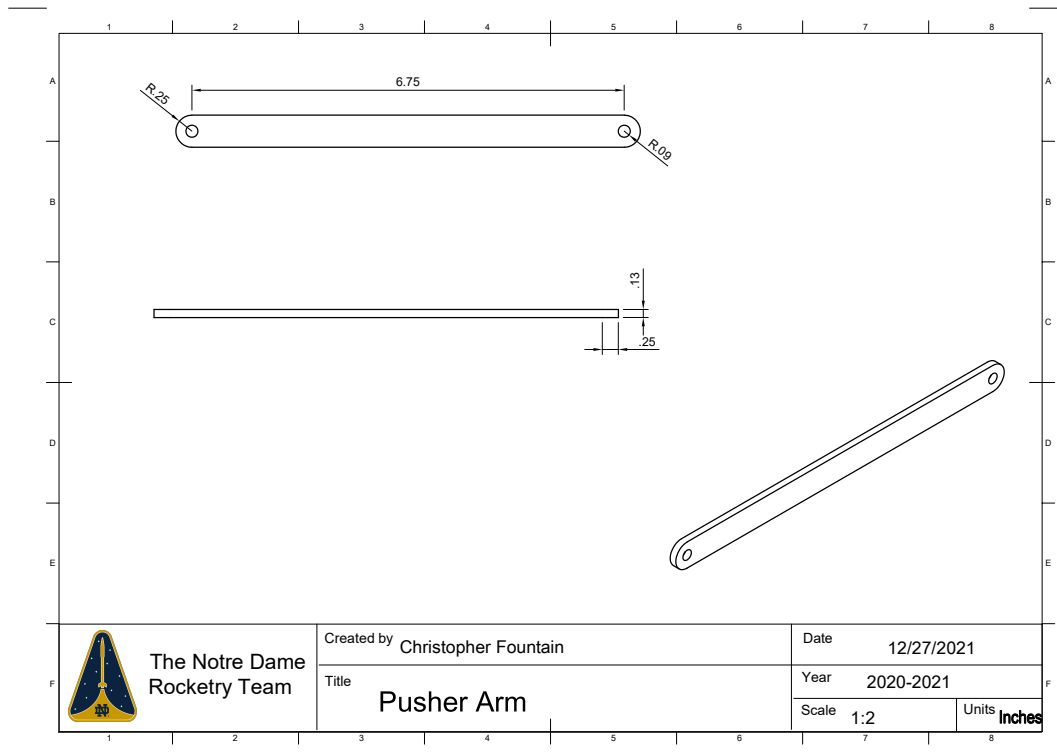


Figure 70: As Designed Pusher Arms

The pusher arms will interface to the central hub using shoulder screws and locknuts in order to provide a low friction turning surface while ensuring that the mechanism does not loosen over multiple cycles.

### 7.2.6 Lead Screw

The lead screw must be able to function over the entire operating envelope of forces expected to the Apogee Control System to a Factor of Safety of 2. The team has sourced a Thomson linear lead screw and lead screw collar assembly with a maximum dynamic load of 620 lbs, compared to the maximum expected load on the system of 308 lbs. The lead screw is machined out of 18-8 stainless steel, while the collar is machined out of bronze.

### 7.2.7 Central Hub

The central hub will be machined to fit around the collar of the lead screw, acting as an interface between the lead screw and the pusher arms of the mechanism. It will be machined out of 6061 aluminum using a multistage milling process. The central hub is a necessarily complex piece to machine due to the geometries of the lead screw collar and pusher arms. Thus, the primary design drivers for this component are ease of manufacturing and strength. A drawing of the designed central hub is shown in Figure 71.

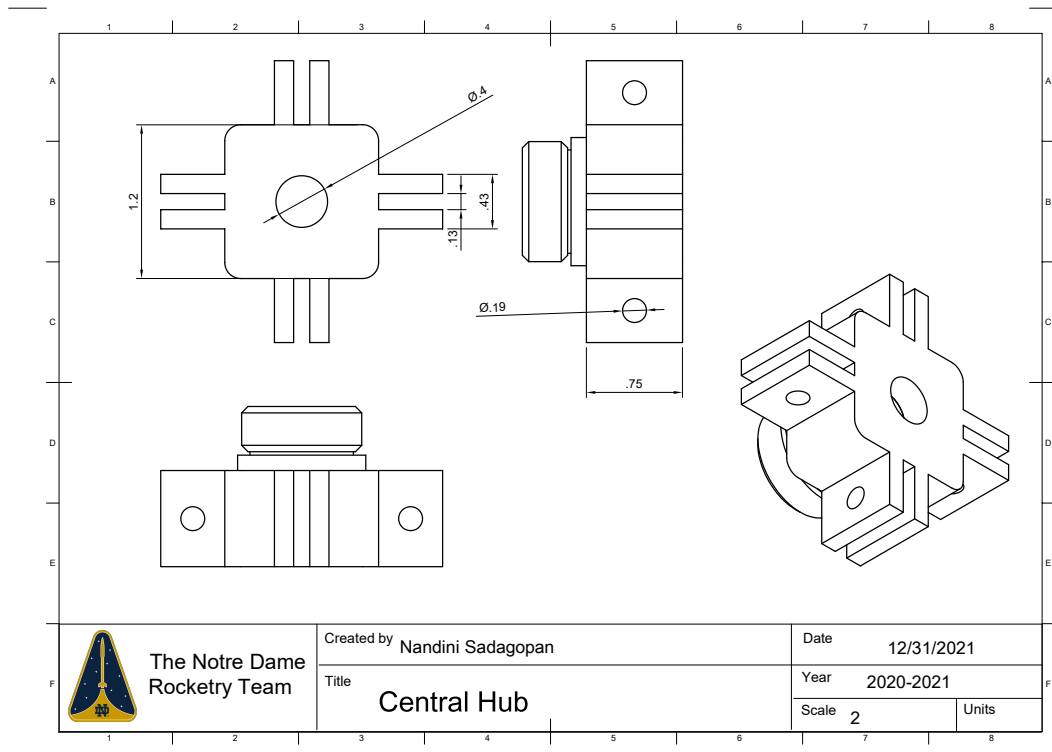


Figure 71: As Designed Central Hub

### 7.2.8 Mounting Blocks

Mounting blocks will be affixed to the fore bulkhead and motor bulkhead to transmit loads through the structural elements of the ACS, reinforcing the section of the ACS bay that includes cutouts for the ACS flaps to interface with the body of the launch vehicle. These mounting blocks are considered to be part of the critical load path for the mechanism, and will be machined out of aluminum using a CNC milling process.

Mounting blocks will interface with the bulkheads using non load bearing shoulder screws, as the mounting blocks themselves will be in compression during the primary loading events of the ACS (drogue parachute deployment, powered ascent). Load bearing screws will affix the bulkhead to the body tube through the mounting blocks. The simulator will interface with these mounting blocks in the event that a payload mass simulator needs to be flown ([NASA 2.19.1.3.2](#)).

### 7.2.9 Load Path Analysis

Finite element analysis was performed on each load bearing component to meet the required Factor of Safety of 2, ensuring structural integrity for all expected loading scenarios during flight. The two ACS loading scenarios that represent the greatest expected structural loading are A) the initial deployment of the drag flaps at burnout and B) the deployment of the drogue parachute. Structural verification in these two load cases is carried out in detail in Section 5.3 with a summary provided below. The force of drag on the launch vehicle shall not exceed 180 lbs due to constraints on the size of available shear pins, corresponding to a maximum angle of deployment at burnout of 12 degrees. This loading case was used to evaluate factor of safety of the pusher arms, flap support arms, hinges, lead screw, and central hub. The factor of safety of each of these components at this loading case is given in Table 53.

**Table 53:** FOS Values for Burnout Drag Deployment

Assembly Component	Yield Strength (psi)	FOS
Pusher Arms	40000	26.84
Flap Support Arms	40000	7.807
Hinges	40000	27.47
Lead Screw	30000	11.26
Central Hub	40000	2.88

The second loading case examined is the deployment of the drogue parachute, which interfaces with the the ACS through a U bolt in the center of the top bulkhead. A series of four airframe interfacing blocks at the fore and aft ends of the system transfer the loads to the airframe of the launch vehicle with standoffs running the length of the system to provide extra rigidity to the structure. The maximum force of deployment, calculated from a worst case scenario instantaneous deployment of the drogue parachute, is 600.43 lbs, equally distributed through both sides of the U bolt. This loading case was used to calculate factor of safety for the fore bulkhead, electronics mount, motor bulkhead, aft bulkhead, fore standoffs, and aft standoffs. The factor of safety of each of these components at this loading case is given in Figure 54.

**Table 54:** FOS Values for Drogue Parachute Deployment

Assembly Component	Yield Strength (psi)	FOS
Fore Bulkhead	35000	2.93
Motor Bulkhead	35000	2.046
Aft Bulkhead	35000	2.35
Fore Standoffs	40000	26.33
Aft Standoffs	40000	26.86

All factors of safety are greater than 2.0, verifying [ACS.6](#) and [ACS.9](#).

### 7.2.10 Motor Sizing and Selection

The motor chosen is a HSR-M9382TH continuous servo motor, which was sized for its high torque properties for the speed of its response. Originally, the team had chosen an SG12 Series Gearbox motor; however choice was altered after the redesign of the mechanism required a lower torque from the motor for the same amount of actuation, allowing for the team to choose the HSR-M9382TH, which has a no load speed of more than double the SG12 Series Gearbox. The properties of the finalized motor choice are given in Figure 55.

**Table 55:** Properties of Finalized Motor Selection: HSR-M9382TH

Property	Value
Stall Torque at 7.4 V (oz-in.)	472
No Load Speed at 7.4 V (sec/60 deg)	0.14
Stall Current (mA)	2700
Weight (oz)	2.4
Cost (USD)	209.90

### 7.3 Aerodynamic Analysis

The second order differential equation describing the acceleration of the launch vehicle after burnout (Equation 5) was solved using an explicit fourth order Runge Kutta algorithm to estimate the maximum decrease in apogee possible due to the deployment of the variable drag surfaces.

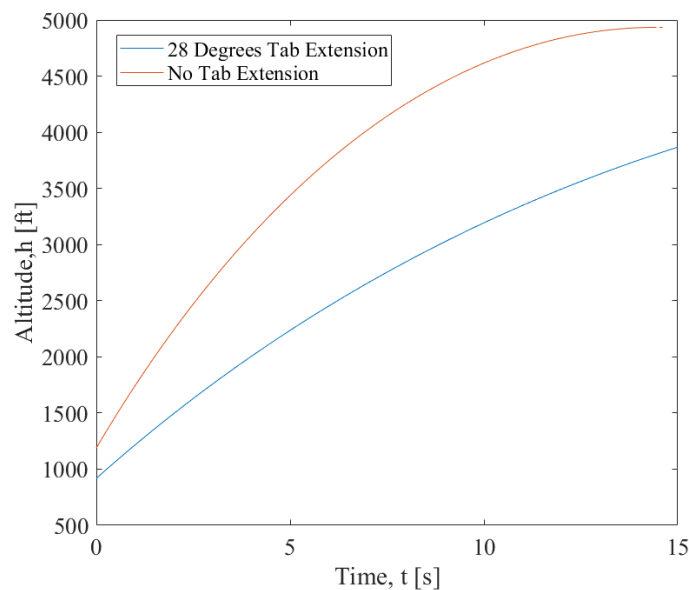
$$x'' = -\frac{1}{2m_r} \rho x'^2 (C_{dr} A_r + C_{dt} A_t) - g \quad (5)$$

where  $x''$  is the acceleration of the launch vehicle  $\rho$  is the air density,  $x'$  is the velocity of the launch vehicle  $C_{dr}$  is the drag coefficient of the launch vehicle without tabs extended,  $A_r$  is the reference area of the launch vehicle,  $C_{dt}$  is the drag coefficient of the tabs, and  $A_t$  is the reference area of the tabs. The drag coefficient of the tabs was estimated as that of an angled flat plate, given by Equation 6

$$C_{dt} = 1.28 \sin(\alpha) \quad (6)$$

where  $\alpha$  is the angle of extension of the tabs. The ACS was limited to a maximum force on the launch vehicle of 180 lbs to prevent excessive drag on the launch vehicle potentially resulting in drag separation before apogee, corresponding to a maximum extension of 28 degrees (ACS.8).

Equation 5 was solved forward in time until apogee for different static extensions of the tabs. Simplifying assumptions of this analysis were: constant air density, constant launch vehicle drag coefficient, no wind speed, zero launch rail angle. The initial velocity was taken from an OpenRocket calculation at the same conditions. The following results were obtained.



**Figure 72:** Estimated Decrease in Apogee of the Launch Vehicle Depending on Various Static Configurations of the Control Surfaces

The maximum decrease in altitude that the Apogee Control System can provide is 1110 ft for the simplified case where the tabs were at the same extension for the duration of the burnout to apogee portion of the flight.

OpenRocket predicts apogees for the launch vehicle without ACS to be between 4944 and 5304 ft depending on launch conditions, which is a range of 360 ft, with a max overshoot of 504 ft. Thus, the team is confident that the

Apogee Control System will be able to control the launch vehicle down to the target apogee regardless of launch day conditions, verifying [ACS.4](#).

The above estimations will be further confirmed with wind tunnel testing in late January, at which time the drag coefficient of the control surfaces at different angles of attack will be empirically measured and compared to this approximation.

## 7.4 Electrical Design

The ACS relies on knowledge of the current position, velocity, and acceleration of the launch vehicle to determine the optimal extension of the drag surfaces. This information is obtained from an array of sensors which each communicate data to the Raspberry Pi 4b microcontroller. This year, the system will be equipped with three major sensors: an accelerometer, an altimeter, and an inertial measurement unit (IMU). This information represents two data points for each acceleration, orientation, and altitude as the IMU records both acceleration and barometric pressure data and the accelerometer records triple axis acceleration providing orientation data. This sensor suite is in accordance with [NDRT ACS.2](#) and [NDRT ACS.3](#). Additionally, the system will be equipped with two limit switches to regulate the position of the mechanism. The integrated electronics suite will be tested at the extremes of the expected temperature envelope to ensure compliance with [NDRT ACS.5](#), operation between 0F and 100F.

### 7.4.1 Accelerometer

An accelerometer allows the system to gain an accurate estimate of the acceleration of the launch vehicle, which can determine when the motor fires, when the launch vehicle lands, or can be combined with other sensors to estimate the vehicle's position and velocity. The team was originally planning on using the Adafruit ADXL377 accelerometer due to its high maximum acceleration. However, this analog sensor was found to be incompatible with the Raspberry Pi 4b microcontroller. Instead, the team chose to utilize a DFRobot Gravity I2C H3LIS200DL Triple Axis Accelerometer Sensor, shown in Figure 73. This sensor also has a high maximum acceleration of 200g, exceeding any acceleration the launch vehicle could experience during flight. It also has a relatively low power consumption of  $33 \mu W$  at 3.3V. Most importantly, it is capable of digital communication with a Raspberry Pi microcontroller using the I<sup>2</sup>C protocol.



Figure 73: DFRobot Gravity I2C H3LIS200DL Triple Axis Accelerometer

### 7.4.2 Altimeter

An altimeter allows the system to roughly determine its current altitude during flight, which can determine when apogee has occurred and can provide an accurate estimate of the vehicle's velocity and acceleration with other sensor data. The altimeter will also collect altitude and velocity versus time data (NASA 2.19.1.9). The altimeter chosen is a BMP390 sensor because it is accurate to within  $\pm 0.25\text{m}$  of the true altitude and can be used in an I<sup>2</sup>C configuration with the Raspberry Pi microcontroller. Figure 74 shows the chosen altimeter.

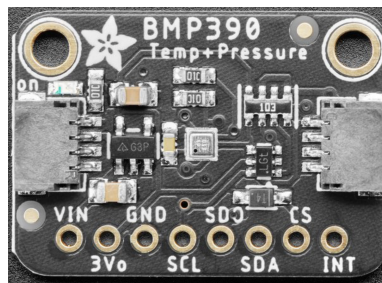


Figure 74: Adafruit BMP390 Altimeter

### 7.4.3 Inertial Measurement Unit

The IMU allows for the accurate detection of the orientation of the launch vehicle, which is useful for isolating the vertical components of velocity and acceleration obtained by other sensors. Additionally, the on-board accelerometer can serve as an independent estimate of the acceleration of the launch vehicle, which increases the redundancy of the system. The IMU chosen is an InvenSense ICM-20948 9DoF sensor, shown in Figure 75. It was chosen because it has a relatively high sampling rate and because each of its sensors have maximum detection ranges which can fully capture any expected conditions during flight.

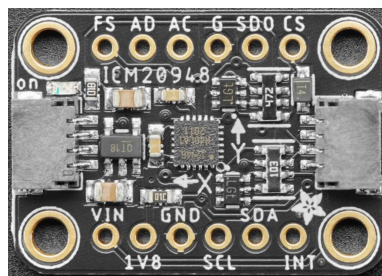


Figure 75: ICM-20948 9DoF IMU

### 7.4.4 Limit Switches

Two limit switches are needed to verify when the drag surfaces have reached their end of travel. Once this is done, the servo can be automatically stopped by the software to ensure that the mechanism does not over-extend in either direction. One switch will be used on the bulkhead at the top of the screw mechanism, and the other will be used on the bottom bulkhead. This will stop the tabs from continuing to retract or extend when they reach their end of travel. The type of limit switch being used is an SDPT (Single Pole Double Throw) micro limit switch (straight lever), shown in Figure 76.

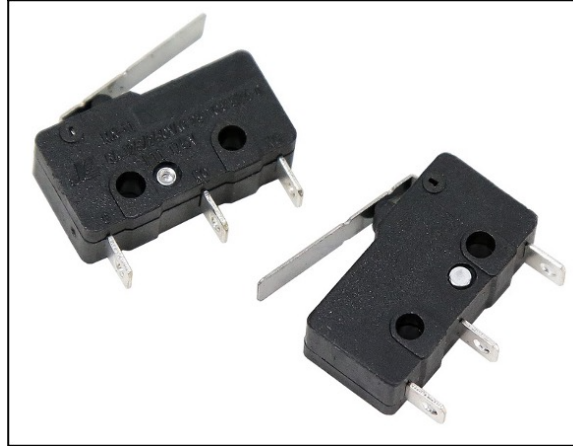


Figure 76: Micro Limit Switches

#### 7.4.5 Battery Selection

The ACS consists of two main circuits. The first is the logic circuit, which consists of the Raspberry Pi 4b microcontroller, along with all of the sensors. The second is the motor circuit, which consists of the servo motor and servo controller used to actuate the drag surfaces. These two circuits share a common ground and a wire to facilitate PWM communication, but are otherwise separate from each other. Each of these circuits have different voltage and current requirements, and are therefore powered by two distinct batteries. Both batteries will be tested at coldest condition to ensure compliance with [NDRT ACS.7](#), battery operation for 3 hours. Batteries will also be protected from impact and brightly marked as hazardous ([NASA 2.22](#)).

**7.4.5.1 3.7 Volt Circuit** The team has chosen the Litr 1s 3.7V 2800mAh LiPo battery for the logic circuit. This battery was chosen for several reasons. First, it can meet the voltage and current requirements of the Raspberry Pi. Additionally, it is relatively cheap, lightweight, and compact for its capacity. Finally, this battery has a fairly high capacity. With the chosen sensors, the logic circuit draws roughly 605.5mA of current. At the capacity of this battery, the team can therefore power the system for over four hours, which well exceeds the time required to complete the mission objectives.

One other important consideration is that the 3.7V supplied by the Litr battery is not quite as high as the 5V required by the Raspberry Pi. The team will use an Adafruit PowerBoost 500C to step up the 3.7V voltage to the 5V which is required to power the system to compensate for this. The PowerBoost will be attached to the ACS sensor PCB that connects it electrically to the microcontroller. This will ensure that there is negligible risk of the Pi losing power during flight. Figure 77 shows an image of the chosen PowerBoost.

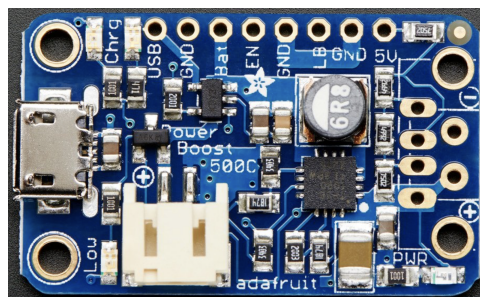


Figure 77: Adafruit Powerboost 500C

**7.4.5.2 7.4 Volt Circuit** The team will use the Ovonix 2s 7.4V 2200mAh LiPo battery to satisfy the motor's larger voltage requirement. This battery was chosen because it meets the minimum voltage and current requirements of the servo motor, while still being relatively small, lightweight, and cost effective. This battery has a high enough capacity to power the servo motor at stall torque for 45 minutes. This will ensure that there is little danger of the mechanism losing power and failing during flight since the ACS mechanism is going to be actuating for less than a minute.

**7.4.5.3 Battery Sensor Selection** The team will be utilizing a battery power sensor in addition to the other sensors normally used. This sensor will be used to ensure that the batteries have sufficient power to ensure that the ACS can complete its mission objectives. This sensor can then be integrated with a warning system to notify the team if a battery replacement needs to be made before launch. The selected power sensor is the Adafruit INA260 High or Low Side Voltage, Current, Power Sensor. This sensor is capable of communicating with the Raspberry Pi using the I2C communication protocol, and is compatible with batteries up to a maximum voltage of 36V, which well exceeds the voltage of the batteries in use by the team.

#### 7.4.6 Printed Circuit Board Design

A printed circuit board will be used to integrate the sensor and microcontroller subsystems, which was designed in the software KiCad. A PCB was chosen over a perfboard because of the security of its electrical connections and lower likelihood of miswiring in the integration process. PCB includes the altimeter, accelerometer, IMU, microcontroller, and servo controller. An image of the rendered PCB design is shown in Figure 78.

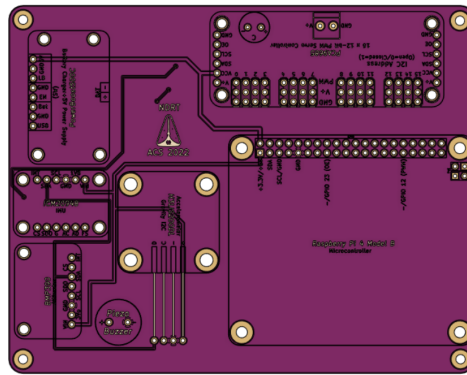
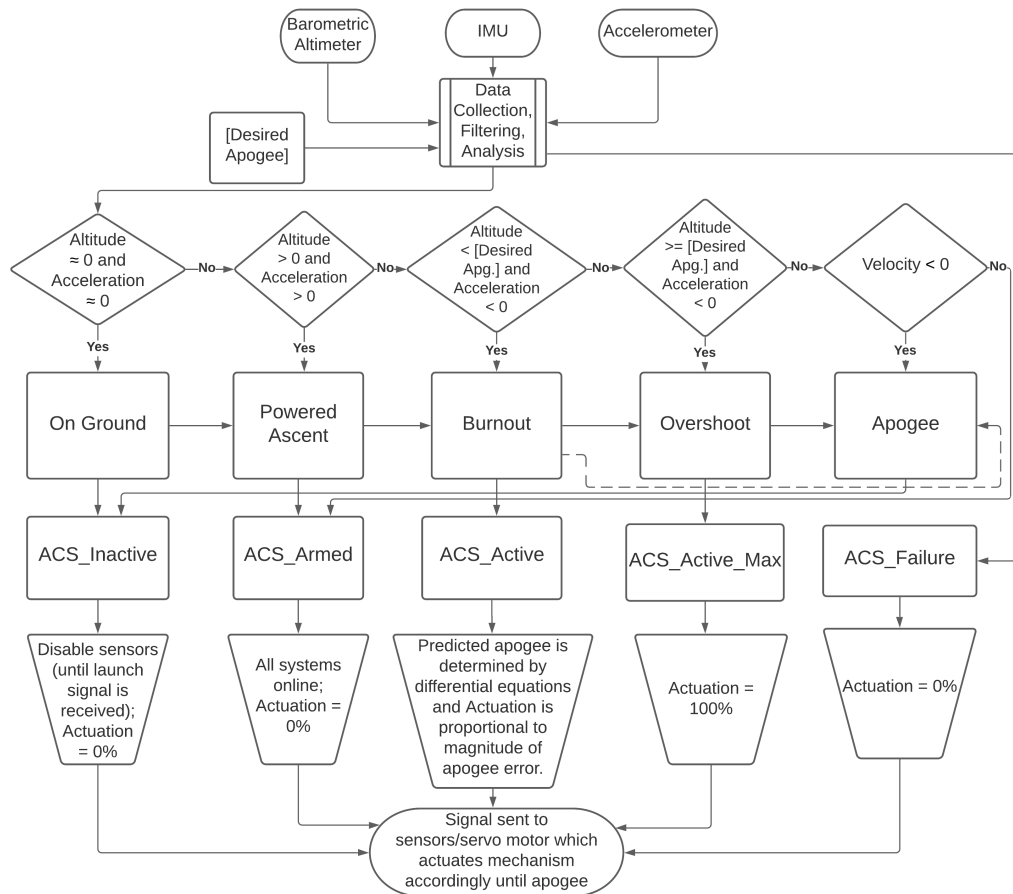


Figure 78: Rendered PCB Design

### 7.5 Control System Design

The overall control flow design of the system is described by Figure 79.





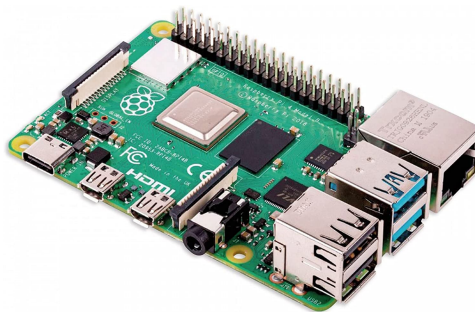
**Figure 79:** ACS Overall Control Code Flow Chart

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](#).

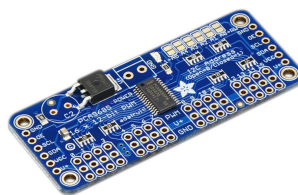
### 7.5.1 Microcontroller Selection

The microcontroller chosen is a Raspberry Pi 4 because it is a relatively powerful single-board embedded computer. Its 1.5 GHz Quad-Core processor allows it to perform operations with low latency and its MicroSD card slot allows it to store Python programs on a MicroSD card. This will enable the microcontroller to perform compute-intensive tasks such as data filtering and make programmed trajectory predictions based on the current state of the launch vehicle. The microcontroller can operate in a temperature range of 0-50°C, making it fit for purpose. It is also capable of communicating with a servo controller to send and receive Pulse Width Modulation (PWM) signals from the servo motor that actuates the ACS tabs. The Raspberry Pi is attached to a main PCB along with the other sensors. The microcontroller is shown in [Figure 80](#).



**Figure 80:** Raspberry Pi 4 Microcontroller

**7.5.1.1 Servo Controller Selection** The servo controller being used is an Adafruit PCA9685 16-Channel 12-bit PWM/Servo Driver compatible with the I<sup>2</sup>C interface of the microcontroller. It has a terminal block for power input and allows up to 16 servos to be controlled independently. It is also 5V compliant and has a built-in clock, which makes it free running. Using a servo controller allows smoother PWM signals to be passed from the microcontroller to the servo as compared to connecting the servo directly to the Raspberry Pi PWM pins. This lets the Raspberry Pi control the servo very precisely and minimizes servo motor jitter when actuating the ACS tabs. The PCA9685 is attached to a main PCB along with the other sensors. The servo controller is shown in [Figure 81](#).



**Figure 81:** Adafruit PCA9685 16-Channel 12-bit PWM/Servo Driver

### 7.5.2 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. The system is able to read in some of these values from the sensor array, which provides an estimate of the height, as well as two redundant estimates of the acceleration of the launch vehicle. However, the system cannot use these 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 memoryless. 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. In comparison, some filters require the storage and retrieval of many past data points at each iteration, which causes the system to run more slowly and take up more memory.

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  $\Phi_k$  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 timestep  $k$ . This matrix is derived from basic kinematics equations, and is defined in Equation 7.

$$\Phi_k = \begin{pmatrix} 1 & \Delta & \frac{1}{2}\Delta^2 \\ 0 & 1 & \Delta \\ 0 & 0 & 1 \end{pmatrix} \quad (7)$$

In the above equation,  $\Delta$  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 8

$$\hat{x}_{k(-)} = \Phi_{k-1} \hat{x}_{k-1(+)} \quad (8)$$

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  $\Phi_k$ . 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 9.

$$\hat{x}_{k(+)} = \hat{x}_{k(-)} + K_k(z_k - H_k \hat{x}_{k(-)}) \quad (9)$$

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. After this point, the Kalman filter 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 10 - 12 are used. Note that here,  $I$  represents the identity matrix.

$$P_{k(-)} = \Phi_{k-1} P_{k-1(+)} \Phi_{k-1}^T + Q_{k-1} \quad (10)$$

$$P_{k(+)} = [I - K_k H_k] P_{k(-)} \quad (11)$$

$$K_k = P_{k(+)} H_k^T [H_k P_{k(+)} H_k^T + R_k]^{-1} \quad (12)$$

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. To demonstrate the efficacy of the Kalman filter, the team used the Kalman filter to filter data obtained from one of the subscale flights. This flight was performed without any kind of drag surfaces attached, and the resulting plots can be seen in Figure 82.

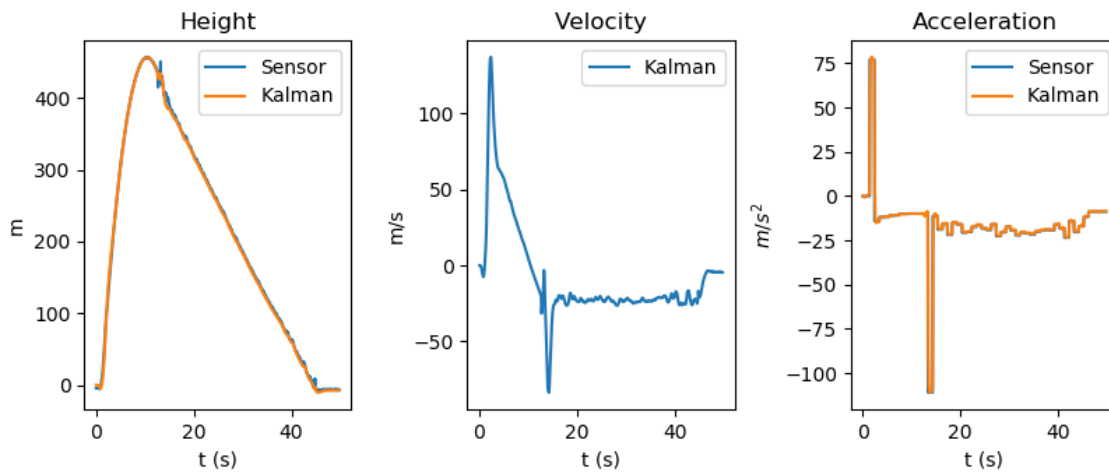


Figure 82: Kalman Filtered Subscale Data

Figure 82 demonstrates that the Kalman filter is capable of smoothing out otherwise noisy data and giving a reasonable approximation of the velocity of the launch vehicle.

### 7.5.3 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 13.

$$\Phi(s) = K_P E(s) + K_D s E(s) + K_I \frac{E(s)}{s} \quad (13)$$

Here,  $E(s)$  is the error in the frequency domain,  $\Phi$  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 Integration

The system will be integrated into the fin can of the launch vehicle at a position so that the fins extend near the center of pressure. Screws and mounting blocks will keep the ACS housed in its bay, with the component being entirely between two bulkheads composed of garolite. An exploded view of the integrated system is shown in Figure 83. Four cuts 90 degrees apart from each other will be made to allow for successful actuation of the drag tabs. Hinges have been added on the bottom side of the top bulkhead to keep the tabs from interfering with the body tube. Such an addition allows the drag tabs to actuate with a greater range of freedom. The ideal position for the drag tabs is when the tabs are 60 degrees away from the launch vehicle, with the pushrods and the drag tabs perpendicular at this point. An additional part will be attached at the base of the pushrods to allow for their vertical motion, as printing internal threading is unrealistic due to limitations involving precision cutting.

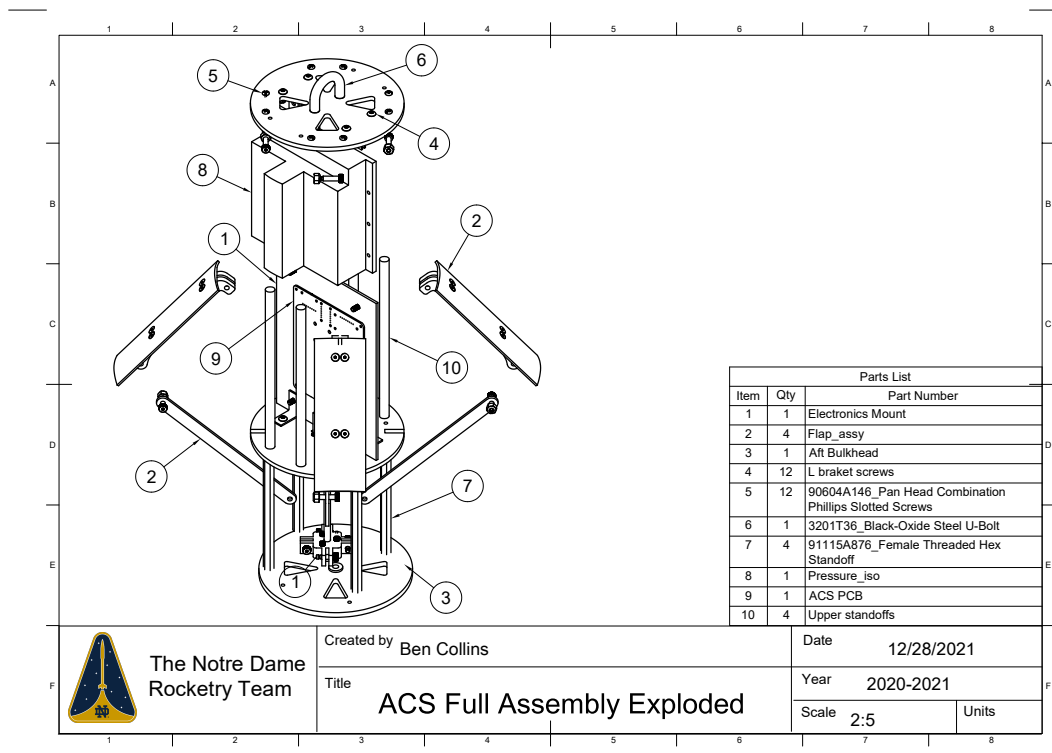


Figure 83: ACS Integrated System Exploded View

### 7.7 Detailed Mass Estimate

Each component that will be included in the Apogee Control System, along with its mass, component type, MGA%, and predicted mass is listed in Table 56 (NASA 2.19.1.3.1).

**Table 56:** ACS Mass Breakdown

Component Name	Maturity	Component Type	Basic Mass Estimate	MGA %	Predicted Mass
Top Bulkhead	4	PRIM	4.778	4	4.969
Motor Bulkhead	4	PRIM	4.89	4	5.085
Bottom Bulkhead	4	PRIM	5.729	4	5.958
Top Standoffs	4	PRIM	4.136	4	4.301
Bottom Standoffs	4	PRIM	5.172	4	5.379
Pusher Arms	4	PRIM	2.744	4	2.854
Flap Support Arms	4	PRIM	7.296	4	7.587
Hinges	4	PRIM	1.228	4	1.277
Flaps	4	MECH	3.392	4	3.528
Lead Screw	5	MECH	5.325	4	5.432
Lead Screw Collar	5	MECH	2.984	2	3.044
Central Hub	4	MECH	1.651	4	1.717
Airframe Mounting Blocks	5	PRIM	1.552	2	1.583
Electronics Mount	4	PRIM	7.6	4	7.904
U Bolt	5	PRIM	3.042	2	3.103
PCB	5	ELEC	0.5	3	0.515
Acclerometer	4	ELEC	0.3	8	0.324
Altimeter	4	ELEC	0.3	8	0.324
IMU	4	ELEC	0.3	8	0.324
Microcontroller	5	ELEC	0.423	3	0.436
Servo Controller	5	ELEC	0.317	3	0.327
Limit Switches	5	ELEC	0.1	3	0.103
7.4 V Battery	5	BAT	4.23	2	4.315
3.7 V Battery	5	BAT	1.76	2	1.795
Sensor Cover	4	MECH	2.646	4	2.752
<b>Total</b>			<b>73.04</b>		<b>75.78</b>

## 8 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.

## 8.1 Launch Concerns and Operation Procedures



# LAUNCH OPERATING PROCEDURES

Revision Number	Date	Change Description
1.0	12/21/2021	Initial

### 8.1.1 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.

### 8.1.2 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 8.1.3 through 8.1.9. 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.

### 8.1.3 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

- |   |  |  |
|---|--|--|
| <input type="checkbox"/> Nitrile gloves (1 box)         | <input type="checkbox"/> Fully-stocked first aid kit (See Safety Handbook Section 2.1) | <input type="checkbox"/> Safety glasses (3 minimum)              |
| <input type="checkbox"/> Cut resistant gloves (1 pair)  | <input type="checkbox"/> Dust masks (1 box)  | <input type="checkbox"/> Fire resistant battery bags (5 minimum) |
| <input type="checkbox"/> Heat resistant gloves (1 pair) |  |  |
| <input type="checkbox"/> Leather gloves (1 pair)        |  |  |

### TOOLS

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

### GENERAL EQUIPMENT

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

### VEHICLE EQUIPMENT

- |   |   |   |
|---|---|---|
| <input type="checkbox"/> Payload Bay and nose cone assembly | <input type="checkbox"/> ACS Bay            | <input type="checkbox"/> Airframe mounting screws |
| <input type="checkbox"/> Recovery Bay                       | <input type="checkbox"/> Fin Can            | <input type="checkbox"/> Ballast material         |
|   | <input type="checkbox"/> Motor retainer cap |   |

### ACS EQUIPMENT

- |   |  |
|---|--|
| <input type="checkbox"/> Assembled ACS system without flaps | <input type="checkbox"/> Fully charged battery |
| <input type="checkbox"/> ACS drag flaps (4)                 |  |

### RECOVERY EQUIPMENT

- |  |   |  |
|--|---|--|
| <input type="checkbox"/> Assembled PRM                         | <input type="checkbox"/> Pilot parachute                | <input type="checkbox"/> Drogue recovery shock cord        |
| <input type="checkbox"/> Assembled SRM                         | <input type="checkbox"/> Drogue parachute               | <input type="checkbox"/> Fin can separation quicklinks (2) |
| <input type="checkbox"/> Fully charged altimeter batteries (6) | <input type="checkbox"/> Main recovery quicklinks (4)   | <input type="checkbox"/> Fin can separation shock cord     |
| <input type="checkbox"/> Key for key switches                  | <input type="checkbox"/> Main recovery swivel           | <input type="checkbox"/> GPS                               |
| <input type="checkbox"/> Main parachute                        | <input type="checkbox"/> Main recovery shock cord       | <input type="checkbox"/> Cell phone for GPS connection     |
|  | <input type="checkbox"/> Drogue recovery quicklinks (2) |  |

**LVIS EQUIPMENT**

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

**TEAM MENTOR HANDLED EQUIPMENT**

- Black powder (120g)     E-matches  
 Aerotech L2200G-P Motor (3)     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: \_\_\_\_\_

**8.1.4 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: \_\_\_\_\_

### 8.1.5 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 8.1.5 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: \_\_\_\_\_

### 8.1.6 Recovery Preparation

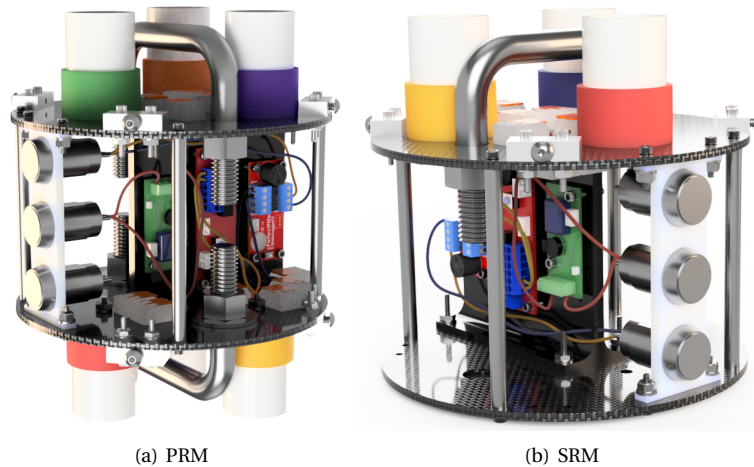
**Required Personnel:** Recovery Lead, 8. Safety Officer, Project Manager, Team Mentor, Systems Lead

**Required PPE:** Nitrile gloves, Safety goggles

#### 8.1.6.1 Inspection Checklist :

**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



**Figure 84:** Recovery Module Assemblies

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 adhesives are secure.
- Inspect bulkhead and U-bolt on SRM. Give the U-bolt a light tug to ensure adhesives are secure.
- Inspect bulkheads and eye bolt on LVIS retention bulkhead. Give the eye bolts a light tug to ensure adhesives are secure.
- Inspect bulkheads and eye bolt on ACS bulkhead. Give the eye bolts a light tug to ensure adhesives are secure.
- 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 duct tape.
- Check that all lithium polymer batteries are fully charged with the use of a multimeter. The nominal voltage of a lithium polymer battery is 3.7 V or 7.4 V. 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.

**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: \_\_\_\_\_

### 8.1.6.2 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.

#### 8.1.6.2.1 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.
- 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. 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 group 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 85 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.
- 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 8.1.9.3).



**Figure 85: 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: \_\_\_\_\_

### 8.1.6.2.2 Drogue Parachute Folding :

Unlike the main parachute, the drogue parachute does not require four team members to fold.

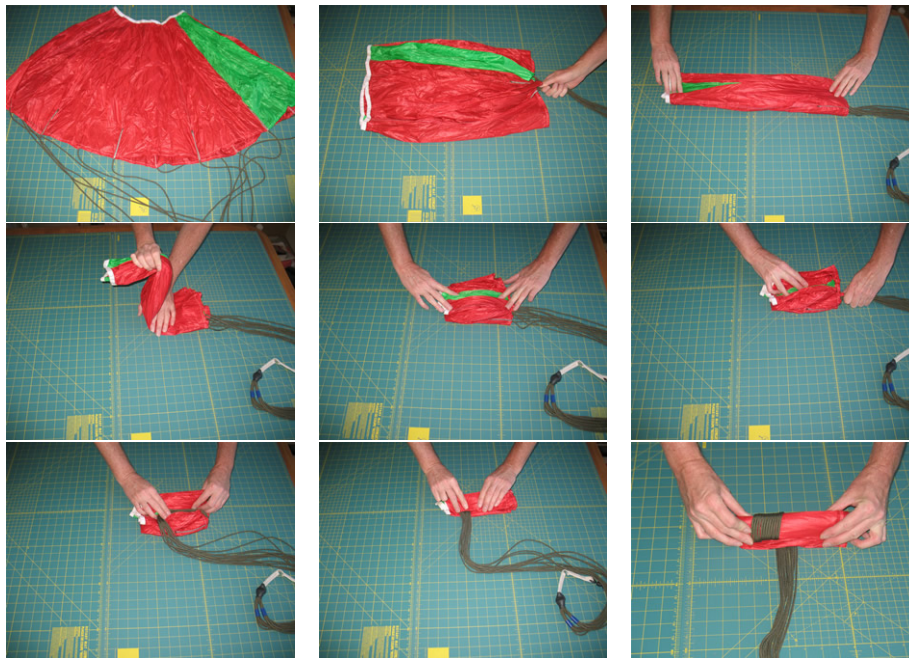
- Raise the parachute in the air, making sure all 4 shroud lines are straight.
- Untangle all cords, if needed.
- Shake the parachute lightly to untangle the cords.
- Attach a quicklink to the open loop at the end connection of all shroud lines.

- Ensure all drogue parachute connections are securely attached, including quicklinks.

**For future steps, reference Figure 86 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.
- 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.
- Loosely roll the parachute in the nomex blanket and fold to easily fit in the launch vehicle body tube.

Drogue parachute is now ready to be installed into the launch vehicle (Launch Procedure Step 8.1.9.3).



**Figure 86:** 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: \_\_\_\_\_

#### 8.1.6.2.3 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 “1”, “2”, and “3”, respectively.
- Make sure the batteries are still fully charged (Step 8.1.6.1).
- Insert a fully charged altimeter battery into each battery slot. Plug batteries into the JST port on the perfboard.

**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: \_\_\_\_\_

#### 8.1.6.2.4 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 “4” and “5”, respectively.
- Make sure the batteries are still fully charged (Step 8.1.6.1).
- Insert a fully charged altimeter battery into each battery slot. Plug batteries into the JST port on the perfboard.

**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: \_\_\_\_\_

#### 8.1.6.2.5 Black Powder Separation Charges :

**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, 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.

**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: \_\_\_\_\_

#### 8.1.6.2.6 Parachute Integration :

**Note:** Remove the masking tape from the shroud lines from Steps 8.1.6.2.1 and 8.1.6.2.2, 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 8.1.9.3) 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 8.1.6 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: \_\_\_\_\_

#### 8.1.7 Launch Vehicle Identification System (LVIS) Preparation

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

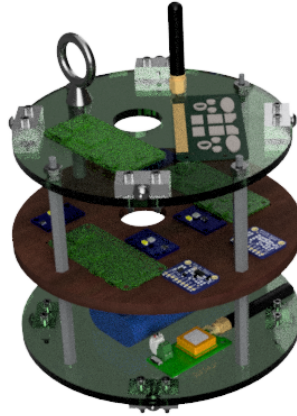
**Required PPE:** None for LVIS preparation

##### 8.1.7.1 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.





**Figure 87:** Launch Vehicle Identification System (LVIS)

- 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 all lithium-polymer batteries are fully charged with the use of a multimeter. The nominal voltage of a lithium polymer battery is 3.7 V or 7.4 V. If the batteries 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.

**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: \_\_\_\_\_

#### 8.1.7.2 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 8.1.7.1).
- Install the 3.7 V batteries into the appropriate slot.
- Ensure the correct SD card has been inserted into the Raspberry Pi.

**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 8.1.9.2) 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: \_\_\_\_\_

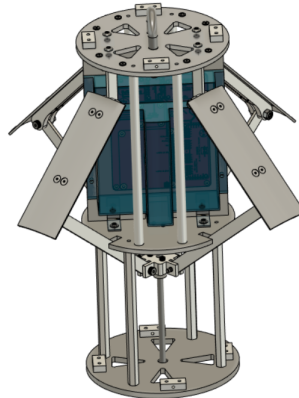
Safety Officer Signature: \_\_\_\_\_

Project Manager Signature: \_\_\_\_\_

### 8.1.8 Apogee Control System (ACS) Preparation

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

**Required PPE:** None for ACS preparation



**Figure 88:** Apogee Control System (ACS)

#### 8.1.8.1 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.

**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: \_\_\_\_\_

#### 8.1.8.2 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.

#### 8.1.8.2.1 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.

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

#### 8.1.8.2.2 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 8.1.8.1).
- 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. The arming LED should turn on. The launched state LED should NOT turn on.

See "ACS Integration" (Section 8.1.9.1) 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: \_\_\_\_\_

### 8.1.9 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



**Figure 89:** Launch Vehicle Model

**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.

### 8.1.9.1 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 8.1.9.1 steps.
- Ensure the system is still not in the launched state.
- Review all 8.1.9.1 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 8.1.8 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: \_\_\_\_\_

### 8.1.9.2 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 8.1.9.2 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: \_\_\_\_\_

### 8.1.9.3 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.

#### 8.1.9.3.1 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.
- Insert the folded main parachute in the fore section of the PRM. Ensure it is easily removable from the body tube.**
- Insert the folded drogue parachute in the aft section of the PRM. Ensure it is easily removable from the body tube.**
- 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.

#### 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 8.1.6.2.1 Main Parachute Folding or 8.1.6.2.2 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 8.1.9.3.1 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: \_\_\_\_\_

#### 8.1.9.3.2 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: \_\_\_\_\_

#### 8.1.9.4 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: \_\_\_\_\_

#### 8.1.9.5 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 9.1 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 8.1.6.
- If a component is found damaged from the shake test, locate a replacement component in team toolboxes; reference Launch Procedure 8.1.3 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: \_\_\_\_\_

#### 8.1.9.6 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.

##### 8.1.9.6.1 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: \_\_\_\_\_

##### 8.1.9.6.2 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 casting.
- Screw on the rear closure of the casting.
- 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: \_\_\_\_\_

#### 8.1.9.7 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: \_\_\_\_\_

**8.1.9.8 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: \_\_\_\_\_

### 8.1.10 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

#### 8.1.10.1 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: \_\_\_\_\_

#### 8.1.10.2 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: \_\_\_\_\_

**8.1.10.3 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 8.1.10.2.
- 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: \_\_\_\_\_

**8.1.10.4 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.

**8.1.10.4.1 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: \_\_\_\_\_

**8.1.10.4.2 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. [8.10.4.1](#).
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: \_\_\_\_\_

- 8.1.10.4.3 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.

**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 [8.1.8](#) 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: \_\_\_\_\_

**8.1.10.4.4 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 8.1.7 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: \_\_\_\_\_

#### 8.1.10.4.5 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 8.1.10 onward.

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

Vehicles Lead Signature: \_\_\_\_\_

Safety Officer Signature: \_\_\_\_\_

#### 8.1.10.4.6 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: \_\_\_\_\_

### 8.1.11 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:**

- 8.1.5 Upon Arrival at Launch Field
- 8.1.6 Recovery Preparation
- 8.1.7 LVIS Preparation
- 8.1.8 ACS Preparation
- 8.1.9 Launch Vehicle Preparation
- 8.1.10 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 8.1.10.4.5.
4. Attempt to launch the vehicle again, repeating all procedures from 8.1.11.
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: \_\_\_\_\_

### 8.1.12 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.

#### 8.1.12.1 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: \_\_\_\_\_

#### 8.1.12.1.1 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 8.1.5.

**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: \_\_\_\_\_

## 8.2 Failure Modes and Effects Analysis

### 8.2.1 Vehicle Flight Mechanics Failure Modes and Effects Analysis

**Table 57:** Vehicle Flight Mechanics Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
VFM.1	Fin Flutter	1. Fin imperfections due to manufacturing failures 2. Fins are improperly attached to the launch vehicle	1. Launch vehicle has unexpected flight trajectory 2. Potential damage to launch vehicle and/or components 3. Potential Injury to nearby personnel, civilians, and/or structures	3	3	9	1. Construction procedures will be written, and they will outline the necessary steps for fin construction and instillation 2. Computer simulations and calculations 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) 3. The material of the fins have been chosen with strength, weight, and system stability in mind 4. Wind tunnel testing procedures have been written to evaluate the forces and flow of the wind on the vehicle, especially the fins. All tests will be performed prior to FRR 5. Fin can drop testing procedures have been written to evaluate the strength of the fins during a ground impact. All tests will be performed prior to FRR 6. Launch Procedures have been written, and they outline the necessary steps for inspecting fin quality before launch	1. Construction procedures will be written prior to construction 2. Calculations and simulations for the fins and stability margin can be found in Section 5.2.2, and they were approved by both the Safety Officer and the Systems Officer 3. Team members ordering the fins and adhesives must consult the team's trusted vendor list and past motor data before making any motor purchase 4. All Testing Procedures can be found in Section 9.1 5. Launch Procedures for fin inspections can be found in Section 8.1.5 6. Material selection for the fins can be found in Section 3.3.5	2	2	4



VFM.2	Launch vehicle is unstable during flight	<ol style="list-style-type: none"> <li>Design fails to place the center of pressure below the center of mass</li> <li>Improper installation of the fins and/or motor results in failure to place the center of pressure below the center of mass</li> </ol>	<ol style="list-style-type: none"> <li>Launch vehicle turns against the wind, resulting in unintended flight trajectory</li> <li>Potential failure to reach target apogee</li> <li>Potential damage to launch vehicle and/or components</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>Construction procedures will be written, and they will outline the necessary steps for fin construction and instillation</li> <li>Computer simulations and calculations have been performed in order to evaluate the location of the center of pressure and center of mass</li> <li>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)</li> <li>The center of mass will be calculated at the launch field in order to ensure the calculated value is accurate</li> <li>The material of the fins has been chosen with strength, weight, and system stability in mind</li> <li>Wind tunnel testing procedures have been written to evaluate the forces and flow of the wind on the vehicle, especially the fins. All tests will be performed prior to FRR</li> <li>The motor will be purchased from a reputable vendor and installed using proper techniques</li> <li>Launch Procedures have been written, and they outline the necessary steps for determining the actual stability of the launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>Construction procedures will be written prior to construction</li> <li>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</li> <li>Launch procedures for stability testing can be found in Section 8.1.9.7</li> <li>Team members ordering the motor and fins must consult the team's trusted vendor list and past motor data before making any motor purchase</li> <li>All Testing Procedures can be found in Section 9.1</li> <li>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</li> </ol>	2	2	4
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VFM.3	Launch vehicle is overstable during flight	<ol style="list-style-type: none"> <li>Design places the center of pressure too far below the center of mass</li> <li>Improper installation of the fins and/or motor places the center of pressure too far below the center of mass</li> </ol>	<ol style="list-style-type: none"> <li>Launch vehicle turns into the wind, resulting in unintended flight trajectory</li> <li>Potential failure to reach target apogee</li> <li>Potential damage to launch vehicle and/or components</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>Construction procedures will be written, and they will outline the necessary steps for fin construction and installation</li> <li>Computer simulations and calculations have been performed in order to evaluate the location of the center of pressure and center of mass</li> <li>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)</li> <li>The center of mass will be calculated at the launch field in order to ensure the calculated value is accurate</li> <li>The material of the fins has been chosen with strength, weight, and system stability in mind</li> <li>Wind tunnel testing procedures have been written to evaluate the forces and flow of the wind on the vehicle, especially the fins. All tests will be performed prior to FRR</li> <li>The motor will be purchased from a reputable vendor and installed using proper techniques</li> <li>Launch Procedures have been written, and they outline the necessary steps for determining the actual stability of the launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>Construction procedures will be written prior to construction</li> <li>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</li> <li>Launch procedures for stability testing can be found in Section 8.1.9.7</li> <li>Team members ordering the motor and fins must consult the team's trusted vendor list and past motor data before making any motor purchase</li> <li>All Testing Procedures can be found in Section 9.1</li> <li>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</li> </ol>	1	2	2
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VFM.4	Launch vehicle initially travels in an unintended line of motion	<ol style="list-style-type: none"> <li>1. Failure to secure the motor at the proper angle</li> <li>2. Failure to properly install the rail buttons at the proper angle</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch vehicle continues to follow an unintended flight trajectory</li> <li>2. Potential failure to reach target apogee</li> <li>3. Potential damage to launch vehicle and/or components</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. Construction procedures will be written, and they will outline the necessary steps for rail button, fin, and motor mount construction and instillation</li> <li>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</li> <li>3. 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)</li> <li>4. Launch Procedures have been written, and they outline the necessary steps for a safe motor transportation to the launch site</li> <li>5. Launch procedures have been written, and they will outline the necessary steps for motor inspection and instillation</li> <li>6. Launch Procedures have been written, and they will outline the necessary steps for installing the launch equipment while following all NAR standards</li> </ol>	<ol style="list-style-type: none"> <li>1. Team members ordering the motor consulted the team's trusted vendor list and past motor data before making any motor purchase</li> <li>2. Construction procedures will be written prior to FRR</li> <li>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</li> <li>4. Calculations and simulations can be found in Section 5, and they were approved by both the Safety Officer and the Systems Officer</li> <li>5. Launch Procedures for motor transportation can be found in Section 8.1.4</li> <li>6. Launch Procedures for motor inspection and integration can be found in Section 8.1.9.6</li> <li>7. Launch Procedures for launch pad setup can be found in Section 8.1.10</li> <li>8. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 8.1.10.4</li> </ol>	2	2	4
VFM.5	Failure of launch vehicle to clear launch rails	<ol style="list-style-type: none"> <li>1. Launch rail deformations</li> <li>2. Selected motor inadequate in clearing launch rail</li> <li>3. Pre-existing motor imperfections</li> <li>4. Rail buttons deformations and/or break during clearance</li> </ol>	<ol style="list-style-type: none"> <li>1. Mission failure due to failed launch</li> <li>2. Potential damage to launch vehicle</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>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)</li> <li>2. The motor has been purchased from a reputable vendor and installed using proper techniques</li> <li>3. The systems squad will allocate and enforce weight limits to each system</li> <li>4. Rail buttons will be purchased from reputable vendors and installed using proper techniques</li> <li>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</li> <li>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</li> <li>7. Launch Procedures have been written, and they outline the necessary steps for motor inspection and integration</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations can be found in Section 5, and they were approved by both the Safety Officer and the Systems Officer</li> <li>2. Team members ordering the motor and rail buttons must consult the team's trusted vendor list and past motor data before making any motor purchase</li> <li>3. All information on weight allocation can be found in Section 3.2.2</li> <li>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</li> <li>5. Launch Procedures for launch pad setup can be found in Section 8.1.10</li> <li>6. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 8.1.4</li> <li>7. Launch Procedures for motor inspection and integration can be found in Section 8.1.9.6</li> <li>8. Construction procedures will be written prior to construction</li> </ol>	1	3	3

VFM.6	Excessive and/or un-balanced drag	<ol style="list-style-type: none"> <li>1. Imperfections with exterior of launch vehicle</li> <li>2. Excessive exterior coatings and/or attachments</li> <li>3. Actual drag exerted on the launch vehicle is greater than calculated</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch vehicle follows an unintended flight trajectory</li> <li>2. Potential failure to reach target apogee</li> <li>3. Potential damage to launch vehicle and/or components</li> </ol>	3	2	6	<ol style="list-style-type: none"> <li>1. Construction procedures will be written, and they will help ensure proper methods are used to mitigate imperfections</li> <li>2. Wind tunnel testing procedures have been written, and they will help highlight possible drag issues with our design. All tests will be performed prior to FRR</li> <li>3. Paint layers to the exterior of our launch vehicle will be as minimal as possible to reduce any potential drag induced by it</li> <li>4. All drag calculations and simulations have been performed and approved by our team graduate student and team University professor</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for identifying any imperfection with launch vehicle exterior prior to launch</li> </ol>	<ol style="list-style-type: none"> <li>1. Construction procedures will be written prior to FRR</li> <li>2. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>3. Our team graduate student and University professor has greater experience with drag calculations and simulations</li> <li>4. Launch Procedures for identifying imperfections can be found in Section <a href="#">8.1.5</a></li> </ol>	1	2	2
VFM.7	Failure to ignite motor	<ol style="list-style-type: none"> <li>1. Malfunction of E-match</li> <li>2. Pre-existing motor imperfections</li> </ol>	<p>Mission failure due to no launch, resulting in project delays and/or competition ineligibility</p>	3	2	6	<ol style="list-style-type: none"> <li>1. The motor will be purchased from a reputable vendor and installed using proper techniques</li> <li>2. Backup motors will be brought to every launch in the event of a defective motor</li> <li>3. Launch Procedures have been written, and they outline the necessary steps for a safe motor transportation to the launch site</li> <li>4. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for motor inspection and integration</li> </ol>	<ol style="list-style-type: none"> <li>1. Team members ordering the motor must consult the team's trusted vendor list and past motor data before making any motor purchase</li> <li>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</li> <li>3. Launch Procedures for motor transportation can be found in Section <a href="#">8.1.4</a></li> <li>4. Launch Procedures for operating launch equipment can be found in Section <a href="#">8.1.10</a></li> <li>5. Launch Procedures for motor inspection and integration can be found in Section <a href="#">8.1.9.6</a></li> </ol>	1	1	1

VFM.8	Insufficient launch rail exit velocity (Failure to meet NASA Vehicles Requirement 2.17)	<ol style="list-style-type: none"> <li>1. Selected motor inadequate in generating sufficient launch rail exit velocity</li> <li>2. Pre-existing motor imperfections</li> <li>3. Excessive launch vehicle mass</li> <li>4. External forces on launch vehicle are greater than calculated</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch vehicle has unexpected flight trajectory</li> <li>2. Potential damage to launch vehicle and/or components</li> <li>3. Potential Injury to nearby personnel, civilians, and/or structures</li> </ol>	2	3	6	<ol style="list-style-type: none"> <li>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)</li> <li>2. The motor will be purchased from a reputable vendor and installed using proper techniques</li> <li>3. The systems squad will allocate and enforce weight limits to each system</li> <li>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</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations can be found in Section 5, and they were approved by both the Safety Officer and the Systems Officer</li> <li>2. Team members ordering the motor must consult the team's trusted vendor list and past motor data before making any motor purchase</li> <li>3. All information on weight allocation can be found in Section 3.4.2</li> <li>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</li> <li>5. Launch Procedures for launch pad setup can be found in Section 8.1.10</li> <li>6. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section 8.1.10.4</li> </ol>	1	3	3
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## 8.2.2 Vehicle Structures Failure Modes and Effects Analysis

**Table 58:** Vehicle Structures Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
VS.1	Centering Ring Failure	<ol style="list-style-type: none"> <li>1. Improper attachment of centering rings</li> <li>2. Centering ring material and/or construction imperfections</li> </ol>	<ol style="list-style-type: none"> <li>1. Motor becomes improperly aligned, resulting in an unintended flight trajectory</li> <li>2. Launch vehicle fails to reach the target apogee</li> <li>3. Potential severe injury to nearby personnel</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Centering rings were chosen based on research and calculations</li> <li>2. Centering ring materials will be purchased from reputable vendors</li> <li>3. Construction procedures will be written prior to any construction and made accessible to all members, and they will outline the necessary steps for centering ring integration</li> </ol>	<ol style="list-style-type: none"> <li>1. Team members ordering the centering ring material must consult the team's trusted vendor list</li> <li>2. Construction procedures will be written prior to FRR</li> <li>3. Centering ring information can be found in Section 3.3.6</li> </ol>	1	4	4
VS.2	Coupler Failure	<ol style="list-style-type: none"> <li>1. Improperly sized couplers</li> <li>2. Improper fastening of couplers to launch vehicle body tube</li> </ol>	<ol style="list-style-type: none"> <li>1. Unexpected launch vehicle body tube separation</li> <li>2. Potential damage to launch vehicle and/or components</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Couplers will be chosen based on research and calculations</li> <li>2. Couplers will be purchased from reputable vendors</li> <li>3. Construction procedures will be written and made accessible to all members, and they will outline the necessary steps for centering ring construction and integration</li> </ol>	<ol style="list-style-type: none"> <li>1. Team members ordering the couplers must consult the team's trusted vendor list</li> <li>2. Construction procedures will be written prior to FRR</li> <li>3. Coupler information can be found in Section 3.3.2</li> </ol>	1	4	4
VS.3	Bulkhead Structural Failure	<ol style="list-style-type: none"> <li>1. Improper bulkhead construction</li> <li>2. Adhesives fail to secure the bulkhead to the body tube</li> <li>3. Bulkhead materials and/or design inadequate at withstanding the forces exerted on the system</li> </ol>	<ol style="list-style-type: none"> <li>1. Potential damage to interior launch vehicle components</li> <li>2. Unintended body tube separation</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. The material and design of the bulkheads and U-bolts was chosen with strength and weight in mind</li> <li>2. Bulkhead material and U-bolts will be purchased from reputable vendors</li> <li>3. Construction procedures will be written and accessible to all members, and they will outline the necessary steps for constructing and integrating the bulkheads and U-bolts</li> <li>4. Bulkhead strength testing procedures have been written, and they will evaluate the amount of weight the U-bolt and bulkhead can withstand to simulate the launch loads and parachute forces. All tests will be performed prior to FRR</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for ensuring bulkhead, U-bolt, and eye-bolt strength on launch day</li> </ol>	<ol style="list-style-type: none"> <li>1. Team members ordering the bulkhead material and U-bolts must consult the team's trusted vendor list</li> <li>2. Construction procedures will be written prior to FRR</li> <li>3. All Testing Procedures can be found in Section 9.1</li> <li>4. Launch Procedures for bulkhead, U-bolt, and eye-bolt strength testing can be found in Sections 8.1.5 and 8.1.6.1</li> </ol>	1	3	3

<p>VS.4</p>	<p>Fin failure</p>	<p>1. Fins are improperly secured to the launch vehicle fin can 2. Fin imperfections due to materials and/or construction method</p>	<p>1. Launch vehicle travels in an unpredictable trajectory 2. Potential damage to launch vehicle and/or components</p>	<p>3</p>	<p>3</p>	<p>9</p>	<p>1. The material and design of the fins was be chosen with strength and weight in mind 2. Wind tunnel testing procedures have been written to evaluate the forces of the wind on the fins. All tests will be performed prior to FRR 3. Fin can drop testing procedures have been written to evaluate the ability of the fin can to withstand touchdown forces. All tests will be performed prior to FRR 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 will be written prior to construction, and they will outline the necessary steps for the propr fin construction and instillation</p>	<p>1. All information on fins can be found in Section 3.3.5 2. All Testing Procedures can be found in Section 9.1 3. Calculations and simulations for the fins and stability margin can be found in Section 5.1.3, 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 8.1.5 5. Construction procedures will be written prior to construction</p>	<p>1</p>	<p>2</p>	<p>2</p>
<p>VS.5</p>	<p>Motor Retainer Failure</p>	<p>1. Motor retainer imperfections 2. Motor retainer improperly secured to the motor</p>	<p>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</p>	<p>2</p>	<p>4</p>	<p>8</p>	<p>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 will 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</p>	<p>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 8.1.9.5 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</p>	<p>1</p>	<p>4</p>	<p>4</p>

<p>VS.6</p>	<p>Motor explosion</p>	<p>1.Improper motor casing instillation 2. Motor imperfections</p>	<p>1. Severe damage to launch vehicle and/or components 2. Severe injury and/or death to nearby personnel</p>	<p>2</p>	<p>4</p>	<p>8</p>	<p>1. The motor will be 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 for motor mount construction and instillation will be written prior to construction</p>	<p>1. Team members ordering the motor must consult the team's trusted vendor list and past motor data before making any motor purchase 2. Launch procedures 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 <a href="#">8.1.4</a> 4. Launch Procedures for operating launch equipment can be found in Section <a href="#">8.1.10</a> 5. Launch Procedures for motor inspection and integration can be found in Section <a href="#">8.1.9.6</a> 6. Construction procedures will be written prior to construction</p>	<p>1</p>	<p>4</p>	<p>4</p>
<p>VS.7</p>	<p>Structural failure upon landing</p>	<p>1.Launch vehicle body constructed with inadequate materials 2. Launch vehicle lands at a greater than anticipated descent velocity</p>	<p>1. Potential damage and/or complete destruction of launch vehicle body 2. Potential damage to nearby personnel, civilians, and/or structures</p>	<p>3</p>	<p>3</p>	<p>6</p>	<p>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 to evaluate the ability of the nose cone to withstand touchdown forces. All tests will be performed prior to FRR 3. Fin can drop testing procedures have been written to evaluate the ability of the fin can to withstand touchdown forces. All tests will be performed prior to FRR 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 will be written prior to construction to ensure safe and consistent results</p>	<p>1. The material of the vehicle structure can be found in Section <a href="#">3.3</a> 2. All Testing Procedures can be found in Section <a href="#">9.1</a> 3. CAD models and/or drawings for the vehicle design can be found in Section <a href="#">3.2</a> 4. Construction procedures will be written prior to construction 5. Launch procedures for the shake test can be found in Section <a href="#">8.1.9.5</a></p>	<p>1</p>	<p>2</p>	<p>2</p>



VS.8	Launch vehicle dropped	<ol style="list-style-type: none"> <li>Careless handling of launch vehicle by personnel</li> <li>Launch vehicle falls off tables while at staging area due to being improperly secured and/or high winds</li> </ol>	<ol style="list-style-type: none"> <li>Potential damage to launch vehicle, especially external extremities such as the fins and nosecone</li> <li>Potential damage to launch vehicle internal components, especially recovery and payload electronics</li> </ol>	3	2	6	<ol style="list-style-type: none"> <li>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.</li> <li>Launch Procedures have been written, and they outline the necessary steps for maintaining the launch vehicle components on the tables.</li> </ol>	<ol style="list-style-type: none"> <li>Launch Procedures for launch vehicle transportation to the launch rail can be found in Section <a href="#">8.1.10.4</a></li> <li>Launch Procedures for maintaining launch vehicle components can be found in Section <a href="#">8.1.9</a></li> </ol>	1	1	1
VS.9	Failure to transmit tracking position of independent sections of the vehicle at all times (NASA Recovery Requirement 3.12)	<ol style="list-style-type: none"> <li>Transmitter radio frequency shielded by outside components</li> <li>Additional tracking devices in other components interfere with each other's ability to transmit tracking positions</li> </ol>	Failure to track all launch vehicle independent sections accurately during the flight	3	2	6	<ol style="list-style-type: none"> <li>The material of the body tubes was chosen with strength, weight, and data transmissibility in mind</li> <li>Long-distance testing procedures have been written in order to ensure the system's data can be transmitted long distances. All tests will be performed prior to FRR.</li> <li>Transmitting frequencies of all electronic devices have been chosen to avoid potential interference</li> <li>System interference testing procedures have been written, and it will ensure all components don't interfere with data transmissibility. All tests will be performed prior to FRR.</li> <li>Launch Procedures have been written, and they outline the necessary steps for ensuring the transmissibility of LVIS prior to launch</li> <li>Launch Procedures have been written, and they outline the necessary steps for ensuring the recovery system is working properly prior to integration and launch.</li> <li>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.</li> </ol>	<ol style="list-style-type: none"> <li>The material of the vehicle structure can be found in Section <a href="#">3.3</a></li> <li>All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>Launch procedures for the shake test can be found in Section <a href="#">8.1.9.5</a></li> <li>Launch Procedures for ensuring LVIS transmissibility can be found in Section <a href="#">8.1.9.2</a></li> <li>Launch Procedures for ensuring recovery system is working properly can be found in Sections <a href="#">8.1.6</a> and <a href="#">8.1.9.3</a></li> <li>All transmitter frequencies will be reported to NASA prior to launch in order to compare the team's frequencies with other nearby teams' frequencies</li> </ol>	1	2	2

### 8.2.3 Apogee Control System Failure Modes and Effects Analysis

**Table 59:** Apogee Control System Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
ACS.1	Power system failure	<ol style="list-style-type: none"> <li>Improper construction and/or integration procedures yield damaged electronics</li> <li>Intense vibrations and/or heat during launch result in damaged electronics</li> <li>Batteries are insufficiently charged due to team negligence and/or frigid weather</li> </ol>	<ol style="list-style-type: none"> <li>Launch vehicle potentially overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to ACS failing to function properly, failing <a href="#">NASA Vehicles Requirement 2.1</a></li> <li>Launch vehicle fails to reach the target apogee of 4,800 ft</li> </ol>	4	3	12	<ol style="list-style-type: none"> <li>All electronic components will be properly checked prior to every test, departure for launch site, and before integration at every launch.</li> <li>ACS battery duration testing procedures have been written, and they will be performed under multiple situations in order to evaluate the quality of the system's batteries. All tests will be performed prior to FRR</li> <li>All batteries brought to the launch site will be required to be fully charged prior to launch.</li> <li>Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries.</li> <li>Launch Procedures have been written, and they outline the PPE required and the procedure for checking battery quality.</li> <li>Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>Launch Procedures Section <a href="#">8.1.3</a> highlight the importance of storing all batteries in fire resistant bags when not in use</li> <li>Launch Procedures for checking battery voltage can be found in Section <a href="#">8.1.3</a> and in every other section that involves battery instillation</li> <li>Launch Procedures for transporting ACS electronics can be found in Section <a href="#">8.1.4</a></li> <li>Launch Procedures for ACS preparation for launch can be found in Section <a href="#">8.1.8</a></li> <li>Launch Procedures for ACS integration into launch vehicle can be found in Section <a href="#">8.1.9.1</a></li> <li>All Testing Procedures can be found in Section <a href="#">9.1</a></li> </ol>	2	2	4

ACS.2	Mechanism for securing the Apogee Control System to the launch vehicle is damaged before apogee is reached	<ol style="list-style-type: none"> <li>1. Improper installation of ACS sensors</li> <li>2. ACS sensor programming ineffective at reading sensor data during launch</li> <li>3. Loss of power to electrical systems</li> <li>4. Sensors incorrectly calibrated</li> </ol>	<ol style="list-style-type: none"> <li>1. ACS fails to properly deploy, resulting in the launch vehicle failing to reach the target apogee of 4,800 ft</li> <li>2. Potential shift of the ACS inside the launch vehicle, resulting in internal component damage and/or unintended mass distribution</li> <li>3. Premature deployment of ACS from fin can</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>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</li> <li>2. CAD models and drawings have been created prior to construction to accurately fabricate the ACS containment mechanism</li> <li>3. The University of Notre Dame Engineering Innovation Hub Manager will approve of all construction methods prior to part machining</li> <li>4. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section 9.1</li> <li>2. Launch Procedures for ACS preparation for launch can be found in Section 8.1.8</li> <li>3. Launch Procedures for ACS integration into launch vehicle can be found in Section 8.1.9.1</li> </ol>	2	2	4
ACS.3	Incorrect and/or unavailable sensor data	<ol style="list-style-type: none"> <li>1. Improper installation of ACS sensors</li> <li>2. ACS sensor programming ineffective at reading sensor data during launch</li> <li>3. Loss of power to electrical systems</li> <li>4. Sensors incorrectly calibrated</li> </ol>	Launch vehicle fails to reach the target apogee of 4,800 ft	4	3	12	<ol style="list-style-type: none"> <li>1. ACS will be tested with simulated flight data in order to evaluate the system's accuracy with testing procedures, which have already been written. All tests will be performed prior to FRR.</li> <li>2. ACS battery duration testing procedures have been written and will be performed under multiple situations in order to evaluate the quality of the system's batteries. All tests will be performed prior to FRR.</li> <li>3. Redundancy will be implemented into the system</li> <li>4. ACS sensors will be purchased from reputable vendors and installed using proper methods</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section 9.1</li> <li>2. Launch Procedures for ACS preparation for launch can be found in Section 8.1.8</li> <li>3. Launch Procedures for ACS integration into launch vehicle can be found in Section 8.1.9.1</li> </ol>	2	2	4

ACS.4	Apogee Control System electronics become unsecured during launch	<ol style="list-style-type: none"> <li>1. Intense vibrations and/or heat during flight</li> <li>2. Improper construction and/or installation of ACS electronics</li> <li>3. Extension and/or retraction of ACS flaps induce unexpected forces on the inside of the body tube</li> </ol>	<ol style="list-style-type: none"> <li>1. ACS electronics become unsecured, resulting in internal component damage and/or unintended mass distribution</li> <li>2. Launch vehicle potentially undershoots or overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to damaged electronics, failing <a href="#">NASA Vehicles Requirement 2.1</a></li> <li>3. Launch vehicle fails to reach the target apogee of 4,800 ft due to damaged electronics</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle</li> <li>2. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> <li>3. Wind tunnel testing procedures have been written, and they will be performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps mechanism. All tests will be performed prior to FRR.</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures for ACS preparation for launch can be found in Section <a href="#">8.1.8</a></li> <li>2. Launch Procedures for ACS integration into launch vehicle can be found in Section <a href="#">8.1.9.1</a></li> <li>3. Launch Procedures for shake test can be found in Section <a href="#">8.1.9.5</a></li> </ol>	1	4	4
ACS.5	Micro-controller sends improper command signals	<ol style="list-style-type: none"> <li>1. Improper programming of ACS electronics systems</li> <li>2. Flight sensor data computations yield unexpected errors</li> </ol>	<ol style="list-style-type: none"> <li>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 <a href="#">NASA Vehicles Requirement 2.1</a></li> <li>2. Launch vehicle fails to reach the target apogee of 4,800 ft due to improper command signals</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. ACS control algorithm and flap deployment mechanics will be tested with simulated flight data in order to evaluate the system's ability to filter data with testing procedures, which have already been written. All tests will be performed prior to FRR.</li> <li>2. ACS battery duration testing procedures have been written and will be performed under multiple situations in order to evaluate the quality of the system's batteries. All tests will be performed prior to FRR.</li> <li>3. Redundancy will be implementation of the system</li> <li>4. ACS micro-controller will be purchased from reputable vendors and installed using proper methods</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>2. ACS sensor information can be found in Section <a href="#">7.4</a></li> <li>3. Launch Procedures for ACS preparation for launch can be found in Section <a href="#">8.1.8</a></li> <li>4. Launch Procedures for ACS integration into launch vehicle can be found in Section <a href="#">8.1.9.1</a></li> </ol>	2	2	4

ACS.6	Flap extension and/or retraction mechanism failure	<ol style="list-style-type: none"> <li>1. Flap unable to extend and/or retract during flight due to extreme outside forces hindering movement</li> <li>2. Improper construction and/or installation methods of the ACS</li> <li>3. Mechanism's materials insufficient for withstanding flight loads</li> <li>4. Intense vibrations and/or heat during launch damage ACS mechanisms</li> <li>5. Flaps lock inward or outward in a motion singularity</li> </ol>	<ol style="list-style-type: none"> <li>1. Flaps cannot properly deploy or retract, resulting in the launch vehicle failing to reach the target apogee of 4,800 ft</li> <li>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 <a href="#">NNASA Vehicles Requirement 2.1</a></li> <li>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 <a href="#">NASA Vehicles Requirement 2.1</a></li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>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</li> <li>2. CAD models and drawings have been created prior to construction to accurately fabricate the flap deployment mechanism</li> <li>3. The University of Notre Dame Engineering Innovation Hub Manager will approve of all construction methods prior to part machining</li> <li>4. ACS wind tunnel testing procedures have been written and will be performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps mechanism. All tests will be performed prior to FRR.</li> <li>5. ACS flap mechanism torque testing procedures have been written and will be performed in order to evaluate the system's ability to withstand the highest expected load with a safety factor of 1.25. All tests will be performed prior to FRR.</li> <li>6. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle</li> <li>7. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>2. All CAD models for the ACS design can be found in Section <a href="#">7.2</a></li> <li>3. Calculations for flap extensions can be found in Section <a href="#">7.3</a>, and it was approved by both the Safety Officer and the Systems Officer</li> <li>4. Launch Procedures for ACS preparation for launch can be found in Section <a href="#">8.1.8</a></li> <li>5. Launch Procedures for ACS integration into launch vehicle can be found in Section <a href="#">8.1.9.1</a></li> </ol>	2	2	4
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ACS.7	Micro controller damaged and/or unresponsive during flight	<ol style="list-style-type: none"> <li>1. Battery pack fails to consistently output a voltage within the microcontroller's necessary range</li> <li>2. Improper construction and/or installation of the battery pack</li> </ol>	<ol style="list-style-type: none"> <li>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 <a href="#">NASA Vehicles Requirement 2.1</a></li> <li>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</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. All electronic components will be properly checked prior to every test, departure for launch site, and before integration at every launch</li> <li>2. ACS battery duration testing procedures have been written and will be performed under multiple situations in order to evaluate the quality of the system's batteries. All tests will be performed prior to FRR.</li> <li>3. All batteries brought to the launch site will be required to be fully charged prior to launch</li> <li>4. Launch Procedures have been written, and they outline the necessary steps for performing a shake test on the launch vehicle</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> <li>6. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries.</li> <li>7. Launch Procedures have been written, and they outline the PPE required and the procedure for checking battery quality.</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>2. Launch Procedures Section <a href="#">8.1.3</a> highlight the importance of storing all batteries in fire resistant bags when not in use</li> <li>3. Launch Procedures for checking battery voltage can be found in Section <a href="#">8.1.3</a> and in every other section that involves battery installation</li> <li>4. Launch Procedures for transporting ACS electronics can be found in Section <a href="#">8.1.4</a></li> <li>5. Launch Procedures for ACS preparation for launch can be found in Section <a href="#">8.1.8</a></li> <li>6. Launch Procedures for ACS integration into launch vehicle can be found in Section <a href="#">8.1.9.1</a></li> <li>7. Launch Procedures for shake test can be found in Section <a href="#">8.1.9.5</a></li> </ol>	1	3	3
ACS.8	Apogee Control System has a slow response time, resulting in belated adjustments during flight	<ol style="list-style-type: none"> <li>1. Current data filters unable to process flight data at an adequate speed</li> <li>2. Flight data exceeds the memory capacity of the microcontroller</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch vehicle potentially overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to belated adjustments, failing <a href="#">NASA Vehicles Requirement 2.1</a></li> <li>2. Launch vehicle likely fails to reach the target apogee of 4,800 ft due to belated adjustments</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. The Kalman filtration system has been chosen based on the criteria of speed and memory</li> <li>2. ACS will be tested with simulated flight data in order to evaluate the system's accuracy and speed with testing procedures, which have already been written. All tests will be performed prior to FRR.</li> </ol>	<ol style="list-style-type: none"> <li>1. ACS data filtration system information can be found in Section <a href="#">7.5.2</a></li> <li>2. All Testing Procedures can be found in Section <a href="#">9.1</a></li> </ol>	2	2	4

ACS.9	Apogee Control System flaps are damaged during deployment and/or retraction	<ol style="list-style-type: none"> <li>1. Flap materials unable to withstand intense launch vibrations and/or winds</li> <li>2. Interior launch vehicle walls buckle</li> <li>3. Ineffective construction and/or installation of ACS flaps</li> </ol>	<ol style="list-style-type: none"> <li>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 <a href="#">NASA Vehicles Requirement 2.1</a></li> <li>2. Launch vehicle fails to reach the target apogee of 4,800 ft due to ACS flaps unable to function</li> <li>3. ACS flaps disconnect from vehicle, resulting in potential damage to nearby personnel, structures, or environment</li> </ol>	2	3	6	<ol style="list-style-type: none"> <li>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</li> <li>2. The University of Notre Dame Engineering Innovation Hub Manager will approve of all construction methods prior to part machining</li> <li>3. ACS wind tunnel testing procedures have been written and will be performed in order to evaluate the forces exerted during the extensions and retraction of the ACS flaps. All tests will be performed prior to FRR.</li> <li>4. ACS drop test procedures have been written and will be performed in order to evaluate the ability to of the system to withstand launch touchdown. All tests will be performed prior to FRR.</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>2. All CAD models for the ACS design can be found in Section <a href="#">7.2</a></li> <li>3. Calculations for flap extensions can be found in Section <a href="#">7.3</a>, and it was approved by both the Safety Officer and the Systems Officer</li> <li>4. Launch Procedures for ACS preparation for launch can be found in Section <a href="#">8.1.8</a></li> <li>5. Launch Procedures for ACS integration into launch vehicle can be found in Section <a href="#">8.1.9.1</a></li> </ol>	1	2	2
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## 8.2.4 Recovery Failure Modes and Effects Analysis

**Table 60:** Recovery Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
R.1	Power system failure	<ol style="list-style-type: none"> <li>1. Improper construction procedures yield damaged electronics</li> <li>2. Intense vibrations and/or heat during launch result in damaged electronics</li> <li>3. Batteries are Insufficiently charged due to team negligence</li> </ol>	<ol style="list-style-type: none"> <li>1. Failure of recovery to deploy parachutes, resulting in launch vehicle landing with unacceptably high kinetic energy (Failure to comply with <a href="#">NASA Recovery Requirement 3.3</a>)</li> <li>2. Potential high velocity vehicle impact with civilians, leading to severe injuries or death</li> <li>3. Potential damage to nearby buildings or natural structures via impact</li> <li>4. Catastrophic damage to vehicle and components</li> </ol>	4	4	16	<ol style="list-style-type: none"> <li>1. All electronic components will be properly checked prior to every test, departure for launch site, and before integration at every launch</li> <li>2. Recovery battery duration testing procedures have been written for multiple situations in order to evaluate the quality of the system's batteries. All tests will be performed prior to FRR</li> <li>3. All batteries brought to the launch site are required to be fully charged prior to launch</li> <li>4. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries.</li> <li>5. Launch Procedures have been written, and they outline the PPE required and the procedure for checking battery quality.</li> <li>6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures Section <a href="#">8.1.3</a> highlight the importance of storing all batteries in fire resistant bags when not in use</li> <li>2. Launch Procedures for checking battery voltage can be found in Section <a href="#">8.1.3</a> and in every other section that involves battery instillation</li> <li>3. Launch Procedures for transporting recovery electronics can be found in Section <a href="#">8.1.3</a></li> <li>4. Launch Procedures for recovery preparation for launch can be found in Section <a href="#">8.1.6</a></li> <li>5. Launch Procedures for recovery integration into launch vehicle can be found in Section <a href="#">8.1.9.3</a></li> </ol>	2	3	6



R.2	Vehicle fails to separate once reaching apogee	<p>1. Malfunction with altimeters communicating data</p> <p>2. Black powder charges incorrectly integrated</p>	<p>1. Parachute(s) do not deploy</p> <p>2. Vehicle falls with kinetic energy larger than required (Failure to meet <a href="#">NASA Recovery Requirement 3.3</a>)</p> <p>3. Free fall vehicle can cause damage to surrounding structures and/or people</p> <p>4. Severe damage to vehicle</p>	3	4	12	<p>1. Redundancy will be implemented in black powder charges</p> <p>2. Separate recovery systems with individual avionics and black powder charges will be integrated into body tube</p> <p>3. Altimeters will be properly shielded from interference</p> <p>4. Altimeters, system interference, redundancy, and more will be tested with testing procedures, which have been written. All tests will be performed prior to FRR</p> <p>5. Black powder and altimeters will be supplied from reputable sources and installed using proper methods</p> <p>6. Launch Procedures have been written, and they outline the necessary steps for inserting black powder charges.</p> <p>7. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</p>	<p>1. All Testing Procedures can be found in Section <a href="#">9.1</a></p> <p>2. Launch Procedures for black powder instillation can be found in Section <a href="#">8.1.6.2.5</a></p> <p>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</p> <p>4. Launch Procedures for recovery preparation for launch can be found in Section <a href="#">8.1.6</a></p> <p>5. Launch Procedures for recovery integration into launch vehicle can be found in Section <a href="#">8.1.9.3</a></p> <p>6. Ejection charge sizing can be found in Section <a href="#">4.3.2</a></p>	1	4	4
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R.3	Premature body tube separation	<ol style="list-style-type: none"> <li>1. Body tubes not properly pinned together</li> <li>2. Shear Pins fail to hold vehicle body tubes together</li> <li>3. Altimeters supply false reading, causing premature black powder ignition</li> <li>4. ACS flaps extend during motor burnout, and the shear pins are unable to withstand the intense drag induced by the flaps</li> </ol>	<ol style="list-style-type: none"> <li>1. Potential loss of interior components</li> <li>2. Potential high velocity impact with civilians, leading to severe injuries or death</li> <li>3. Potential damage to nearby buildings or natural structures via impact</li> <li>4. Potential high velocity impact, resulting in potential damage to launch vehicle and/or components</li> <li>5. Vehicle potentially fails to reach desired apogee</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Shear pins have been carefully selected to withstand the forces exerted on the system during flight</li> <li>2. Shear pins will be purchased from reputable vendors and installed using proper methods</li> <li>3. Altimeters will be purchased from reputable vendors and installed using proper methods</li> <li>4. Altimeters, system interference, redundancy, shear pins, and more will be tested with testing procedures, which have already been written. All tests will be performed prior to FRR</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for inserting shear pins</li> <li>6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> <li>7. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>2. All Testing Procedures can be found in Section 9.1</li> <li>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</li> <li>4. Launch Procedures for recovery preparation for launch can be found in Section 8.1.6</li> <li>5. Launch Procedures for recovery integration into launch vehicle can be found in Section 8.1.9.3</li> <li>6. Launch Procedures for shear pin insertion can be found in Section 8.1.9.8</li> <li>7. Calculations for flap extensions can be found in Section 7.3, and it was approved by both the Safety Officer and the Systems Officer</li> <li>8. Launch Procedures for ACS preparation for launch can be found in Section 8.1.8</li> <li>9. Launch Procedures for ACS integration into launch vehicle can be found in Section 8.1.9.1</li> </ol>	1	4	4
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R.4	Vehicle components fully deatch during launch	<ol style="list-style-type: none"> <li>Shock cords and/or recovery system ineffective at resisting high loads</li> <li>Black powder detonation pressure damages shock cord strength and/or recovery system</li> <li>Incorrect integration of shock cords, or complete absence of shock cords integration</li> </ol>	<ol style="list-style-type: none"> <li>Launch vehicle components lands with unacceptably high kinetic energy (Failure to comply with <a href="#">NASA Recovery Requirement 3.3</a>)</li> <li>Potential high velocity impact with civilians, leading to severe injuries or death</li> <li>Potential damage to nearby buildings or natural structures via impact</li> <li>Damage to vehicle components</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>Shock cords will be purchased from reputable vendors and installed using proper methods</li> <li>Shock cords will be carefully selected to withstand the forces exerted on the system during flight</li> <li>Recovery system structural materials be chosen based on their ability to withstand the forces exerted on the system during flight</li> <li>Recovery system ground separation testing procedures have been written in order to evaluate the structural integrity of the system during black powder ignition. All tests will be performed prior to FRR.</li> <li>Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>Safety factor calculations for shock cords can be found in <a href="#">Section 4.5</a>, and all safety factor calculations were approved by both the Safety Officer and Systems Officer</li> <li>Safety factor calculations for recovery structural components can be found in <a href="#">Section 4.5</a>, and the safety factor calculations were approved by both the Safety Officer and Systems Officer</li> <li>All Testing Procedures can be found in <a href="#">Section 9.1</a></li> <li>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</li> <li>Launch Procedures for recovery preparation for launch can be found in <a href="#">Section 8.1.6</a></li> <li>Launch Procedures for recovery integration into launch vehicle can be found in <a href="#">Section 8.1.9.3</a></li> </ol>	1	4	4
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R.5	Main parachute fails to reduce descent velocity to acceptable levels after deployment	<ol style="list-style-type: none"> <li>1. Main parachute too small to reduce the vehicle descent velocity</li> <li>2. Recovery systems deploy main parachute at an incorrect time</li> <li>3. Entanglement of shock chords causes incorrect deployment of main parachute</li> <li>4. Main parachute damaged during deployment by black powder charges</li> <li>5. Ineffective installation of main parachute</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch vehicle lands with unacceptably high kinetic energy (Failure to comply with <a href="#">NASA Recovery Requirement 3.3</a>)</li> <li>2. Potential high velocity impact with civilians, leading to severe injuries</li> <li>3. Potential damage to nearby buildings or natural structures via impact</li> <li>4. Damage to vehicle and/or components</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>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</li> <li>2. Black powder, altimeters, and the main parachute will all be purchased from reputable vendors and installed using proper methods</li> <li>3. Main parachute deployment testing procedures have been written in order to evaluate the parachute's ability to fully deploy over a short period of time. All tests will be performed prior to FRR</li> <li>4. Altimeters, system interference, redundancy, and more will be tested with testing procedures, which have been written. All tests will be performed prior to FRR</li> <li>5. Main parachute will be properly protected from black powder charges with the use of a nomex blanket</li> <li>6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. Main parachute information can be found in <a href="#">Section 4.4.1</a></li> <li>2. All calculations and simulations for the main parachute can be found in <a href="#">Section 5.3</a>, and they were approved by both the Safety Officer and the Systems Officer</li> <li>3. All Testing Procedures can be found in <a href="#">Section 9.1</a></li> <li>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</li> <li>5. Launch Procedures for recovery preparation for launch can be found in <a href="#">Section 8.1.6</a></li> <li>6. Launch Procedures for recovery integration into launch vehicle can be found in <a href="#">Section 8.1.9.3</a></li> </ol>	2	4	8
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R.6	Drogue parachute fails to reduce descent velocity to acceptable levels after apogee	<ol style="list-style-type: none"> <li>1. Drogue parachute not sized correctly to reduce the vehicle descent velocity</li> <li>2. Recovery systems deploy drogue parachute at an incorrect time</li> <li>3. Shock cords and/or shroud lines become tangled prohibiting full deployment of drogue parachute</li> <li>4. Drogue parachute damaged during deployment by black powder charges</li> <li>5. Ineffective installation of drogue parachute</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch vehicle lands with unacceptably high kinetic energy (Failure to comply with <a href="#">NASA Recovery Requirement 3.3</a>)</li> <li>2. Potential high velocity impact with civilians, leading to severe injuries</li> <li>3. Potential damage to nearby buildings or natural structures via impact</li> <li>4. Damage to vehicle and/or components</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Drogue 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</li> <li>2. Black powder, altimeters, and the drogue parachute will all be purchased from reputable vendors and installed using proper methods</li> <li>3. Drogue parachute deployment testing procedures have been written in order to evaluate the parachute's ability to fully deploy over a short period of time. All tests will be performed prior to FRR</li> <li>4. Altimeters, system interference, redundancy, and more will be tested with testing procedures, which have been written. All tests will be performed prior to FRR</li> <li>5. Drogue parachute will be properly protected from black powder charges with the use of a nomex blanket</li> <li>6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. Drogue parachute information can be found in Section <a href="#">4.4.2</a></li> <li>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</li> <li>3. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>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</li> <li>5. Launch Procedures for recovery preparation for launch can be found in Section <a href="#">8.1.6</a></li> <li>6. Launch Procedures for recovery integration into launch vehicle can be found in Section <a href="#">8.1.9.3</a></li> </ol>	2	4	8
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R.7	Premature Apogee Control System detachment from fin can	<ol style="list-style-type: none"> <li>1. Improper construction and/or installation of ACS and/or recovery systems</li> <li>2. Shear Pins fail to hold vehicle tubes together</li> <li>3. Altimeters supply false reading, causing premature black powder ignition</li> </ol>	<ol style="list-style-type: none"> <li>1. Potential high velocity vehicle and/or component impact with civilians, leading to severe injuries or death</li> <li>2. Damage to vehicle and/or components</li> <li>3. Launch vehicle potentially overshoots the acceptable apogee range of 4,000 ft to 6,000 ft due to loss of ACS, failing <a href="#">NASA Vehicles Requirement 2.1</a></li> <li>4. Launch vehicle fails to reach the target apogee of 4,800 ft due to loss of ACS (<a href="#">NASA Vehicles Requirement 2.3</a>)</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Shear pins have been carefully selected to withstand the forces exerted on the system during flight</li> <li>2. Shear pins will be purchased from reputable vendors and installed using proper methods</li> <li>3. Altimeters will be purchased from reputable vendors and installed using proper methods</li> <li>4. Altimeters, system interference, redundancy, shear pins, and more will be tested with testing procedures, which have already been written. All tests will be performed prior to FRR</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for inserting shear pins</li> <li>6. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> <li>7. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. Safety factor calculations for shear pins can be found in Section <a href="#">4.3</a>, and all safety factor calculations were approved by both the Safety Officer and Systems Officer</li> <li>2. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>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</li> <li>4. Launch Procedures for recovery preparation for launch can be found in Section <a href="#">8.1.6</a></li> <li>5. Launch Procedures for recovery integration into launch vehicle can be found in Section <a href="#">8.1.9.3</a></li> <li>6. Launch Procedures for shear pin insertion can be found in Section <a href="#">8.1.9.8</a></li> <li>7. Launch Procedures for ACS integration into launch vehicle can be found in Section <a href="#">8.1.9.1</a></li> <li>8. Launch Procedures for ACS preparation for launch can be found in Section <a href="#">8.1.8</a></li> </ol>	1	4	4
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R.8	Vehicle lands outside the allowable recovery radius of 2,500 ft (Failure to comply with <a href="#">NASA Recovery Requirement 3.10</a> )	<ol style="list-style-type: none"> <li>1. Main or drogue parachutes deploy early (above 600 ft AGL; 5150 ft AGL respectively)</li> <li>2. Main or drogue parachutes are too large</li> </ol>	<ol style="list-style-type: none"> <li>1. LVIS mission failure due to a vehicle landing zone outside the 2,500 by 2,500 ft grid</li> <li>2. Low velocity vehicle impact with civilians, leading to injuries such as bruises or cuts</li> <li>3. Damage to nearby buildings or natural structures via impact</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. Calculations have been performed to determine the maximum expected drift radius</li> <li>2. Redundancy will be implemented in black powder charges</li> <li>3. Altimeters will be purchased from reputable vendors</li> <li>4. Altimeters will be properly shielded from interference</li> <li>5. Black powder and altimeters will be supplied from reputable sources and installed using proper methods</li> <li>6. 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</li> <li>7. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> <li>8. Launch Procedures have been written, and they outline the necessary steps for inserting black powder charges.</li> </ol>	<ol style="list-style-type: none"> <li>1. All maximum drift radius calculations and simulations can be found in Section <a href="#">5.2.3</a>, and they were approved by both the Safety Officer and Systems Officer</li> <li>2. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>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</li> <li>4. Ejection charge sizing can be found in Section <a href="#">4.3.2</a></li> <li>5. Launch Procedures for recovery preparation for launch can be found in Section <a href="#">8.1.6</a></li> <li>6. Launch Procedures for recovery integration into launch vehicle can be found in Section <a href="#">8.1.9.3</a></li> </ol>	1	2	2
R.9	Recovery System fails to separate ACS from fin can	<ol style="list-style-type: none"> <li>1. Inaccurate altimeter data results in failure of e-match to ignite black powder charges</li> <li>2. Black powder charges set incorrectly</li> <li>3. Improper installation of recovery system and/or ACS</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch vehicle component lands with unacceptably high kinetic energy (Failure to comply with <a href="#">NASA Recovery Requirement 3.3</a>)</li> <li>2. Potential high velocity vehicle impact with civilians, leading to severe injuries or death</li> <li>3. Potential damage to nearby buildings or natural structures via impact</li> <li>4. Damage to vehicle and/or components</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>1. Redundancy will be implemented in black powder charges</li> <li>2. Altimeters will be properly shielded from interference</li> <li>3. Altimeters will be purchased from reputable vendors and installed using proper methods</li> <li>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</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> <li>6. Launch Procedures have been written, and they outline the necessary steps for ACS preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>2. Launch Procedures for recovery preparation for launch can be found in Section <a href="#">8.1.6</a></li> <li>3. Launch Procedures for recovery integration into launch vehicle can be found in Section <a href="#">8.1.9.3</a></li> <li>4. Launch Procedures for ACS integration into launch vehicle can be found in Section <a href="#">8.1.9.1</a></li> <li>5. Launch Procedures for ACS preparation for launch can be found in Section <a href="#">8.1.8</a></li> <li>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</li> </ol>	1	4	4

R.10	Parachute fully detaches from vehicle during launch	<ol style="list-style-type: none"> <li>Shock chord's connection to vehicle fails to resist high loads</li> <li>Shock chord ineffective at resisting high loads</li> <li>Black powder detonation pressure damages shock cord or connection strength</li> <li>Incorrect integration of shock chord and/or main parachute, or complete absence of shock chord integration</li> </ol>	<ol style="list-style-type: none"> <li>Launch vehicle lands with unacceptably high kinetic energy (Failure to comply with <a href="#">NASA Recovery Requirement 3.3</a>)</li> <li>Potential high velocity vehicle impact with civilians, leading to severe injuries or death</li> <li>Potential damage to nearby buildings or natural structures via impact</li> <li>Damage to vehicle and/or components</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>Shock cords will be purchased from reputable vendors and installed using proper methods</li> <li>Shock cords will be carefully selected to withstand the forces exerted on the system during flight</li> <li>Recovery system structural materials be chosen based on their ability to withstand the forces exerted on the system during flight</li> <li>Recovery system ground separation testing procedures have been written in order to evaluate the structural integrity of the system during black powder ignition. All tests will be performed prior to FRR.</li> <li>Launch Procedures have been written, and they outline the necessary steps for Recovery preparation and integration into launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>Safety factor calculations for shock cords can be found in <a href="#">Section 4.5</a>, and all safety factor calculations were approved by both the Safety Officer and Systems Officer</li> <li>Safety factor calculations for recovery structural components can be found in <a href="#">Section 4.5</a>, and the safety factor calculations were approved by both the Safety Officer and Systems Officer</li> <li>All Testing Procedures can be found in <a href="#">Section 9.1</a></li> <li>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</li> <li>Launch Procedures for recovery preparation for launch can be found in <a href="#">Section 8.1.6</a></li> <li>Launch Procedures for recovery integration into launch vehicle can be found in <a href="#">Section 8.1.9.3</a></li> </ol>	1	4	4
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## 8.2.5 Launch Vehicle Identification System (LVIS) Failure Modes and Effects Analysis

**Table 61:** 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 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. All Testing Procedures can be found in Section 9.1	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 in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements. All tests will be performed before FRR 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 9.1 2. Launch Procedures for shake test can be found in Section 8.1.9.5 3. Launch Procedures for LVIS preparation can be found in Section 8.1.7 4. Launch Procedures for LVIS integration can be found in Section 8.1.9.2 5. LVIS design, which includes redundancy, can be found in Section 6.5	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 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 6.5 2. All Testing Procedures can be found in Section 9.1	2	3	6

LVIS.4	Data Overload	<ol style="list-style-type: none"> <li>Inadequate LVIS sensors chosen</li> <li>Sensor imperfections</li> <li>Simulation data does not accurately include all necessary forces</li> </ol>	<ol style="list-style-type: none"> <li>Flight path is disproportional on different axes based on inaccurate data, resulting in inaccurate grid coordinate</li> <li>Flight path is proportional but scaled improperly due to disconnect in simulation algorithm, resulting in inaccurate grid coordinate</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>LVIS sensors have been supplied from reputable sources and installed using proper methods</li> <li>Maximum grid dimensions (250 ft by 250 ft) reduce necessary precision in calculations</li> <li>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</li> <li>The Klamon filtering method will be applied during launch to provide rapid filtering of data</li> <li>The Gauss-Newton filtering method will be applied post launch to provide accurate data</li> </ol>	<ol style="list-style-type: none"> <li>All Testing Procedures can be found in Section 9.1</li> <li>Information on the LVIS filtering methods can be found in Section 6.6.2</li> </ol>	1	4	4
LVIS.5	Antenna Obstruction	LVIS unable to transmit the necessary signal due to landing configuration, distance from computer, improper installation, and/or structural damage	No grid coordinate is returned, resulting in complete payload mission failure	2	4	8	<ol style="list-style-type: none"> <li>The material of the payload body tube has been confirmed to facilitate data transmissibility</li> <li>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</li> <li>Launch Procedures have been written, and they outline the necessary steps for preparing LVIS for launch</li> <li>Launch Procedures have been written, and they outline the necessary steps for integrating LVIS into the launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>All Testing Procedures can be found in Section 9.1</li> <li>The material of the payload body tube can be found in Section 3.3.2</li> <li>Launch Procedures for LVIS preparation can be found in Section 8.1.7</li> <li>Launch Procedures for LVIS integration can be found in Section 8.1.9.2</li> </ol>	1	4	4
LVIS.6	Launch vehicle lands nearby and/or between grid borders	<ol style="list-style-type: none"> <li>Launch vehicle, as determined by the grid layout and LVIS systems, lands between and/or nearby grid borders</li> <li>The location of the payload body tube is to be reported if complications occur</li> </ol>	Slight inaccuracies in LVIS software may result in the incorrect grid coordinate being reported	2	3	6	<ol style="list-style-type: none"> <li>Use of maximum grid dimensions (250 ft by 250 ft) reduces the chances of grid intersection</li> <li>Redundancy has been implemented in LVIS design</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>All Testing Procedures can be found in Section 9.1</li> <li>LVIS design, which includes redundancy, can be found in Section 6.5</li> </ol>	1	3	3

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

**Table 62:** Launch Vehicle Identification System Integration Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
LL1	LVIS attachment to launch vehicle compromises data collection and/or transmission	<ol style="list-style-type: none"> <li>1. Data from sensors is manipulated by mechanical structures, such as damping</li> <li>2. Additional devices in nearby electronics interfere with LVIS's ability to transmit and/or receive data</li> <li>3. Improper installation of LVIS into launch vehicle</li> </ol>	Obstructed LVIS data is inaccurate and/or missing, resulting in inaccurate grid location and payload mission failure	4	4	16	<ol style="list-style-type: none"> <li>1. 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</li> <li>2. Launch vehicle system components have been designed to mitigate risk of transmission interference</li> <li>3. The material of the payload body tube has been confirmed to facilitate data transmissibility</li> <li>4. Launch Procedures have been written, and they outline the necessary steps for preparing LVIS for launch</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for integrating LVIS into the launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section 9.1</li> <li>2. The material of the payload body tube can be found in Section 3.3.2</li> <li>3. Launch Procedures for LVIS preparation can be found in Section 8.1.7</li> <li>4. Launch Procedures for LVIS integration can be found in Section 8.1.9.2</li> </ol>	2	3	6
LL2	Excessive vibrations and/or accelerations during flight	<ol style="list-style-type: none"> <li>1. Actual forces exerted on LVIS is greater than calculated</li> <li>2. LVIS design and/or materials insufficient for maintaining its structural integrity</li> <li>3. Improper installation of LVIS into launch vehicle</li> </ol>	Damaged LVIS reports inaccurate data or is unable to report data entirely, resulting in partial or complete payload mission failure	3	4	12	<ol style="list-style-type: none"> <li>1. 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</li> <li>2. LVIS materials and design have been carefully selected to withstand the forces exerted on the system during flight</li> <li>3. Launch Procedures have been written, and they outline the necessary steps for preparing LVIS for launch</li> <li>4. Launch Procedures have been written, and they outline the necessary steps for integrating LVIS into the launch vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section 9.1</li> <li>2. LVIS material selection and CAD models can be found in Section 6.4</li> <li>3. Launch Procedures for LVIS preparation can be found in Section 8.1.7</li> <li>4. Launch Procedures for LVIS integration can be found in Section 8.1.9.2</li> </ol>	2	3	6

LL3	LVIS power failure	<ol style="list-style-type: none"> <li>1. Failure to charge batteries prior to launch</li> <li>2. Failure to check battery voltages prior to launch</li> <li>3. Frigid weather conditions shorten battery life</li> <li>4. Improper installation of LVIS into launch vehicle</li> <li>5. Intense vibrations and/or heat during launch result in dislodged power systems</li> </ol>	LVIS will operate incorrectly, or it will not be able to operate entirely, resulting in payload mission failure	2	4	8	<ol style="list-style-type: none"> <li>1. All electronic components are properly checked prior to every test, departure for launch site, and before integration at every launch</li> <li>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</li> <li>3. All batteries brought to the launch site are required to be fully charged prior to launch</li> <li>4. Launch Procedures for LVIS battery storing, transportation, testing, and integration at the launch field have been and made accessible to all team members</li> <li>5. Launch Procedures for LVIS integration has been written and made accessible to all team members</li> </ol>	<ol style="list-style-type: none"> <li>1. All Testing Procedures can be found in Section <a href="#">9.1</a></li> <li>2. Launch Procedures for battery storing can be found in Section <a href="#">8.1.3</a></li> <li>3. Launch Procedures for battery transportation can be found in Section <a href="#">8.1.4</a></li> <li>4. Launch Procedures for LVIS battery testing can be found in Sections <a href="#">8.1.3</a> and <a href="#">8.1.7</a></li> <li>5. Launch Procedures for LVIS battery integration can be found in Section <a href="#">8.1.7</a></li> <li>6. Launch Procedures for LVIS integration into launch vehicle can be found in Section <a href="#">8.1.9.2</a></li> </ol>	1	4	4
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### 8.2.7 Launch Support Equipment Failure Modes and Effects Analysis

**Table 63:** 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	<ol style="list-style-type: none"> <li>1. Failure to turn off the launch controller after the previous vehicle launch</li> <li>2. Faulty launch controller</li> </ol>	Motor ignites prematurely, resulting in severe damage and/or death to the launch vehicle and/or nearby personnel.	3	4	12	<ol style="list-style-type: none"> <li>1. Only NDRT-purchased launch controllers will be utilized at launches to ensure quality</li> <li>2. All launch equipment — including launch controller, wires and motor — will be thoroughly inspected prior to motor installation</li> <li>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</li> <li>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</li> <li>5. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>2. Launch Procedures for launch pad setup can be found in Section <a href="#">8.1.10</a></li> <li>3. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section <a href="#">8.1.10.4</a></li> <li>4. Launch Procedures for launch equipment operation can be found in Section <a href="#">8.1.10</a> and <a href="#">8.1.11</a></li> </ol>	1	4	4

LE.2	Launch rail is positioned at an angle less than five degrees or greater than ten degrees, violating <a href="#">NASA General Requirement 1.12</a>	<ol style="list-style-type: none"> <li>1. Failure to properly set up the launch equipment</li> <li>2. Failure to properly position the launch vehicle on the launch pad</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch vehicle travels in an unintended trajectory, resulting in potential harm to nearby personnel, civilians, and/or structures</li> <li>2. Potential failure to reach target apogee due to undershooting</li> <li>3. Vehicle potentially lands outside the allowable recovery radius of 2,500 ft (Failure to comply with <a href="#">NASA Recovery Requirement 3.10</a>)</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. Launch equipment will constructed while following all NAR standards</li> <li>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</li> <li>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</li> <li>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</li> <li>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</li> <li>6. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>2. A protractor will be used to ensure the launch rail angle is between five degrees and ten degrees</li> <li>3. Launch Procedures for launch pad setup can be found in Section <a href="#">8.1.10</a></li> <li>4. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section <a href="#">8.1.10.4</a></li> <li>5. Launch Procedures for launch equipment operation can be found in Section <a href="#">8.1.10</a> and <a href="#">8.1.11</a></li> </ol>	1	3	3
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LE.3	Unstable launch rail	<p>1.Improper installation of vehicle on the launch rail base                  2. Launch rail is not properly locked while in the vertical position</p>	<p>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 <a href="#">NASA Recovery Requirement 3.10</a>)</p>	3	3	9	<p>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</p>	<p>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 <a href="#">8.1.10</a>                  3. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section <a href="#">8.1.10.4</a></p>	1	3	3
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LE.4	Failure of launch controller to ignite the motor	<ol style="list-style-type: none"> <li>1. Improper installation of the wired connection between the launch controller and the motor</li> <li>2. Faulty wires and/or controller</li> </ol>	Motor does not ignite, resulting in no launch	3	2	6	<ol style="list-style-type: none"> <li>1. Only NDRT-purchased launch controllers will be utilized at launches to ensure quality</li> <li>2. All launch equipment — including launch controller, wires and motor — will be thoroughly inspected prior to motor installation</li> <li>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</li> <li>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</li> <li>5. Launch procedures have been written and made accessible to all members, and they outline the necessary steps for operating launch equipment</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>2. Launch Procedures for launch pad setup can be found in Section <a href="#">8.1.10</a></li> <li>3. Launch Procedures for installing the launch vehicle on the launch rail can be found in Section <a href="#">8.1.10.4</a></li> <li>4. Launch Procedures for launch equipment operation can be found in Section <a href="#">8.1.10</a> and <a href="#">8.1.11</a></li> </ol>	1	2	2
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### 8.3 Project Risk Analysis

**Table 64:** Project Risks

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severe	After
PR.1	Team member leaves team	1. Injury or illness 2. Member contracts COVID-19 and has to go into quarantine or isolation 3. Member prioritizes other commitments 4. Member is asked to leave due to inappropriate actions	Project delays	5	2	10	1. Multiple team members will be assigned to the same task to ensure task completion 2. All team members will be made aware of the task's details to ensure task completion 3. A NDRT Google Drive will be created and shared with all team members as a unified reference of all team information in the event a reallocation of tasks is necessary	1. All team leaders 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	<ol style="list-style-type: none"> <li>Insufficient PPE is available or worn</li> <li>Insufficient training</li> </ol>	<ol style="list-style-type: none"> <li>Injury to personnel</li> <li>Potential revocation of workshop space privileges</li> <li>Potential damage to launch vehicle, resulting in project delays</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>It will be the duty of the Safety Officer to ensure that all necessary PPE will be available at all times in the workshop</li> <li>All team members must complete the necessary safety training prior to construction eligibility.</li> <li>Standard Operating Procedures have been written, and they outline the necessary PPE and operation steps required for such tasks</li> <li>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</li> <li>NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines all material properties</li> </ol>	<ol style="list-style-type: none"> <li>The Safety Officer will take inventory of workshop's PPE bi-weekly once construction has started</li> <li>Additional PPE will be ordered by January 5th to ensure all PPE will arrive at the University of Notre Dame before the start of the Spring Semester (February 3rd)</li> <li>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</li> <li>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</li> <li>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</li> <li>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</li> <li>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</li> </ol>	1	3	3
PR.3	Shipping and/or manufacturing delays from vendors	<ol style="list-style-type: none"> <li>The parts' anticipated arrival date conflicts with team deadlines</li> <li>The shipped part is incorrect or does not meet the team's quality standards</li> </ol>	<ol style="list-style-type: none"> <li>Project delays</li> <li>Potential inability to compete in competition due to incomplete vehicle</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>Custom parts will be ordered well in advance to ensure they will arrive in time</li> <li>Additional components and materials will be purchased than necessary</li> <li>NDRT has compiled a list of trusted vendor based on previous purchases</li> </ol>	<ol style="list-style-type: none"> <li>All custom parts should be ordered before January 5th to ensure arrival before the start of Spring Semester (February 3rd)</li> <li>Additional material will always be purchased in case a component breaks and/or more material is simply required</li> <li>Squads must consult the list of trusted vendors before purchasing any parts or materials</li> <li>All purchases from vendors not on the list of trusted vendors must be approved by the Project Manager and the Systems Officer</li> </ol>	2	2	4

<p>PR.4</p>	<p>Failure to meet all necessary Requirements</p>	<ol style="list-style-type: none"> <li>1. Team prioritization of NDRT generated requirements over NASA's requirements</li> <li>2. Inefficient time management</li> <li>3. Miscommunication among team members</li> <li>4. Misunderstanding of expected requirements</li> </ol>	<p>Team is ineligible to participate in competition</p>	<p>2</p>	<p>4</p>	<p>8</p>	<ol style="list-style-type: none"> <li>1. NASA requirements are to be understood by all team members prior to the start of the design process</li> <li>2. The Systems squad will help ensure all teams are meeting all NASA requirements</li> <li>3. Strong communication between all squads, team members, and team leaders</li> </ol>	<ol style="list-style-type: none"> <li>1. All NASA requirements will be met in accordance to SLI Handbook</li> <li>2. The team uses Gantt charts to track the progress of all subsystems to ensure everyone is on track</li> </ol>	<p>1</p>	<p>4</p>	<p>4</p>
<p>PR.5</p>	<p>Complete destruction or loss of full-scale or subscale vehicle</p>	<ol style="list-style-type: none"> <li>1. Uncontrolled descent</li> <li>2. Energetics operate in unintended manners</li> </ol>	<ol style="list-style-type: none"> <li>1. If occurred during launch, failure to design a reusable launch vehicle, as outlined in NASA Vehicles Requirement 2.4.</li> <li>2. Team must construct an entirely new vehicle, resulting in project delays and increasing the costs of the project</li> <li>3. Depending on when the hazard occurs, the team may be ineligible to compete in the competition due to time requirements for constructing a new vehicle</li> </ol>	<p>2</p>	<p>4</p>	<p>8</p>	<ol style="list-style-type: none"> <li>1. Extensive testing of all subsystems will occur prior to launch</li> <li>2. Detailed CAD models and drawings will be created prior to construction to accurately manufacture all subsystems</li> <li>3. Construction Procedures will be written to help eliminate all construction-related imperfections</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. List of all Testing Procedures can be found in Section 9.1</li> <li>2. Construction Procedures will be written prior to construction</li> <li>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</li> </ol>	<p>1</p>	<p>4</p>	<p>4</p>

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)	<ol style="list-style-type: none"> <li>Poor weather conditions on intended launch days</li> <li>Incomplete construction of vehicle</li> <li>Failure to schedule a launch date that is suitable for both the team and our mentor, Dave Brunsting</li> <li>RSO deems team's launch vehicle unsuitable for launch on launch days</li> </ol>	Team is ineligible to participate in competition	2	4	8	<ol style="list-style-type: none"> <li>Multiple launch dates and locations have been chosen to provide the team with multiple opportunities to conduct the subscale launch</li> <li>A Technology Readiness Level schedule has been implemented to ensure that all systems are going to finish by their deadlines</li> <li>The team is planning on launching subscale on the first available date</li> </ol>	<ol style="list-style-type: none"> <li>Subscale has already been launched, and all information on the results of the launch can be found in Section 3.5</li> <li>The tentative date for demonstration launch is February 5th, with the backup date as February 12th</li> <li>The team uses Gantt charts to track the Technology Readiness Level schedule of all subsystems to ensure progress is on track</li> <li>The team began subscale construction at least two weeks before the tentative launch date</li> </ol>	1	3	3
PR.7	Insufficient materials and parts to fully complete construction	<ol style="list-style-type: none"> <li>Parts to complete the project are not ordered</li> <li>Insufficient funds to purchase all necessary parts and materials</li> </ol>	<ol style="list-style-type: none"> <li>Project delays</li> <li>Potential inability to compete in competition due to incomplete vehicle</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>Design squads will purchase materials and parts as soon as they know the amount necessary in order to ensure availability</li> <li>Design squads will make a list of all parts and materials necessary for construction</li> <li>All CAD drawings will include the part's materials</li> <li>Construction Procedures will be written, and they will include all necessary parts and materials for the construction of each component</li> </ol>	<ol style="list-style-type: none"> <li>All design squad materials should be purchased before January 15th so they will arrive at the University before the start of the Spring Semester (February 3rd)</li> <li>Construction Procedures will be written prior to construction</li> </ol>	1	4	4
PR.8	Transportation to Launch Field Complications	<ol style="list-style-type: none"> <li>Transportation method of launch vehicle breaks down or is unable to start</li> <li>Car accident</li> <li>Excessive traffic</li> </ol>	<ol style="list-style-type: none"> <li>Damage to launch vehicle leaves it unlaunchable</li> <li>Arriving late to the launch site, or missing the launch entirely</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>Chosen transportation is known to be reliable</li> <li>Extra time is built into transportation schedule to account for unexpected complications</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>Transportation methods must have no pre-existing mechanical failures</li> <li>Launch procedures for transportation can be found in Section 8.1.4</li> </ol>	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	<ol style="list-style-type: none"> <li>1. Potential ineligibility to launch due to unsafe conditions or failure to meet NASA Vehicles Requirement 2.6</li> <li>2. If resolved, Team potentially forgets to recheck crucial launch procedure steps upon resuming the checklist, resulting in unintended conditions during launch</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>1. Launch procedures have been written, and they outline all troubleshooting steps necessary for resolving launch complications</li> <li>2. Proper transportation of launch vehicle and components to the launch site to reduce complications</li> <li>3. Launch Procedures will be revised to increase the clarity of the steps when need be</li> <li>4. Launch vehicle and components will be evaluated before departure from the workshop</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedure troubleshooting follows each section of instructions when applicable</li> <li>2. Launch Procedures for evaluating all components before departure can be found in Section 8.1.3</li> <li>3. Launch Procedures for evaluating all components at the launch field can be found in Sections 8.1.6, 8.1.7, 8.1.8, and 8.1.9</li> </ol>	1	4	4
PR.10	Contracting an illness, especially COVID-19	Respiratory transmission of an extremely contagious virus	<ol style="list-style-type: none"> <li>1. If one contracts COVID-19, potential long-term health effects or death</li> <li>2. Increased likelihood of spreading the virus to other team members</li> <li>3. Increased likelihood of spreading the virus to general population</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>1. All team members must complete the necessary safety training</li> <li>2. All team members must comply with all University of Notre Dame COVID-19 policies</li> <li>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</li> <li>4. Masks are required to be worn at all in-person indoor Educational Outreach events</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>2. The Safety Officer will ensure team compliance with all University, local, state, and national COVID-19 rules and regulations</li> <li>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</li> </ol>	1	4	4

PR.10	Insufficient funds and/or overspending	<ol style="list-style-type: none"> <li>1. Allocation of funds to design squads and/or subsystems is insufficient</li> <li>2. Parts are not efficiently sourced</li> <li>3. Spending on unnecessary components</li> <li>4. Travel prices rise drastically</li> </ol>	<ol style="list-style-type: none"> <li>1. Team takes on debt</li> <li>2. Funds allocated for subsystems diminish, resulting in reduced quality of vehicle subsystems</li> <li>3. Funds allocated for travel diminish, resulting in less available personnel to assist with launches</li> </ol>	2	3	6	<ol style="list-style-type: none"> <li>1. Team fund allocation and spending process has been based on previous years' spending and design</li> <li>2. All parts have been researched to find the best combination of quality and price</li> <li>3. Further actions will be taken to increase corporate sponsorships</li> <li>4. The team card will have a spending limit of \$2,500, and this limit can be replenished upon request to department administrators</li> <li>5. All team purchases will be limited to team leaders to ensure the least amount of people are using team funds at any moment</li> <li>6. All purchases must be reported to ensure all funds are accounted for</li> </ol>	<ol style="list-style-type: none"> <li>1. Team fund allocation and spending process has never led to team debt</li> <li>2. Each purchased part was considered from at least three different vendors</li> <li>3. Complete list of fund allocation can be found in Section 9.4</li> </ol>	2	2	4
PR.11	Approved altitude exceeded during launch	<ol style="list-style-type: none"> <li>1. Launch site does not have proper waiver for the team's altitude requirement</li> <li>2. Team's altitude estimations are drastically lower than the actual altitude value</li> </ol>	Potential legal action due to violation of FAA rules	2	3	6	The team will never use any launch site without the necessary FAA waiver	The team will confirm with the launch site at least one week prior to the launch date the team has attained the proper waiver for the altitude of 4,800 ft	1	3	3
PR.12	Improper testing equipment or procedures	<ol style="list-style-type: none"> <li>1. Equipment does not perform to standards</li> <li>2. Inability to use University resources for complex testing</li> <li>3. Inadequate verification of testing results and procedure</li> </ol>	Incorrect or missing data could lead to faulty analyses, resulting in inaccurate design decisions	3	2	6	<ol style="list-style-type: none"> <li>1. All tests will be confirmed with calculations and simulations</li> <li>2. NDRT's graduate student, Joe Gonzalez, and/or University Professor, Hiroataka Sakaue, can be asked to confirm proper testing methods were used</li> <li>3. The team will reach out to the desired testing facilities early in the year to ensure lab time availability and eligibility</li> <li>4. Testing Procedures have been written to ensure proper testing methods are used. All tests will be performed prior to FRR.</li> </ol>	<ol style="list-style-type: none"> <li>1. The team will reach out to all applicable test facilities upon knowing they want to possibly be used this year</li> <li>2. Testing Procedures can be found in Section 9.1</li> </ol>	1	2	2

PR.13	Team mentor, Dave Brunsting, is unable to attend the scheduled launch date	1. Unforeseen illness or injury 2. Scheduling issues and/or miscommunication	1. No one else on the team is officially allowed to handle Level 2 NAR Certified components, resulting in an ineligibility to launch 2. Project delays	1	3	3	1. NDRT will conform with our Team Mentor the week before, the day before, and the day of the launch to confirm his availability 2. Backup launch dates will be chosen with both the team's availability and the Team Mentor's availability in mind	1. Subscale has already been launched, and all information on the results of the launch can be found in Section 3.5 2. The tentative date for demonstration launch is February 5th, with the backup date as February 12th. Both of these dates work for the team and the Team Mentor	1	2	2
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## 8.4 Personnel Hazard Analysis

### 8.4.1 Construction Personnel Hazards

**Table 65:** Construction Personnel Hazards

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	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	<ol style="list-style-type: none"> <li>All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear respirators when working with airborne particles.</li> <li>Standard Operating Procedures have been written, and they outline the necessary PPE required and operation steps for such tasks.</li> <li>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.</li> <li>The NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines all material properties.</li> </ol>	<ol style="list-style-type: none"> <li>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.</li> <li>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.</li> <li>Standard Operating Procedures for hand sanding can be found in SOP Section 1.3.2</li> <li>Standard Operating Procedures for the belt sander can be found in SOP Section 1.2.3</li> <li>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</li> <li>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</li> <li>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</li> </ol>	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	<ol style="list-style-type: none"> <li>1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear respirators when working with toxic fumes.</li> <li>2. Standard Operating Procedures have been written, and they outline the necessary PPE required and operation steps for such tasks.</li> <li>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.</li> <li>4. The NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines all material properties.</li> </ol>	<ol style="list-style-type: none"> <li>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.</li> <li>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.</li> <li>3. Standard Operating Procedures for hand sanding can be found in SOP Section 1.3.2</li> <li>4. Standard Operating Procedures for the belt sander can be found in SOP Section 1.2.3</li> <li>5. Standard Operating Procedures for the epoxying can be found in SOP Section 1.3.1</li> <li>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</li> <li>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</li> <li>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</li> </ol>	1	4	4
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C.3	Contact with the rotating component or cutting blade of a tool or machine	<ol style="list-style-type: none"> <li>1. Improper use of any rotary tool, such as a portable drill, drill press, or a dremel</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Severe injury to, or loss of, extremities</li> <li>2. Severe skin abrasions or cuts to the contact region</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. All team members must complete the necessary safety training prior to construction eligibility</li> <li>2. Standard Operating Procedures have been written, and they outline the necessary PPE and operation steps required for such tasks.</li> <li>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.</li> </ol>	<ol style="list-style-type: none"> <li>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.</li> <li>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.</li> <li>3. Standard Operating Procedures for the dremel can be found in SOP Section 1.1.1</li> <li>4. Standard Operating Procedures for the portable drill can be found in SOP Section 1.1.3</li> <li>5. Standard Operating Procedures for the drill press can be found in SOP Section 1.2.4</li> <li>6. Standard Operating Procedures for the lathe can be found in SOP Section 1.2.6</li> <li>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</li> <li>8. Standard Operating Procedures for wire cutters and strippers can be found in SOP Section 1.1.5</li> <li>9. Standard Operating Procedures for the hand saw can be found in SOP Section 1.1.2</li> <li>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</li> <li>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</li> </ol>	1	4	4
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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	<p>1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear long pants, short sleeves, and tie long hair back when operating on rotating or fast-moving machinery.</p> <p>2. 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.</p>	<p>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</p> <p>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</p> <p>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</p> <p>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</p>	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	<p>1. All team members must complete the necessary safety training prior to construction eligibility.</p> <p>2. Standard Operating Procedures have been written, and they outline the necessary PPE and operation steps required for such tasks.</p> <p>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.</p>	<p>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</p> <p>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</p> <p>3. Standard Operating Procedures for the belt sander can be found in SOP Section 1.2.3</p> <p>4. Standard Operating Procedures for hand sanding can be found in SOP Section 1.3.2</p> <p>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</p> <p>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</p>	1	4	4

C.6	Electric shock	<ol style="list-style-type: none"> <li>Improper operation on exposed wiring</li> <li>Buildup of static electricity</li> </ol>	Electrocution, leading to short term burns or potentially long term injuries or death	3	4	12	<ol style="list-style-type: none"> <li>All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all tools must be disconnected to a power source when not in use.</li> <li>Standard Operating Procedures have been written, and they will outline the necessary PPE required for such tasks.</li> <li>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.</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>Standard Operating Procedures for wire cutters and strippers can be found in SOP Section 1.1.5</li> <li>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</li> <li>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</li> </ol>	1	4	4
C.7	Skin contact with strong adhesive materials	Improper application of adhesive materials, such as epoxy	<ol style="list-style-type: none"> <li>Potentially severe allergic reaction</li> <li>Severe skin irritation and/or permanent skin damage to the contact region</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must wear chemical-resistant gloves when operating on strong adhesive materials.</li> <li>Standard Operating Procedures have been written, and they outline the necessary PPE and operation steps required for such tasks.</li> <li>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.</li> <li>The NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines all material properties.</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>Standard Operating Procedures for epoxying can be found in Section 1.3.1</li> <li>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</li> <li>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</li> <li>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</li> </ol>	2	3	6

C.8	Materials become unsecured during construction	<ol style="list-style-type: none"> <li>Improper utilization of motion-restriction tools</li> <li>Excessive force is applied to materials</li> </ol>	<ol style="list-style-type: none"> <li>Potential cuts, abrasions, or blunt bodily damage to nearby personnel</li> <li>Damage to vehicle materials results in project delays</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all tools must be disconnected to a power source when not in use.</li> <li>Standard Operating Procedures that require clamping highlight this necessity in the procedure</li> <li>Construction Procedures that require clamping will highlight this necessity in the procedure</li> <li>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.</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>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</li> <li>Construction Procedures will be written prior to construction</li> </ol>	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	<ol style="list-style-type: none"> <li>All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all members use wear hearing protection when in the presence of loud machinery.</li> <li>Standard Operating Procedures have been written, and they outline the necessary PPE required for loud machinery.</li> <li>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.</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>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</li> <li>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</li> </ol>	1	3	3

C.10	Fire	<ol style="list-style-type: none"> <li>1. Sparks from metal cutting</li> <li>2. Overheating parts</li> <li>3. Electronics short-circuit</li> <li>4. Lithium-Polymer battery explosion</li> <li>5. Leaving heat-inducing equipment, such as a soldering iron, in inappropriate locations</li> <li>6. Leaving vulnerable fire-hazard materials and tools unattended</li> </ol>	<ol style="list-style-type: none"> <li>1. Burns, resulting in short term health issues or death, or long term scarring on skin and extremities</li> <li>2. Smoke inhalation, resulting in short and long term health issues or death due to smoke suffocation</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>1. All team members must complete the necessary safety training prior to construction eligibility. In particular, the training outlines that all team members must not wear loose clothing when operating near flammable materials and all team members must clean up their workspace after operating with flammable materials.</li> <li>2. Standard Operating Procedures have been written, and they outline the necessary PPE and clean-up steps required for such tasks.</li> <li>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.</li> <li>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.</li> <li>5. Construction Procedures that handle potential fire hazards highlight the necessary steps and PPE</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>3. Standard Operating Procedures for soldering can be found in SOP Section 1.1.4</li> <li>4. Standard Operating Procedure for laser cutter can be found in SOP Section 1.2.5</li> <li>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</li> <li>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</li> <li>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</li> <li>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</li> <li>9. Construction Procedures will be written prior to construction</li> </ol>	1	3	3
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C.11	Blunt damage	Improper handling of heavy tools or project materials	<ol style="list-style-type: none"> <li>1. Potential bodily damage, especially to extremities</li> <li>2. Potential damage to tools or stock materials</li> </ol>	4	2	8	<ol style="list-style-type: none"> <li>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</li> <li>2. Construction Procedures that handle heavy materials and/or equipment highlight the necessary steps</li> <li>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.</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>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</li> <li>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</li> <li>5. Construction Procedures will be written prior to construction</li> </ol>	2	2	4
C.12	Tripping or falling	<ol style="list-style-type: none"> <li>1. Trip hazards exist on the floor, such as loose cords, backpacks, liquid spills, or project materials</li> <li>2. Carrying large equipment or materials hinders one's ability to observe potential obstacles</li> </ol>	<ol style="list-style-type: none"> <li>1. Potential injury</li> <li>2. Tripping or falling into nearby work, resulting in further injuries</li> <li>3. Potential damage to nearby materials and/or vehicle</li> </ol>	4	2	8	<ol style="list-style-type: none"> <li>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.</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>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</li> <li>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</li> </ol>	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	<ol style="list-style-type: none"> <li>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.</li> <li>2. Standard Operating Procedures have been written, and they outline the necessary PPE and operation required for such tasks.</li> <li>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.</li> <li>4. The NDRT Safety Data Sheet has been updated and made available to all team members, and it outlines all material properties.</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>3. Standard Operating Procedures for soldering can be found in SOP Section 1.1.4</li> <li>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</li> <li>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</li> <li>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</li> </ol>	1	3	3
C.14	Pinch-points	<ol style="list-style-type: none"> <li>1. Electronics clamp down at unintended times</li> <li>2. Improper handling of heavy machinery or tools</li> <li>3. Improper handling of heavy equipment</li> <li>4. Operation on components with small clearance for extremities</li> </ol>	Severe injury to or loss of extremities	2	3	6	<ol style="list-style-type: none"> <li>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.</li> <li>2. Standard Operating Procedures have been written, and they outline the necessary PPE required for such tasks.</li> <li>3. Construction Procedures that require small clearances highlight the necessary steps</li> <li>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.</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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</li> <li>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</li> <li>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</li> <li>5. Construction Procedures will be written prior to construction</li> </ol>	1	2	2



8.4.2 Launch Operations Personnel Hazards

Table 66: Launch Operation Personnel Hazards

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
L.1	Motor explosion near launch area	1. Motor imperfections 2. Improper installation of motor into vehicle body	Severe injury to personnel or death	3	4	12	1. The motor will be carefully transported to the launch site and inspected prior to installation. 2. The motor will be purchased from a reputable vendor and installed using proper techniques. 3. Launch Procedures have been written, and they outline the necessary procedures for motor transportation, inspection, and installation	1. Launch Procedure Section 8.1.4 outlines the transportation procedures for launch 2. Launch Procedure Section 8.1.9.6.1 outlines the necessary steps for motor inspection prior to launch. 3. Launch Procedure Section 8.1.9.6.2 outlines the necessary steps for motor inspection prior to launch. 4. Section 3.4.3 outlines the motor selection justification 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 8.1.10 4. Launch Procedures for launch vehicle component installation can be found in Section 8.1.9 5. Stability calculations can be found in Section 5.1.3	1	4	4

L.3	Uncontrolled vehicle descent	<ol style="list-style-type: none"> <li>1. The vehicle lands on personnel upon proper descent under a parachute</li> <li>2. Failure of vehicle's recovery systems</li> </ol>	<ol style="list-style-type: none"> <li>1. High velocity impact with personnel, leading to severe injury or death</li> <li>2. Low velocity impact with personnel, leading to injuries such as bruises or cuts</li> <li>3. Damage to nearby buildings or natural structures via impact</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Launch procedures have been written, and they outline the necessary steps for all launch vehicle component integration.</li> <li>2. Recovery system testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements.</li> <li>3. Vehicle drift will be restricted to less than 2,500 ft (NASA Recovery Requirement 3.10).</li> <li>4. The maximum allowable kinetic energy of the vehicle is understood to be 75 ft-lbf at landing (NASA Recovery Requirement 3.3).</li> <li>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.</li> <li>6. Main and drogue parachute drift calculations have been performed and approved by the Project Manager and the Safety Officer.</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures for launch vehicle component installation can be found in Section <a href="#">8.1.9</a></li> <li>2. Recovery testing procedures can be found in Section <a href="#">9.1</a></li> <li>3. A more detailed look at recovery system hazards and mitigations can be found in the recovery Failure Modes and Effects Analysis tables.</li> <li>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.</li> <li>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.</li> <li>6. Main and drogue parachute drift calculations can be found in Section <a href="#">5.2</a></li> </ol>	2	3	6
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L.4	Unncontrolled LVIS descent	<ol style="list-style-type: none"> <li>Unintended separation of LVIS from launch vehicle during launch</li> <li>Failure of LVIS recovery systems</li> </ol>	<ol style="list-style-type: none"> <li>Personnel injury via impact</li> <li>Damage to nearby buildings or natural structures via impact</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>Launch procedures have been written, and they outline the necessary steps for all launch vehicle component integration.</li> <li>Recovery system testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements.</li> <li>Vehicle drift will be restricted to less than 2,500 ft (NASA Recovery Requirement 3.10).</li> <li>The maximum allowable kinetic energy of the vehicle is understood to be 75 ft-lbf at landing (NASA Recovery Requirement 3.3).</li> <li>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.</li> <li>Main and drogue parachute drift calculations have been performed and approved by the Project Manager and the Safety Officer.</li> </ol>	<ol style="list-style-type: none"> <li>Launch Procedures for launch vehicle component installation can be found in Section <a href="#">8.1.9</a></li> <li>Recovery testing procedures can be found in Section <a href="#">9.1</a></li> <li>A more detailed look at recovery system hazards and mitigations can be found in the recovery Failure Modes and Effects Analysis tables.</li> <li>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.</li> <li>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.</li> <li>Main and drogue parachute drift calculations can be found in Section <a href="#">5.2</a></li> </ol>	2	2	4
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L.5	Uncontrolled ACS body tube descent	<ol style="list-style-type: none"> <li>Unintended separation of ACS body tube from launch vehicle during launch</li> <li>Failure of recovery system's shock cord</li> </ol>	<ol style="list-style-type: none"> <li>Personnel injury via impact</li> <li>Damage to nearby buildings or natural structures via impact</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>Launch procedures have been written, and they outline the necessary steps for all launch vehicle component integration.</li> <li>Recovery system testing procedures have been written in order to ensure the system will act accurately, reliably, and in accordance to all NASA Requirements.</li> <li>Vehicle drift will be restricted to less than 2,500 ft (NASA Recovery Requirement 3.10).</li> <li>The maximum allowable kinetic energy of the vehicle is understood to be 75 ft-lbf at landing (NASA Recovery Requirement 3.3).</li> <li>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.</li> <li>Main and drogue parachute drift calculations have been performed and approved by the Project Manager and the Safety Officer.</li> </ol>	<ol style="list-style-type: none"> <li>Launch Procedures for launch vehicle component installation can be found in Section <a href="#">8.1.9</a></li> <li>Recovery testing procedures can be found in Section <a href="#">9.1</a></li> <li>A more detailed look at recovery system hazards and mitigations can be found in the recovery Failure Modes and Effects Analysis tables.</li> <li>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.</li> <li>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.</li> <li>Main and drogue parachute drift calculations can be found in Section <a href="#">5.2</a></li> </ol>	2	2	4
L.6	Ignited motor heat	<ol style="list-style-type: none"> <li>Motor retains high temperatures even after landing</li> <li>Personnel recover the motor immediately after landing</li> <li>Personnel are positioned too close to the launchpad during motor burnout</li> </ol>	<ol style="list-style-type: none"> <li>Short term skin burns, and potentially long term scarring</li> <li>High temperatures increase the motor's likelihood of explosion</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>Team members will wait a considerable amount of time after landing before touching the launch vehicle.</li> <li>Team members will not approach the launch vehicle until the Range Safety Officer grants permission.</li> <li>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.</li> </ol>	<ol style="list-style-type: none"> <li>Launch Procedure Section <a href="#">8.1.12.1</a> outlines the necessary steps for post-launch retrieval of the launch vehicle</li> <li>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.</li> </ol>	1	2	2

L.7	Battery leakage or explosion	<ol style="list-style-type: none"> <li>Battery experiences intense vibrations and high temperatures during launch</li> <li>Battery is damaged during its transportation to launch field</li> <li>Battery was purchased with pre-existing defects</li> </ol>	<ol style="list-style-type: none"> <li>Chemical burns from the battery acid</li> <li>Potential battery explosion, resulting in personnel injuries</li> <li>Chemical leakage from battery is harmful to nearby personnel and the environment</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>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.</li> <li>The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines how PPE should be worn.</li> <li>Launch Procedures have been written, and they outline the PPE required and the procedure for dealing with damaged batteries.</li> <li>Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries.</li> <li>Launch Procedures have been written, and they outline the PPE required and the procedure for checking battery quality.</li> </ol>	<ol style="list-style-type: none"> <li>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.</li> <li>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.</li> <li>The updated NDRT Safety Handbook is readily available to all members, and a digital version is shared with all members.</li> <li>Launch Procedures for handling damaged batteries can be found in Section 8.1.3</li> <li>Launch Procedures Section 8.1.3 highlight the importance of storing all batteries in fire resistant bags when not in use</li> <li>Launch Procedures for checking battery voltage can be found in Section 8.1.3 and in every other section that involves battery instillation</li> </ol>	2	2	4
L.8	Operation of sharp or rotating tools for assembling the launch vehicle's interior systems	<ol style="list-style-type: none"> <li>Launch vehicle assembly may require sharp tools, such as pliers and scissors</li> <li>Launch vehicle assembly may require rotating tools, such as drills</li> </ol>	<ol style="list-style-type: none"> <li>Severe injury to extremities</li> <li>Severe skin abrasions or cuts to the contact region</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>All team members must complete the necessary safety training prior to launch.</li> <li>Standard Operating Procedures have been written, and they outline the necessary PPE and operation steps required for such tasks.</li> <li>The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines how PPE should be worn.</li> <li>Launch Procedures have been written, and they outline all PPE available at the launch site.</li> </ol>	<ol style="list-style-type: none"> <li>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.</li> <li>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.</li> <li>Standard Operating Procedures document has been written and made accessible to all team members.</li> <li>Launch Procedure sections all include all necessary PPE required for completing the procedure.</li> <li>Launch Procedure Section 8.1.3 outlines all PPE brought to the launch</li> <li>The updated NDRT Safety Handbook is readily available to all members, and a digital version is shared with all members.</li> <li>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.</li> </ol>	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	<p>1. All team members must complete the necessary safety training prior to launch.</p> <p>2. The NDRT Safety Handbook has been updated and made accessible to all team members, and it outlines how PPE should be worn.</p> <p>3. Launch Procedures have been written, and they outline all PPE available at the launch site.</p>	<p>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.</p> <p>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.</p> <p>3. Launch Procedure sections all include all necessary PPE required for completing the procedure.</p> <p>4. Launch Procedure Section 8.1.3 outlines all PPE brought to the launch</p> <p>5. The updated NDRT Safety Handbook is readily available to all members, and a digital version is shared with all members.</p> <p>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.</p>	2	1	2
L.10	Intense frigid weather	Inclement weather conditions	Prolonged exposure can result in hypothermia and/or Frostbite	2	3	6	<p>1. Team leads will inform all team members attending of the launch day conditions.</p> <p>2. All members attending will be required to wear proper clothes, especially multiple layers, for intense frigid weather.</p>	<p>1. It will be the responsibility of the Safety Officer to provide weather information to all members attending the launch at the day of the launch.</p> <p>2. It will be the responsibility of the Safety Officer and Project Manager to provide all potential weather hazards to all members attending the launch in the email prior to launch.</p> <p>3. The Safety Officer will bring extra gloves, hats, and blankets to the launch site in the event someone forgets to bring their own.</p> <p>4. Launch Procedures Sections 8.1.2 and 8.1.4 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</p>	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 will be the responsibility of the Safety Officer to provide weather information to all members attending the launch at the day of the launch. 2. It will be the responsibility of the Safety Officer and Project Manager to provide all potential weather hazards to all members attending the launch in the email prior to launch. 3. Launch Procedures Sections 8.1.2 and 8.1.4 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 will be the responsibility of the Safety Officer to provide weather information to all members attending the launch at the day of the launch. 2. it will be the responsibility of the Safety Officer and Project Manager to provide all potential weather hazards to all members attending the launch in the email prior to launch. 3. The Safety Officer will bring sunscreen to the launch site in the event someone forgets to bring their own. 4. Launch Procedures Sections 8.1.2 and 8.1.4 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 8.1.10.4 2. Launch Procedures for maintaining launch vehicle components can be found in Section 8.1.9	1	2	2

## 8.5 Environmental

### 8.5.1 Environmental Risks to Vehicle

**Table 67: Environmental Risks to Vehicle**

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	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	<ol style="list-style-type: none"> <li>1. Potential failure of recovery systems to properly operate, or recovery systems fail to operate entirely</li> <li>2. Potential failure of LVIS to properly operate, or LVIS fails to operate entirely</li> <li>3. Potential failure of ACS to properly operate, or ACS fails to operate entirely</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. All electrical components will be stored in re-sealable fire resistant bags when not in use.</li> <li>2. Altimeters for recovery, payload, and apogee control system will be shielded.</li> <li>3. Electrical components will be securely fastened to structural components or brackets in the launch vehicle.</li> <li>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</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures to ensure the recovery electronics are safe and ready for integration can be found in Section 8.1.6</li> <li>2. Launch Procedures to ensure the LVIS electronics are safe and ready for integration can be found in Section 8.1.7</li> <li>3. Launch Procedures to ensure the ACS electronics are safe and ready for integration can be found in Section 8.1.8</li> <li>4. Launch Procedures to ensure all system electronics are safe and ready for integration can be found in Section 8.1.9</li> <li>5. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 8.1.11 and 8.1.5</li> </ol>	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	<ol style="list-style-type: none"> <li>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)</li> <li>2. Launch will be postponed if wind speeds exceed 20 miles per hour.</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for the fins and stability margin can be found in Section 5.1.3, and they were approved by both the Safety Officer and the Systems Officer</li> <li>2. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 8.1.11 and 8.1.5</li> </ol>	1	4	4



EV.3	Inadequate ground visibility of launch vehicle during its flight	Low cloud cover on launch day	<ol style="list-style-type: none"> <li>1. Failure of team to track the entire flight path, leading to potential loss of vehicle or injury to nearby personnel</li> <li>2. Launching the launch vehicle into clouds violates the NAR High Power Rocket Safety Code Rule 9</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Launch will not occur when cloud cover hides the vehicle from eyesight during any segment of the flight or descent.</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures for ensuring the launch is safe to occur can be found in Sections <a href="#">8.1.11</a> and <a href="#">8.1.5</a></li> <li>2. The Range Safety Officer will always have full authority as to when launches may proceed.</li> </ol>	1	3	3
EV.4	Launch vehicle lands in trees or other elevated structures	<ol style="list-style-type: none"> <li>1. Trees or other elevated structures exist in the proximity of the launch area</li> <li>2. Vehicle's recovery landing area exceeds expected radius</li> </ol>	<ol style="list-style-type: none"> <li>1. Loss or damage of vehicle and/or payload</li> <li>2. Vehicle's actual recovery area potentially violated <a href="#">NASA Recovery Requirement 3.10</a></li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. The drogue parachute and main parachute sizings were based on calculations and flight simulations.</li> <li>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)</li> <li>3. Launches will occur in an open field away from any trees.</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations in Section <a href="#">5.2.3</a> show the maximum possible simulated drift of the vehicle is within the acceptable range of 2,500 ft (NASA Recovery Requirement 3.10).</li> <li>2. Launch Procedures for ensuring the launch is safe to occur and free from obstacles can be found in Sections <a href="#">8.1.11</a> and <a href="#">8.1.5</a></li> </ol>	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	<ol style="list-style-type: none"> <li>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.</li> <li>2. All transmission frequencies will be reported prior to flight.</li> <li>3. All electrical components will be stored in fire resistant bags when not in use.</li> <li>4. Launch Procedures have been written, and they outline the necessary steps for ensuring the transmissibility of LVIS prior to launch</li> <li>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.</li> <li>6. Transmitter testing procedures have been written to ensure the transmitters work. All tests will be performed prior to FRR</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. All transmitter frequencies will be reported to NASA prior to competition launch and compared to other devices at the launch site.</li> <li>2. All Testing Procedures can be found in Section 9.1</li> <li>3. Launch Procedures for ensuring LVIS transmissibility can be found in Section 8.1.9.2</li> <li>4. Launch Procedures for ensuring recovery system is working properly can be found in Sections 8.1.6 and 8.1.9.3</li> <li>5. The Range Safety Officer will always have full authority as to when launches may proceed.</li> <li>6. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 8.1.11 and 8.1.5</li> </ol>	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	<ol style="list-style-type: none"> <li>1. Expected launch angle not accurate, potentially missing our target and/or minimum required apogee (<a href="#">NASA Vehicles Requirement 2.1</a> &amp; <a href="#">NASA Vehicles Requirement 2.3</a>)</li> <li>2. Forces acting on the sides of rocket can be greater than calculated, resulting in unintended flight performance</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. The launch pad will be positioned at a <math>0^\circ \pm 1^\circ</math> angle with respect to the ground during all vehicle flights using a digital level.</li> <li>2. Launch Procedures have been written, and they outline the necessary steps for ensuring the launch pad is positioned at a <math>0^\circ \pm 1^\circ</math> angle with respect to the ground</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures for ensuring the launch pad is positioned at a <math>0^\circ \pm 1^\circ</math> angle with respect to the ground can be found in Sections 8.1.10.3 and 8.1.10.4.5</li> </ol>	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 outline 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 <a href="#">8.1.11</a> and <a href="#">8.1.5</a>	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 <a href="#">8.1.4</a> 3. Launch Procedures for the motor inspection and Integration can be found in Section <a href="#">8.1.9.6</a>	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	<ol style="list-style-type: none"> <li>1. Adhesive materials were researched prior to purchase from reputable brands, as determined by the NDRT Project Manager.</li> <li>2. Bonding materials will be stored correctly according to material-specific Safety Data Sheets.</li> <li>3. Assemblies with components attached via bonding material will be properly stored and transported according to material-specific Safety Data Sheets.</li> <li>4. Standard Operating Procedures have been written, and they will outline the correct procedure for epoxying.</li> </ol>	<ol style="list-style-type: none"> <li>1. Standard Operating Procedures for epoxying can be found in SOP Section 1.3.1</li> <li>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.</li> <li>3. Routine workshop checks will occur, during which storage of bonding materials will be checked and corrected as necessary.</li> </ol>	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	<ol style="list-style-type: none"> <li>1. All electrical components will be stored in re-sealable fire resistant bags when not in use.</li> <li>2. All electronics will be protected from direct sunlight once integrated into launch vehicle.</li> <li>3. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries.</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures Section <a href="#">8.1.3</a> highlight the importance of storing all batteries in fire resistant bags when not in use</li> <li>2. Launch Procedures for Recovery system preparation can be found in Section <a href="#">8.1.6</a></li> <li>3. Launch Procedures for LVIS preparation can be found in Section <a href="#">8.1.7</a></li> <li>4. Launch Procedures for ACS preparation can be found in Section <a href="#">8.1.8</a></li> <li>5. Launch Procedures for launch vehicle preparation can be found in Section <a href="#">8.1.9</a></li> </ol>	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	<ol style="list-style-type: none"> <li>1. Batteries will be stored in a dedicated protective container prior to assembly on launch day.</li> <li>2. Batteries will be fully charged prior to transportation to launch site.</li> <li>3. Batteries will not be charged at temperatures below freezing 32°F/0°C.</li> <li>4. Multiple batteries will be packed for launch day in the event a battery loses charge between departure and vehicle flight.</li> <li>5. Launch Procedures are in an order that allows electronics to be the last integrated component, immediately prior to vehicle setup on launch rail.</li> <li>6. Launch will not occur if the Range Safety Officer, Team Mentor, or Safety Officer deem the temperature to be too cold.</li> <li>7. Launch Procedures have been written, and they outline the PPE required and the procedure for storing and transporting batteries.</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures Section 8.1.3 highlight the importance of storing all batteries in fire resistant bags when not in use</li> <li>2. Launch Procedures for checking battery voltage can be found in Section 8.1.3 and in every other section that involves battery instillation</li> <li>3. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 8.1.11 and 8.1.5</li> <li>4. All Launch Procedures can be found in Section 8.1</li> </ol>	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	<ol style="list-style-type: none"> <li>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)</li> <li>2. Launch will be postponed if wind speeds exceed 20 miles per hour.</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for the fins and stability margin can be found in Section 5.1.3, and they were approved by both the Safety Officer and the Systems Officer</li> <li>2. Launch Procedures for ensuring the launch is safe to occur can be found in Sections 8.1.11 and 8.1.5</li> </ol>	2	2	4

EV.13	Excessive vehicle drift during parachuted descent	Wind speeds greater than 20 mph occur at the launch site	<ol style="list-style-type: none"> <li>1. Vehicle lands outside the allowable drift radius, violating <a href="#">NASA Recovery Requirement 3.10</a></li> <li>2. Low velocity vehicle impact with unsuspecting civilians, leading to injuries such as bruises or cuts</li> <li>3. Damage to nearby buildings or structures via impact</li> </ol>	3	2	6	<ol style="list-style-type: none"> <li>1. The parachute will be designed to optimise reduction of both descent velocity and drift radius.</li> <li>2. Launch will be postponed if wind speeds exceed 20 miles per hour.</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for the drogue parachute and main parachute can be found in Section 5.2, and they have been verified by the Safety Officer and Systems Officer.</li> <li>2. Expected drift calculations can be found in Section 5.2.3, and they have been verified and approved by the Safety Officer and Systems Officer.</li> <li>3. Launch Procedures for ensuring the launch is safe to occur and free from obstacles can be found in Sections 8.1.11 and 8.1.5</li> </ol>	1	2	2
EV.14	Physical damage to vehicle due to severe weather conditions	Hail or lightning	<ol style="list-style-type: none"> <li>1. Body of the vehicle can become compromised, affecting flight dynamics</li> <li>2. Overall vehicle weakened, causing higher risk of individual component failure</li> <li>3. If the motor is struck by lightning, possible motor explosion, resulting in catastrophic damage to all nearby launch vehicle components</li> </ol>	2	3	6	<ol style="list-style-type: none"> <li>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</li> <li>2. Launch Procedures have been written, and they outline the necessary steps for complete launch vehicle assembly</li> <li>3. Components of the vehicle will be reliable, durable, and able to withstand minor physical forces.</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Procedures for ensuring the launch is safe to occur and free from obstacles can be found in Sections 8.1.11 and 8.1.5</li> <li>2. All Launch Procedures can be found in Section 8.1</li> <li>3. The Range Safety Officer will always have full authority as to when launches may proceed.</li> </ol>	1	1	1

EV15	Alteration to vehicle structure and/or component geometry due to swelling	Weather conditions, such as high humidity and/or temperature changes	<p>1. Components do not fit together, resulting in difficulty or inability to assemble the launch vehicle</p> <p>2. If already assembled, components are unable to separate, resulting in unintended performance of components during launch</p>	2	3	6	<p>1. Launch Procedures have been written, and they outline the necessary steps for a safe component transportation to the launch site</p> <p>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.</p> <p>3. Components of the vehicle will be reliable, durable, and able to withstand minor physical forces.</p> <p>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</p>	<p>1. Launch Procedures for ensuring the launch is safe to occur and free from obstacles can be found in Sections <a href="#">8.1.11</a> and <a href="#">8.1.5</a></p> <p>2. All Launch Procedures can be found in Section <a href="#">8.1</a></p> <p>3. The Range Safety Officer will always have full authority as to when launches may proceed.</p> <p>4. Launch Procedures outlining the entire launch checklist list can be found in Section <a href="#">8.1.3</a></p> <p>5. Launch Procedures for all component transportation can be found in Section <a href="#">8.1.4</a></p>	1	2	2
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8.5.2 Vehicle Risks to Environment

Table 68: Vehicle Risks to Environment

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
VE.1	Solder, Wire, or Plastic Waste	<ol style="list-style-type: none"> <li>1. Use of solder to secure wire connections in electrical components</li> <li>2. Use of wires for connecting electrical components</li> <li>3. Use of plastic for prototyping and subscale construction</li> <li>3. Improper disposal of solder, wires, and/or plastic</li> </ol>	<ol style="list-style-type: none"> <li>1. Solder, wires, and/or plastics disposed of in a landfill may never fully decompose (plastics may take over 1,000 years to decompose)</li> <li>2. Potential damage to wildlife which may ingest or be injured by solder, wires, and/or plastics</li> <li>3. Contamination of nearby agricultural land</li> </ol>	4	3	12	<ol style="list-style-type: none"> <li>1. Solder, wires, and plastics will be disposed of according to local recycling guidelines, when possible</li> <li>2. Solder, wires, and plastics will be disposed of properly according to local landfill guidelines, when recycling is not possible</li> <li>3. All members completing construction using solder, wires, and plastics will minimize waste</li> <li>4. Alternative wire connection mechanisms, such as lever wire connectors, will be favored over solder, when possible</li> <li>5. Standard Operating Procedures have been written, and they outline the necessary steps for soldering</li> </ol>	<ol style="list-style-type: none"> <li>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</li> <li>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.</li> <li>3. Standard Operating Procedures for soldering can be found in SOP Section 1.1.4</li> <li>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</li> <li>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</li> <li>6. A recycling bin is always present in the team workshop, and emptied regularly by University of Notre Dame maintenance staff</li> </ol>	2	1	2



<p>VE.2</p>	<p>High velocity impact of any launch vehicle component (NASA Recovery Requirement 3.3)</p>	<p>1. High wind speeds, resulting in unintended flight trajectories 2. Failure of recovery systems to properly reduce launch vehicle descent velocity</p>	<p>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</p>	<p>3</p>	<p>4</p>	<p>12</p>	<p>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</p>	<p>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 can be found in Section 3.4.3 3. All recovery information can be found in Section 4. Notably, recovery deployment can be found in Section 4.3 4. Recovery Testing Procedures have been written, and they can be found in Section 9.1 5. Launch Procedures for recovery preparation and integration can be found in Sections 8.1.6 and 8.1.9.3, 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.</p>	<p>1</p>	<p>3</p>	<p>3</p>
<p>VE.3</p>	<p>Airborne fiberglass particulates, such as styrene (C8H8) gas</p>	<p>Use of sanding for any fiberglass material</p>	<p>1. Airborne particles reduce local air quality 2. Contamination of nearby agricultural land 3. Exposure to styrene poses a health risk to team members</p>	<p>3</p>	<p>4</p>	<p>12</p>	<p>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</p>	<p>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</p>	<p>1</p>	<p>3</p>	<p>3</p>

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	<ol style="list-style-type: none"> <li>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</li> <li>Safety documentation for all materials will be kept available for team members</li> <li>The motor and black powder will be chosen with environmental impact and performance both in mind, and it will be installed with proper techniques</li> </ol>	<ol style="list-style-type: none"> <li>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.</li> <li>NDRT Safety Data Sheet Document Section 4.4 contains safety data sheets for Black Powder</li> <li>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</li> <li>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</li> <li>Launch Procedures Section 8.1.9.6 outlines motor installation into launch vehicle</li> </ol>	5	1	5
VE.5	Launch Vehicle Components fully separate from vehicle during flight	<ol style="list-style-type: none"> <li>Failure to properly secure launch vehicle components, or complete failure to secure launch vehicle components</li> <li>Failure of launch vehicle components to maintain properly secured amidst the intense vibrations and heat of launch</li> <li>ACS flaps extend during motor burnout, and the shear pins are unable to withstand the intense drag induced by the flaps</li> </ol>	<ol style="list-style-type: none"> <li>Wildlife could ingest small components, resulting in terrible reactions</li> <li>Contact with sharp and/or abrasive surfaces of launch components may inflict damage to wildlife</li> <li>Impact velocity of launch vehicle components can inflict damage to nearby wildlife, crops, and/or buildings</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>Components in the vehicle are designed to be secured using reliable fasteners, adhesives, and/or shear pins</li> <li>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</li> <li>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</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>Calculations and simulations for vehicle structural components (Section 3.3) and recovery structural components (Section 4.5) have been verified and approved by both the Safety Officer and Systems Lead</li> <li>All Testing Procedures have been written, and they can be found in Section 9.1</li> <li>Detailed CAD models and drawings will be used to accurately fabricate, assemble, and integrate the launch vehicle and all internal systems</li> </ol>	1	2	2

<p>VE.6</p>	<p>Vehicle and/or LVIS debris</p>	<p>1. Launch vehicle explodes due to motor explosion 2. Extreme miscalculation of black powder charges results in excessive, unintended forces on system</p>	<p>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 ingested by wildlife, resulting in injury or death 3. Tiny components may be sharp or abrasive, and contact with wildlife can result in injury</p>	<p>2</p>	<p>4</p>	<p>8</p>	<p>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</p>	<p>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 can be found in Section 3.4.3 3. All recovery information can be found in Section 4. Notably, recovery deployment can be found in Section 4.3 4. Recovery and Vehicles Testing Procedures have been written, and they can be found in Section 9.1 5. Launch Procedures for recovery preparation and integration can be found in Sections 8.1.6 and 8.1.9.3, 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.</p>	<p>1</p>	<p>4</p>	<p>4</p>
<p>VE.7</p>	<p>Battery acid discharge</p>	<p>1. Battery ruptured by sharp object and/or impact 2. Intense vibrations and temperatures during launch may impact the structural strength of the battery</p>	<p>1. Contamination of nearby soil and/or groundwater 2. Contamination of nearby agricultural land</p>	<p>2</p>	<p>4</p>	<p>8</p>	<p>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</p>	<p>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 9.1 4. Launch Procedures for battery storing can be found in Section 8.1.3 5. Launch Procedures for battery transportation can be found in Section 8.1.4 6. Launch Procedures for battery testing can be found in Section 8.1.3</p>	<p>1</p>	<p>4</p>	<p>4</p>

VE.8	Fire	<p>1. Motor burnout generates flames</p> <p>2. Electrics short circuit</p> <p>3. Dry grass, due to local droughts and/or dry humidity</p>	<p>1. Severe burns to nearby personnel or wildlife or possible death</p> <p>2. Destruction of nearby natural habitats and/or agricultural land</p> <p>3. Carbon Dioxide is generated from fires, resulting in increased Greenhouse gas emissions</p>	2	4	8	<p>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.</p> <p>2. 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.</p> <p>3. The NDRT Safety Data Sheet will be updated and made available to all team members, and it will outline all material properties. All team members must consult the SDS before operating with any flammable materials.</p> <p>4. The motor will be installed correctly and carefully by an individual with at least NAR/TRA Level 2 certification</p> <p>5. All electronics will be inspected prior to departure to the launch site, and again immediately prior to integration into vehicle</p> <p>6. All electronics will remain OFF until necessary</p> <p>7. The launch pad will be positioned in an area free of debris or flammable objects</p> <p>8. Launch procedures have be written, and they will outline the necessary steps for all electronics integration</p>	<p>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</p> <p>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</p> <p>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</p> <p>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</p> <p>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</p> <p>6. Launch Procedures for electronics integration can be found in Sections <a href="#">8.1.6</a>, <a href="#">8.1.7</a>, <a href="#">8.1.8</a>, and <a href="#">8.1.9</a></p> <p>7. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR</p> <p>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.</p>	1	4	4
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VE.9	Hydrogen Chloride (HCl gas) emission	Use of Ammonium perchlorate (NH <sub>4</sub> ClO <sub>4</sub> ) motors, resulting in release of hydrogen chloride	Hydrogen chloride (HCl gas) and water (H <sub>2</sub> O) react to form hydrochloric acid (HCl aqueous), resulting in contaminated waters and/or habitats	3	2	6	<p>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.</p> <p>2. Important material properties for all materials are listed in the NDRT Safety Data Sheet Document</p>	<p>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.</p> <p>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</p> <p>3. The Range Safety Officer will always have full authority as to when launches may proceed</p>	3	1	3
VE.10	Loss of Body Tube(s) and/or Vehicle Components Upon landing	<p>1. Vehicle lands outside the allowable drift radius, violating <a href="#">NASA Recovery Requirement 3.10</a></p> <p>2. Launch vehicle body tubes and/or components land in difficult recovery locations, such as high grass, cornfields, and/or water</p>	<p>1. Leftover vehicle components can be harmful to nearby wildlife, agriculture, and/or habitats</p> <p>2. Components may never fully decompose</p>	2	3	6	<p>1. GPS will be installed to all launch vehicle subsystems, per NASA Vehicles Requirement 3.12</p> <p>2. Long-distance testing procedures have been written, and it will ensure all electronics can send signals at far distances. All tests will be performed before FRR</p> <p>3. Calculations for maximum expected drift radius have been performed</p>	<p>1. Long-distance Testing Procedures can be found in Section 9.1</p> <p>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 5.2</p>	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	<p>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.)</p> <p>2. The Safety Handbook outlines the necessary PPE required for ear protection and its location in the workshop and at launch field</p> <p>3. Launch Procedures have been written, and they outline the procedure for launch vehicle integration on launch rail</p> <p>4. Launch Procedures have been written, and they outline the procedure for setting up the launch pad</p> <p>5. Personnel will stand at least 300 ft. from the launch pad when viewing the launch, as required by the NAR</p>	<p>1. Launch Procedures for launch pad setup can be found in Section 8.1.10</p> <p>2. Launch Procedures for launch vehicle integration on launch pad can be found in Section 8.1.10.4</p> <p>3. The Range Safety Officer will designate safe areas to view the launch in accordance with NAR guidelines</p> <p>4. The Range Safety Officer will always have full authority as to when launches may proceed</p> <p>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</p> <p>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</p>	1	2	2

VE.12	Paint chips off of the exterior of the launch vehicle during transportation and/or flight	<ol style="list-style-type: none"> <li>1. Use of paint to decorate the exterior of the launch vehicle</li> <li>2. Intense vibrations and heat during launch</li> <li>3. Launch vehicle impact velocity</li> </ol>	<ol style="list-style-type: none"> <li>1. Paint left un-recovered may take a while to fully decompose</li> <li>2. Potential damage to wildlife who may ingest paint</li> <li>3. Contamination of nearby agricultural land if chipped off during flight</li> </ol>	2	2	4	<ol style="list-style-type: none"> <li>1. The amount of paint emissions from black powder charges will be minimized, such that there are negligible effects on personnel or environment</li> <li>2. Components that require sanding will be noted in step-by-step fabrication procedures</li> <li>3. Safety documentation for motors will be made available for team members</li> <li>4. Painting will be completed professionally in a licensed paint shop with appropriate coatings and employees</li> <li>5. Launch Procedures have been written, and they outline the necessary steps for vehicle transportation and integration</li> <li>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</li> </ol>	<ol style="list-style-type: none"> <li>1. All professional paint shops must have proper licenses and certifications</li> <li>2. NDRT Safety Data Sheet Document Section 4.1 contains the Acrylic Enamel Paint SDS, and is readily available for all members</li> <li>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</li> <li>4. Fan can and nose cone impact testing procedures can be found in Section <a href="#">9.1</a></li> <li>5. Launch Procedures for vehicle transportation and instillation on launch pad can be found in Section <a href="#">8.1.10.4</a></li> </ol>	1	1	1
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## 9 Project Plan

### 9.1 Testing

The team has developed 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 will be 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 is to maximize confidence in the launch vehicle for the competition flight in April.

**Table 69:** 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	Incomplete
LVT.2	Subscale Demonstration Flight	NASA 2.18	Pass
LVT.3	Bulkhead Static Loading Test	LV.2	Incomplete
LVT.4	Motor Mount Tube Static Loading Test	LV.2	Incomplete
LVT.5	Body Tube Static Loading Test	LV.2	Incomplete
LVT.6	Bulkhead Dynamic Loading Test	LV.2	Incomplete
RT.1	Launch Vehicle Demonstration Flight	R.2	Incomplete
RT.2	Subscale Demonstration Flight	NASA 2.18	Pass
RT.3	Ground Ejection Demonstration	NASA 3.2	Incomplete
RT.4	Simulated Flight Demonstration	N/A	Incomplete
RT.5	Altimeter Disarming Demonstration	N/A	Incomplete
RT.6	GPS Functionality and Range Demonstration	NASA 3.12, NASA 3.12.2	Incomplete
RT.7	Electronics Isolation Demonstration	NASA 3.13, NASA 3.13.3, NASA 3.13.4	Incomplete
RT.8	Battery Duration Demonstration	R.4	Incomplete
RT.9	Bulkhead Static Loading Test	R.1	Incomplete
RT.10	Bulkhead Dynamic Loading Test	R.1	Incomplete
RT.11	Shear Pin Test	NASA 3.9, ACS.6	Incomplete
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	Incomplete
LVIST.4	Sensor Module Demonstration	N/A	Incomplete
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	Incomplete
LVIST.8	Main Parachute Impulse Event Demonstration	LVIS.6	Incomplete
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	Incomplete
ACST.2	Payload Demonstration Flight	N/A	Incomplete

**Table 69:** Testing Overview (continued)

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

### 9.1.1 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	Incomplete
RT.1	All separation events occur as designed, parachutes open without tangling, and launch vehicle is safely recovered	R.2	Incomplete

**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. Scheduled for early February.

**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.

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

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



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 3.5.4, and discussion of data collected from the subscale flight by LVIS is discussed in Section 6.10. 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	Incomplete
RT.3	PRM and SRM bulkhead assemblies withstand static loading up to and beyond twice the maximum expected in-flight load	R.1	Incomplete
ACST.9	ACS bulkheads withstand static loading up to and beyond twice the maximum expected in-flight load	ACS.6	Incomplete

**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
- 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 (423 lbf for payload bulkhead, 676 lbf for fin can bulkhead)
  - (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:** Incomplete. Scheduled for January.

**Next Steps:** If factor of safety of each bulkhead is greater than or equal to 2.0, test is passed. If factor of safety for any test article is less than 2.0, adjust material selection, bulkhead thickness, interface hardware size, or epoxy application and repeat test if time and financial resources permit.

**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

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	Incomplete

**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 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 motor 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 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:** Incomplete. Scheduled for January.

**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	Incomplete

**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:** Incomplete. Scheduled for January.

**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	Incomplete
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	Incomplete
ACST.10	ACS bulkhead assembly test article withstands dynamic loading up to and beyond twice the maximum expected parachute force (600 lbf)	ACS.6	Incomplete

**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

- 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:**

- For each test article:
  - Locate frame above a balcony such that the test article can free fall without obstruction
  - Drop test article such that it falls the calculated height

**Analysis Procedure:**

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

**Results:** Incomplete. Scheduled for January.

**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.

**9.1.2 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:**

- Team mentor only: load black powder into a single charge well with the E-match
- Assemble the launch vehicle such that the wire leads are accessible from a safe distance, as determined by the RSO
- Place vehicle on ground, clear of any obstructions

**Test Procedure:**

- For each separation point:
  - Team mentor only: close circuit on 12V battery to ignite black powder
  - Wait for launch vehicle sections to come to rest before handling them

**Analysis Procedure:**

- If black powder does not separate vehicle sections, charge was too small
- If black powder separates vehicle sections with too much force (as deemed by RSO or team mentor), charge was too large

**Results:** Incomplete. Scheduled for same day as launch vehicle demonstration flight.

**Next Steps:** Repeat test for each separation event until team mentor agrees that all separation location charges are sized appropriately.

#### RT.4: Simulated Flight Demonstration

**Objective:** Verify that altimeters activate at simulated expected altitudes

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	Incomplete

#### Materials and Equipment Needed:

- Flight altimeters
- Holiday light bulbs
- Team-made pressure chamber

#### Test Setup:

1. Plug a light into each E-match terminal on altimeter
2. Plug battery into altimeter; turn switch to "ON" position
3. Place altimeter into pressure chamber, and seal such that internal air is isolated from the outside

#### Test Procedure:

1. For each altimeter:
  - (a) Draw syringe on lid of container to remove air from chamber
  - (b) Once syringe reaches maximum extension and pressure inside chamber is no longer decreasing, the light for the drogue terminal should turn on
  - (c) Plunge syringe back down, increasing pressure in the chamber
  - (d) Before the syringe is completely plunged down, the light for the main terminal should turn on

#### Analysis Procedure:

1. If either light does not turn on, either altimeter is faulty or pressure chamber is not sealed properly

**Results:** Incomplete. Scheduled for January

**Next Steps:** If both lights activate, the demonstration passes. If one or both lights fails to turn on, identify cause of failure and repeat until successful.

#### 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 with arming switch connected
- Holiday light bulbs

- Team-made pressure chamber

**Test Setup:**

1. Plug a light into each E-match terminal on altimeter
2. Plug battery into altimeter; turn switch to "ON" position
3. Place altimeter into pressure chamber, and seal such that internal air is isolated from the outside

**Test Procedure:**

1. For each altimeter:
  - (a) Draw syringe on lid of container to remove air from chamber
  - (b) Once syringe reaches maximum extension and pressure inside chamber is no longer decreasing, the light for the drogue terminal should turn on
  - (c) Plunge syringe back down, increasing pressure in the chamber
  - (d) Before the syringe is completely plunged down, the light for the main terminal should turn on
  - (e) Remove altimeter from chamber and turn arming switch to "OFF" position

**Analysis Procedure:**

1. Inspect to see that altimeter and both charge terminal lights turn off when switch is turned

**Results:** Incomplete. Scheduled for January

**Next Steps:** If both lights de-activate, the demonstration passes. If one or both lights fails to turn off, identify cause of failure and repeat until successful.

**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)	<a href="#">NASA 3.12</a> , <a href="#">NASA 3.12.2</a>	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:** Incomplete. Scheduled for January

**Next Steps:** If the transmitter can send coordinates to the receiver both at boot-up and at range, the demonstration passes. If the GPS fails to transmit coordinates at any point during the demonstration, the cause of failure must be identified and the demonstration must be repeated.

### RT.7: Electronics Isolation Demonstration

**Objective:** Verify that altimeters are not prematurely triggered by external electronic interference

Test ID	Success Criteria	Requirements Satisfied	Result
RT.7	Altimeters do not activate light bulb indicators due to electronic interference	NASA 3.13, NASA 3.13.3, NASA 3.13.4	Incomplete

#### Materials and Equipment Needed:

- PRM assembly and recovery tube
- ACS motor
- GPS transmitter
- LVIS transmission module
- Light bulb indicators

#### Test Setup:

1. Plug a light into each E-match terminal on each altimeter
2. Plug batteries into altimeters; make sure arming switches are in "OFF" position
3. Integrate SRM into recovery tube

#### Test Procedure:

1. Turn arming switches to "ON" position
2. Activate ACS servo motor and actuate it while in close physical proximity to recovery tube
3. Activate GPS transmitter and place near recovery tube
4. Activate LVIS transmission module and place near recovery tube
5. Wait for 5 minutes and de-activate the external systems
6. With the arming switches still in the "ON" position, remove the SRM from the recovery tube

#### Analysis Procedure:

1. Inspect that none of the light bulb indicators are on

**Results:** Incomplete. Scheduled for January

**Next Steps:** If no lights activate, the demonstration passes. If any light turns on, identify and address cause of failure and repeat until successful.

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

**Objective:** Verify that flight batteries can operate for up to three 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	Incomplete



**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 outside in a location which can be easily supervised from indoors
3. Set a timer for three hours and wait
4. After three hours, bring systems inside, careful not to unplug or de-activate them

**Analysis Procedure:**

1. Inspect that all systems remain on and functional

**Results:** Incomplete. Scheduled for January

**Next Steps:** If all systems remain on after the three hours, demonstration passes. If one or more systems loses power, battery capacity selection must be revisited and the demonstration must be repeated.

**RT.11: Shear Pin Test**

**Objective:** Verify that shear pins are strong enough to hold the main and drogue separation points while the ACS produces its maximum possible drag force

Test ID	Success Criteria	Requirements Satisfied	Result
RT.11	Body tube sections do not separate when loaded in tension with weight equivalent to maximum ACS drag (180 lbf)	NASA 3.9, ACS.6	Incomplete

**Materials and Equipment Needed:**

- Payload tube
- Recovery tube
- ACS tube
- Shear pins (same configuration that will be used in flight)
- Bulkheads in payload tube and ACS tube with anchor points (eyebolts/U-bolts will work)
- Weight to simulate ACS drag
- Safety glasses

**Test Setup:**

1. Assemble payload tube, recovery tube, and ACS tube together and insert shear pins
2. Hang assembly from anchor point on payload tube

**Test Procedure:**

1. Note: hanging assembly should be close to the ground to minimize energy release upon tube separation
2. Load weight onto ACS tube anchor point gradually until one of the separation points comes apart

- Note the load at which the tubes separate

**Analysis Procedure:**

- Compare separation load to the maximum drag force due to ACS. Separation load should be greater than 180 lbf, which is the maximum ACS drag.

**Results:** Incomplete. Scheduled for January

**Next Steps:** If the body tubes separate due to a load greater than 180 lbf, the shear pin configuration is valid. If separation load is less than or close to 180, the shear pin configuration must be reconsidered and the test repeated.

**9.1.3 LVIS Testing****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.	<a href="#">NASA 2.19.2.1</a> , <a href="#">NASA 2.19.2.2</a> , <a href="#">NASA 4.2.2.6, R.1</a>	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:**

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

**Analysis Procedure:**

- Verify grid location with GPS coordinates collected at landing site

**Results:** Incomplete. Scheduled for February

**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	Incomplete
ACST.4	Each sensor's data can individually be read into ACS flight computer .	N/A	Incomplete

**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:** Incomplete. Scheduled for January

**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.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	Incomplete

**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:** Incomplete. Scheduled for January

**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. Scheduled for January

**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. Scheduled for January

**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. Scheduled for January

**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. Scheduled for January

**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.

#### 9.1.4 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	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 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:** Incomplete. Scheduled for early February.

**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 early February.

**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	Incomplete

### 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

**Results:** Incomplete. Scheduled for January.

**Next Steps:** If all success criteria are met, ACS simulated flight demonstration is passed. If not, identify and address causes of failure and repeat demonstration until passed.

## 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	Incomplete

### Materials and Equipment Needed:

- Fully integrated ACS
- ACS flap movement override panel

### Test Setup:

1. Plug override panel into port on ACS PCB
2. Activate ACS

### Test Procedure:

1. Override flap movement in one direction until contact with limit switch stops travel
2. Repeat in opposite direction

### Analysis Procedure:



1. Verify that travel being stopped is due to detection from limit switch, not the motor stalling due to mechanical limits

**Results:** Incomplete. Scheduled for January.

**Next Steps:** If success criteria are met, demonstration passes. If travel is stopped for other reasons, cause must be identified and addressed. Demonstration must be repeated until passed.

### 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
- ACS tube
- ACS flap movement override panel
- Weights to simulate drag force on the flaps

#### Test Setup:

1. Attach weights to ACS flaps such that each flap is weighted to twice the maximum drag force it can produce
2. Plug override panel into port on ACS PCB
3. Activate ACS

#### Test Procedure:

1. Override flap movement in one direction until contact with limit switch stops travel
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. Scheduled for January.

**Next Steps:** If success criteria are met, demonstration passes. If the motor stalls and flap movement fails, motor sizing or maximum allowable drag produced must be reconsidered and the demonstration repeated until passed.

## 9.2 Requirements Compliance

### 9.2.1 NASA General Requirements

**Table 70: 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.	In Progress	I	The roles of team advisors are limited to providing feedback to the team on work done by the students. Motor assembly, handling black powder charges, and installing electric matches 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.	In Progress	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.	Needs Attention	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:	In Progress	I	The Project Manager has created and maintains an active team roster which has been submitted with the CDR.	See team roster attached to CDR submission
1.4.1	Students actively engaged in the project throughout the entire year.	In Progress	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.	In Progress	I	Inspection will verify the identification of two team mentors at most.	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.	In Progress	I	The team has engaged with 50 participants in direct STEM activities, and plans to reach at least 250 by the FRR due date.	9.3
1.6	The team will establish and maintain a social media presence to inform the public about team activities.	In Progress	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 70: 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.	In Progress	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, which it builds every report off of. 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, which it builds every report off of. 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 owns 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 Wifi 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 70: 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.	In Progress	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

## 9.2.2 NASA Launch Vehicle Requirements

Table 71: 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.	In Progress	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. Launch vehicle demonstration flights are scheduled for early February.	5.1.2, IVT.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.	5.1.2
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.	4.6.1
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 plans on launching twice on vehicle demonstration flight days. Consecutive launches on the same day without repairs or modifications will verify reusability. Safe descent and landing of the launch vehicle during a demonstration flight will verify recoverability.	IVT.1, 4.1

**Table 71: 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.	3.3.2
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.	3.3.2
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.	3.3.1
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.	Incomplete	D	Demonstration on launch day will verify a vehicle preparation time of less than 2 hours.	The launch vehicle demonstration flight is scheduled for early February.	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.	Incomplete	D	Demonstration on launch day will verify an on-pad wait time of up to 2 hours.	The launch vehicle demonstration flight is scheduled for early February.	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.	3.4.3
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).	In Progress	I	Inspection will verify the absence of an external launch support system in the system design. Demonstration will verify launch without such equipment.	The team does not plan on using any other external ground support equipment.	8.1.10

**Table 71: 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.	3.4.3
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.	3.4.3
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.	5.1.2
2.11	The launch vehicle will be limited to a single stage.	Complete	I	Visual inspection will insure that the vehicle will be limited to a single stage.	The vehicle has a single stage.	3.4.3
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.	3.1
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.	3.2
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.	3.2
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.	3.2

Table 71: 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.	3.2
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.	In Progress	A	Flight Simulations will be used to verify a minimum off-rail static stability margin of 2.0.	The off-rail stability margin is 2.79.	5.1.3
2.15	The launch vehicle will have a minimum thrust to weight ratio of 5.0 : 1.0.	In Progress	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 9.65.	3.4.3
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.	In Progress	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.	5.1.3, 3.3.3
2.17	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	In Progress	A	Flight Simulations will be used to verify a minimum off-rail velocity of 52 fps.	The vehicle off-rail velocity is 89.2 ft/s.	3.1
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. Subscale models 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.	3.5, 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.	3.5
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.	3.5

**Table 71: 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.	3.5
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.	3.5.4
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.	3.5
2.19	All teams will complete demonstration flights as outlined below.	Incomplete	D	See requirement verifications 2.19.1 through 2.19.2.4	The full-scale demonstration flight is scheduled for early February.	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:	Incomplete	D	The launch vehicle will be launched in its final flight configuration on one of multiple possible launch dates.	The full-scale demonstration flight is scheduled for early February.	LVT.1
2.19.1.1	The vehicle and recovery system will have functioned as designed.	Incomplete	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 full-scale demonstration flight is scheduled for early February.	LVT.1, 5.1.2



**Table 71: NASA Launch Vehicle Requirements (continued)**

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.19.1.2	The full-scale rocket shall be a newly constructed rocket, designed and built specifically for this year's project.	In Progress	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.	3.4.3
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.	Incomplete	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 launch vehicle demonstration flight is scheduled for early February.	6.9, 7.7
2.19.1.3.2	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.	Incomplete	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.	The launch vehicle demonstration flight is scheduled for early February.	6.8, 7.2.8.
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.	Incomplete	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 launch vehicle demonstration flight is scheduled for early February.	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 launch vehicle demonstration flight is scheduled for early February.	3.4.3
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.	Incomplete	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 demonstration flight is scheduled for early February.	5.1.2, 3.4.2

**Table 71: 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).	Incomplete	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 flight is scheduled for early February.	8.1.12
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.	Incomplete	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 launch vehicle demonstration flight is scheduled for early February.	4.1, 6.3, 7.4.2
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.	Incomplete	I	The team has identified multiple potential dates for completing the launch vehicle demonstration flight to account for weather or fabrication delays.	The launch vehicle demonstration flight is scheduled for early February.	9.5

**Table 71: 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 early February.	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.	Incomplete	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 launch vehicle demonstration flight is scheduled for early February.	LVIST.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 February.	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.	Complete	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 February.	9.5

**Table 71: 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 February.	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 addendum, if necessary, prior to the deadline to avoid exclusion from launching at the competition.	The launch vehicle demonstration flight is scheduled for early February.	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 February.	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 February.	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.	Incomplete	I	Inspection will verify that the team's information are in or on the vehicle airframe.	The launch vehicle demonstration flight is scheduled for early February.	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.	Incomplete	I	Inspection will verify that all batteries are sufficiently secured to their respective payloads and are brightly colored and marked as a fire hazard.	The launch vehicle demonstration flight is scheduled for early February.	4.6.1, 6.5.4, 7.4.5

**Table 71: 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.	3.4.3
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.	3.4.3
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.	3.4.3
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.	3.4.3
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.	3.3.6
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.	5.1.1
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).	In Progress	I, A	Flight simulations and measured hardware masses will be used to determine the maximum allowable ballast	The maximum allowable ballast is 82 oz.	5.1.2
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).	In Progress	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.	6.5.2
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.	In Progress	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.	6.5.2
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.	In Progress	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.	4.5.1, 7.2.3

### 9.2.3 NDRT Launch Vehicle Requirements

**Table 72: 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.	In Progress	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 4944 (min apogee) and 5304 (max apogee) without ballast. The launch vehicle demonstration flight is scheduled for early February.	5.1.1, 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 safety of 1.5 to reduce the risk of structural failures in flight and ensure durability for subsequent flights.	In Progress	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 results show that all vehicle components can withstand expected loads with a factor of safety of at least two. Static and dynamic testing will take place in January.	5.3, 5.3.2, 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.	In Progress	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.	3.3
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.	3.3.2
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.	In Progress	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 will use JB Weld to attach the centering rings, fins, and motor retaining ring to the motor mount tube. The launch vehicle demonstration flight is scheduled for early February.	3.3.6, LVT.1

### 9.2.4 NASA Recovery Requirements

Table 73: 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.	Incomplete	D	The staged demonstration of recovery device deployment will be demonstrated at the launch vehicle demonstration flight.	The launch vehicle demonstration flight will take place in early February	LVT.1
3.1.1	The main parachute shall be deployed no lower than 500 feet.	Incomplete	D	The deployment of the main parachute above 500 feet will be demonstrated at the launch vehicle demonstration flight.	The launch vehicle demonstration flight will take place in early February	LVT.1
3.1.2	The apogee event may contain a delay of no more than 2 seconds.	Incomplete	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 flight will take place in early February	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.	Incomplete	T	The team will perform black powder ground ejection tests for each separation point until all charges are sized appropriately.	The launch vehicle demonstration flight will take place in early February, and the ground ejection tests will take place on the same day, prior to flight.	RT.3
3.3	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.	In Progress	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 72 ft-lb.	4.1, 5.2.1
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.	4.6.1
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.	4.6.1, 4.6.2
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.	4.6.3

**Table 73: 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.	4.6.3
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.	4.6, 6.2
3.9	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	Incomplete	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.	The launch vehicle demonstration flight will take place in early February, and the ground ejection tests will take place on the same day, prior to flight.	RT.11
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 2,456 ft.	4.1, 5.2.3
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 s.	4.1, 5.2.2
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.	Incomplete	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 demonstration will take place in January.	4.6.2, 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.	4.6.2
3.12.2	The electronic GPS tracking device(s) will be fully functional during the official competition launch.	Incomplete	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 will take place in January	4.6.2, 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).	Incomplete	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 will take place in January.	RT.7



**Table 73: 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.	4.6.1
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.	4.6.1
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.	Incomplete	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 will take place in January.	4.6.1 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.	Incomplete	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 will take place in January.	4.6.1, RT.7

### 9.2.5 NDRT Recovery Requirements

**Table 74: 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).	In Progress	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 991.06 lbf. Testing will occur in January.	5.3.2, RT.9, RT.10

**Table 74:** 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.	Incomplete	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	The launch vehicle demonstration flight will take place in January.	4.4.2, 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.	Incomplete	D	Demonstration will verify the functionality of all electronic components in both ends of the launch window range.	The full system integration test will be performed in January in both high and low temperatures.	LVIST.1
R.4	Flight batteries shall be sized for 3 hours of operation in all expected flight conditions.	Sizing batteries for 3 hours of operation provides a safety factor of 1.5 from the 2 hour standby requirement given by NASA requirement 2.7. This capability should be upheld in all possible flight conditions, since batteries lose capacity in extreme cold.	Incomplete	D	The battery duration demonstration will verify that flight batteries can power the recovery system for at least three hours in extreme cold weather.	The battery duration demonstration will take place in January.	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.	In Progress	I	Inspection will verify that epoxy joints which are near black powder ejection charges will use high-temperature epoxy.	Epoxy joints for black powder charge wells, Wago connectors on the recovery bulkheads, and the coupler around the SRM will all use JB Weld, a high-temperature epoxy which the team has experience using.	4.5.2

**Table 74: 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.	4.6.1

### 9.2.6 NASA Payload Requirements

**Table 75: 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.	6.3
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 75: 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.	6.7
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 flight is scheduled for early January.	5.2.3, I.VT.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.	6.7
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.	6.7
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.	6.7
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.	6.7
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.	6.7
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.	6.7
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 January, and the payload demonstration flight is scheduled for February.	I.VIST.5, I.VIST.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.	6.7

**Table 75: 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.	6.7
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.	6.7
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.	6.7
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.	6.7
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.	6.2
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
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.	6.2
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 Power Rocketry 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.	8
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.	6.2

**Table 75: 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.	6.2
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 <a href="https://www.faa.gov/uas/faqs">https://www.faa.gov/uas/faqs</a> ).	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.	6.2
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.	6.2

### 9.2.7 NDRT Scoring Payload Requirements

**Table 76: 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 redundant source.	The LVIS has three sub-modules, each of which have two sources of every type of necessary data.	6.5.1
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 safety of 2.0 to reduce the risk of components coming loose during flight	Incomplete	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.	5.3.2
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	Incomplete	D	Demonstration will verify the functionality of all electronic components in both ends of the launch window range.	The full system integration test will be performed in January in both high and low temperatures.	LVIST6

**Table 76:** 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 3 hours of operation in all expected flight conditions.	Sizing batteries for 3 hours of operation provides a safety factor of 1.5 from the 2 hour standby requirement given by NASA requirement 2.7. This capability should be upheld in all possible flight conditions, since batteries lose capacity in extreme cold.	Incomplete	D	The battery duration demonstration will verify that flight batteries can power the LVIS for at least three hours in extreme cold weather.	The battery duration demonstration will take place on in January.	LVIST.7
LVIS.5	The ground station power supply shall be capable of powering the system for a minimum of three hours.	The ground station should be capable of remaining operational for as long as the payload, with a maximum delay time of up to two hours, giving a safety factor of 1.5.	Incomplete	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 battery duration demonstration will take place in January.	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 January.	6.5.1, LVIST.8.

### 9.2.8 NDRT Non-Scoring Payload Requirements

**Table 77:** 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.	Incomplete	D	The ability for the ACS to identify the current stage of flight will be verified during the ACS integration test.	The ACS integration test is scheduled for January.	7.4.6, ACST.1
ACS.2	The ACS shall be capable of recording launch vehicle altitude, linear acceleration, and angular acceleration.	Collecting these measurements is the minimum necessary data-set to track vehicle position and orientation, which allows the system to calculate the projected apogee.	Incomplete	I, D	Inspection will verify that the ACS has sensors capable of recording this information.	The ACS sensor selection covers redundancies in all necessary measurement types.	7.4

**Table 77: 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 redundant source.	The ACS sensor selection covers redundancies in all necessary measurement types.	7.4
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.	In Progress	A, D	CFD will aid in determining a Cd vs. $\alpha$ 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.	CFD results and ACS effectiveness calculations have been completed. The ACS full-system demonstration is scheduled for February.	ACST.1, 7.3
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.	Incomplete	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 full-system demonstration is scheduled for February.	ACST.1, ACST.5
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	In Progress	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 is scheduled for January. Bolt shear calculations have been performed for all load scenarios.	7.2.9, ACST.9, ACST.10
ACS.7	ACS flight batteries shall be sized for 3 hours of operation in all expected flight conditions, including continuous actuation of drag surfaces between motor burnout and apogee.	Sizing batteries for 3 hours of operation provides a safety factor of 1.5 from the 2 hour standby requirement given by NASA 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.	Incomplete	D	The battery duration demonstration will verify that flight batteries can power the ACS for at least three hours in extreme cold weather.	The battery duration demonstration will take place in January.	ACST.6



**Table 77: 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.	In Progress	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 flap actuation demonstration is scheduled for January.	7.3, 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 expected drag force	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 flap actuation demonstration is scheduled for January.	ACST.8, 7.2.9

### 9.2.9 NASA Safety Requirements

**Table 78: 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 CDR 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 78: NASA Safety Requirements (continued)**

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
5.3.1.1	Design of vehicle and payload	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
5.3.1.2	Construction of vehicle and payload components	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
5.3.1.3	Assembly of vehicle and payload	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
5.3.1.4	Ground testing of vehicle and payload	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
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)	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
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 78: NASA Safety Requirements (continued)**

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
5.3.1.8	Recovery activities	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
5.3.1.9	STEM Engagement Activities	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
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.	In Progress	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.	In Progress	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.	In Progress	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.	Section 8, and Launch Procedures Section 8.1.1
5.5	Teams will abide by all rules set forth by the FAA.	In Progress	I	Inspection will verify that the safety officer and the team develop a plan to ensure they abide by all rules set forth by the FAA.	The safety officer has developed a launch procedure plan which includes guidance on abiding by FAA rules.	Section 8, and Launch Procedures Section 8.1.1

### 9.3 STEM Engagement Plan

NDRT is thankful for a successful semester of STEM Engagement events. The team has engaged 129 participants since project acceptance, and 233 participants in total for this school year. 50 of the 129 participants since project acceptance were engaged in direct STEM Education activities ([NASA 1.5](#)).

#### 9.3.1 General Update

The team collected feedback from our participants and partner groups regarding our events of the last semester. This feedback encouraged the team to focus a greater amount on hands-on activities. Upcoming events will focus on applying this feedback and improving the required documentation. The current health landscape continues to evolve, and NDRT continue to follow the guidelines from the University of Notre Dame and our partner organizations. Masks are required to be worn by volunteers and students at all events while indoors. Upcoming events will include both educational and outreach engagement experiences. NDRT will be hosting events with the Robinson Community Learning Center, local libraries, local Scout groups, and local schools among other organizations for the upcoming spring semester. These events will range from series of events with a curriculum to single experiences and exhibitions.

### 9.4 Budget

An overview of NDRT's funding sources can be seen in [Table 79](#). Rollover funds from 2020-2021 and a generous contribution from the Boeing Company are the main sources of 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 early 2022. NDRT intends to pair with additional sponsors and donors in 2022 for technical support, funding, and mentorships.

**Table 79:** 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
<b>Total</b>	<b>\$39,279.59</b>

A system-level overview of the NDRT 2021-22 budget is shown in [Table 80](#). Each category or system in [Table 80](#) has an itemized budget displayed in [Tables 81](#) through [88](#). 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 87](#), 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. One additional note is relevant to [Table 84](#), 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 84](#) with extra columns labeled "EE Dept?" and "EE Cost".

**Table 80:** Overall Budget Summary

Allocation	Amount	Funds Spent/Budgeted	Margin
Launch Vehicle	\$4,000.00	\$4,121.04	103.03%
Apogee Control System	\$1,200.00	\$1,162.64	96.89%
Recovery System	\$1,000.00	\$1,176.34	117.63%
LVIS	\$1,800.00	\$595.86	33.10%
<b>Vehicle Subtotal</b>	<b>\$8,000.00</b>	<b>\$7,051.56</b>	<b>88.14%</b>
Safety	\$300.00	\$184.84	61.61%
STEM Engagement	\$200.00	\$72.87	36.44%
Competition Travel	\$10,500.00	\$10,500.00	100.00%
Miscellaneous	\$500.00	\$405.83	81.17%
<b>TOTAL</b>	<b>\$19,500.00</b>	<b>\$18,215.10</b>	<b>93.41%</b>
Total Revenue	\$39,279.59	\$39,279.59	
Remaining Funds	\$19,779.59	\$21,064.49	

**Table 81:** Launch Vehicle Budget

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
Subscale Vehicle					\$543.94	
G12 Fiberglass Airframe 3in ID, 3.125inch OD, 60 inch length, Standard Wall, Black	Madcow Rocketry	1	\$100.00	\$12.71	\$187.71	Delivered
G12 Fiberglass Coupler 3in OD, 9in length, Green		1	\$22.00			
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					\$3,414.83	
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	Pre-ordered
Fiberglass Body Section, Length: 1 foot	Composite Warehouse	1	\$45.00	\$9.99	\$114.99	Shipping
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	Shipping
EXTREME Carbon Fiber Tubing 6 inch ID; 60 inch length	LOC/PML	2	\$539.95	\$11.49	\$1,474.19	Ordered
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
Licenses					\$80.00	
RockSim Licenses	Apogee Rockets	4	\$20.00	\$0.00	\$80.00	Delivered
<b>TOTAL COST</b>					<b>\$4,121.04</b>	
<b>Budget Allocation</b>					<b>\$4,000.00</b>	
<b>Remaining</b>					<b>-\$121.04</b>	

**Table 82:** 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			
StratolloggerCF	Perfectflite	1	\$70.00	\$0.00	\$70.00	Budgeted
StratolloggerCF	N/A	2	\$0.00	\$0.00	\$0.00	On Hand
StratolloggerCF	N/A	2	\$0.00	\$0.00	\$0.00	On Hand
Stratollogger 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	Budgeted
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	Budgeted
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			
Keyed Switch	N/A	5	\$0.00	\$0.00	\$0.00	On Hand
12" x 24" Carbon Fiber Sheet	Elevated Materials	1	\$98.79	\$22.95	\$121.74	Shipping
0.1" 4-40 Standoff	Amazon	1	\$9.90	\$0.69	\$10.59	Ordered
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	Budgeted
Drogue Shock Cord		1	\$33.50			
Main Shock Cord		1	\$55.50			
Fin Can Shock Cord	OneBadHawk	1	\$12.00	\$4.00	\$16.00	Budgeted
Parachute Protector	Dino Chutes	2	\$14.55	\$8.50	\$37.60	Budgeted
<b>TOTAL COST</b>					<b>\$1,176.34</b>	
<b>Budget Allocation</b>					<b>\$1,000.00</b>	
<b>Remaining</b>					<b>-\$176.34</b>	

Table 83: 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	Budgeted
Al Hex Nut		1	\$3.94					
Sande Plywood (1/4 in)	Home Depot	1	\$29.92	\$0.00	No	\$0.00	\$29.92	Budgeted
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	Budgeted

1/4" Hex Standoff, Female, 4" Overall Length, 10 Pack	Grainger	1	\$17.37	\$10.98	No	\$0.00	\$28.35	Budgeted
SX1238IMLTRT (RF Transceiver)	Semtech	2	\$7.08	\$4.00	Yes	\$18.16	\$0.00	Budgeted
PIC32MM0032GPL (Microcontroller)	Microchip	2	\$1.62	\$4.00	Yes	\$7.24	\$0.00	Budgeted
LDO to Power Microcontroller	STMicroelectronics	2	\$0.60	\$4.00	Yes	\$5.20	\$0.00	Budgeted
High-current 5V Boost Regulator	Texas Instruments	1	\$2.72	\$4.00	Yes	\$6.72	\$0.00	Budgeted
5V Boost Regulator	AMS	1	\$1.36	\$4.00	Yes	\$5.36	\$0.00	Budgeted
UART-to-USB Adapter	Silicon Labs	1	\$2.16	\$4.00	Yes	\$6.16	\$0.00	Budgeted
Patch Antenna	TBD	1	\$50.00	\$0.00	Yes	\$50.00	\$0.00	Budgeted
Dipole Antenna	TBD	1	\$100.00	\$0.00	Yes	\$100.00	\$0.00	Budgeted
<b>TOTAL COST</b>						<b>\$198.84</b>	<b>\$591.54</b>	
<b>Budget Allocation</b>						<b>\$1,000.00</b>	<b>\$1,800.00</b>	
<b>Remaining</b>						<b>\$801.16</b>	<b>\$1,208.46</b>	

**Table 84: ACS Budget**

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
Electronics					\$834.33	
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	Budgeted
Limit Switches	Automation Direct	2	\$12.50	\$10.00	\$35.00	Ordered
Piezo	Adafruit	1	\$1.50	\$0.00	\$2.45	Ordered
On Off Switch		1	\$0.95			
Hardware					\$331.43	
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	Budgeted
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			
<b>TOTAL COST</b>						
<b>Budget Allocation</b>					<b>\$1,200.00</b>	
<b>Remaining</b>					<b>\$37.36</b>	

**Table 85: 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			
<b>TOTAL COST</b>					<b>\$184.84</b>	
<b>Budget Allocation</b>					<b>\$300.00</b>	
<b>Remaining</b>					<b>\$115.16</b>	

**Table 86: 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			
<b>TOTAL COST</b>					<b>\$72.87</b>	
<b>Budget Allocation</b>					<b>\$200.00</b>	
<b>Remaining</b>					<b>\$127.13</b>	

**Table 87: Travel Budget**

Item	Description	Cost	Status
Accommodations	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
<b>TOTAL COST</b>		<b>\$10,500.00</b>	
<b>Allocation</b>		<b>\$10,500.00</b>	
<b>Remaining</b>		<b>\$0.00</b>	

**Table 88: Miscellaneous Budget**

Item	Vendor	Qty	Cost/unit	Fees	Total Cost	Status
Workshop Monitor	Amazon	1	\$139.97	\$14.28	\$264.06	Shipping
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	Ordered
Vacuum Filters	Lowe's	1	\$16.00	\$0.00	\$16.00	Budgeted
Dremel Cutoff Wheels	Grainger	3	\$3.26	\$12.43	\$22.21	Ordered
Wires	Adafruit	1	\$15.95	\$13.27	\$51.12	Ordered
Heat Shrink		1	\$9.95			
Automatic Wire Stripper/Cutter		1	\$11.95			
<b>TOTAL COST</b>					<b>\$405.83</b>	
<b>Budget Allocation</b>					<b>\$500.00</b>	
<b>Remaining</b>					<b>\$94.17</b>	



## 9.5 Timeline

NDRT is on track to meet all milestones, and completed both the subscale test flight and CDR within deadlines. Notable upcoming milestones include the vehicle demonstration flight in early February, with backups in mid- and late-February to meet the vehicle demonstration flight requirement. Additionally, design is on track to begin construction on January 11, when the University of Notre Dame Spring Semester begins. Figure 90 depicts the overall schedule of team milestones throughout the entire mission. Figures 91 through 96 display Gantt charts depicting progress and schedule outlooks for each squad of NDRT. These Figures provide multiple potential dates for completing the launch vehicle demonstration ([NASA 2.19.1.9](#), [NASA 2.19.2](#)).

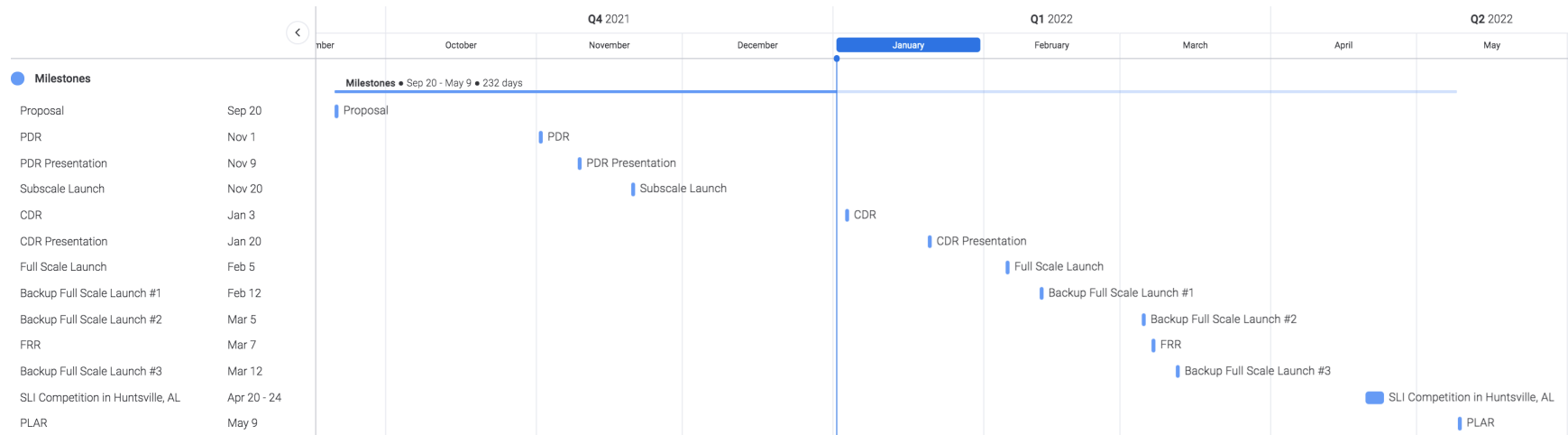


Figure 90: Milestones Gantt Timeline 2021-22

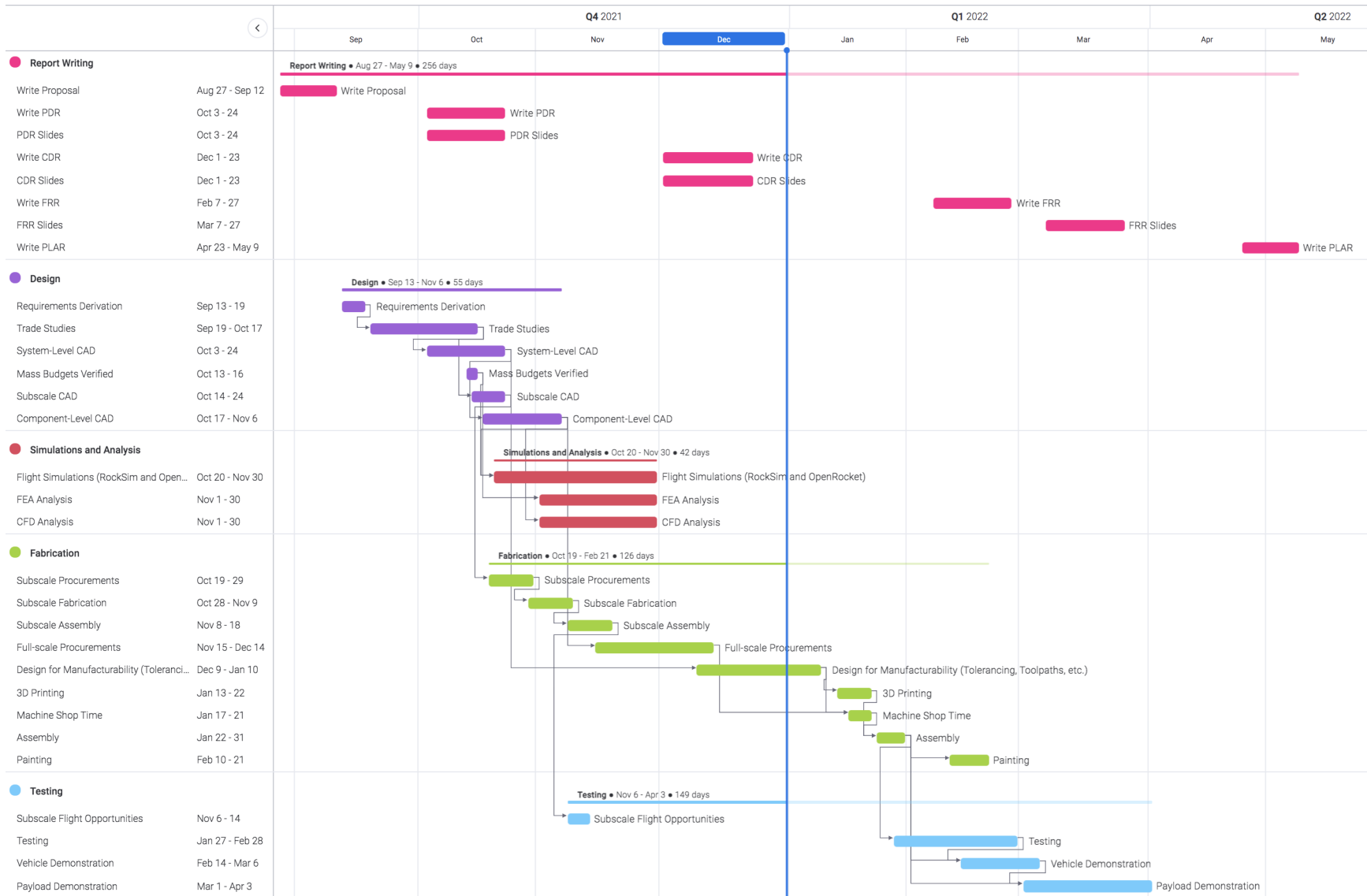


Figure 91: Launch Vehicle Gantt Timeline 2021-22

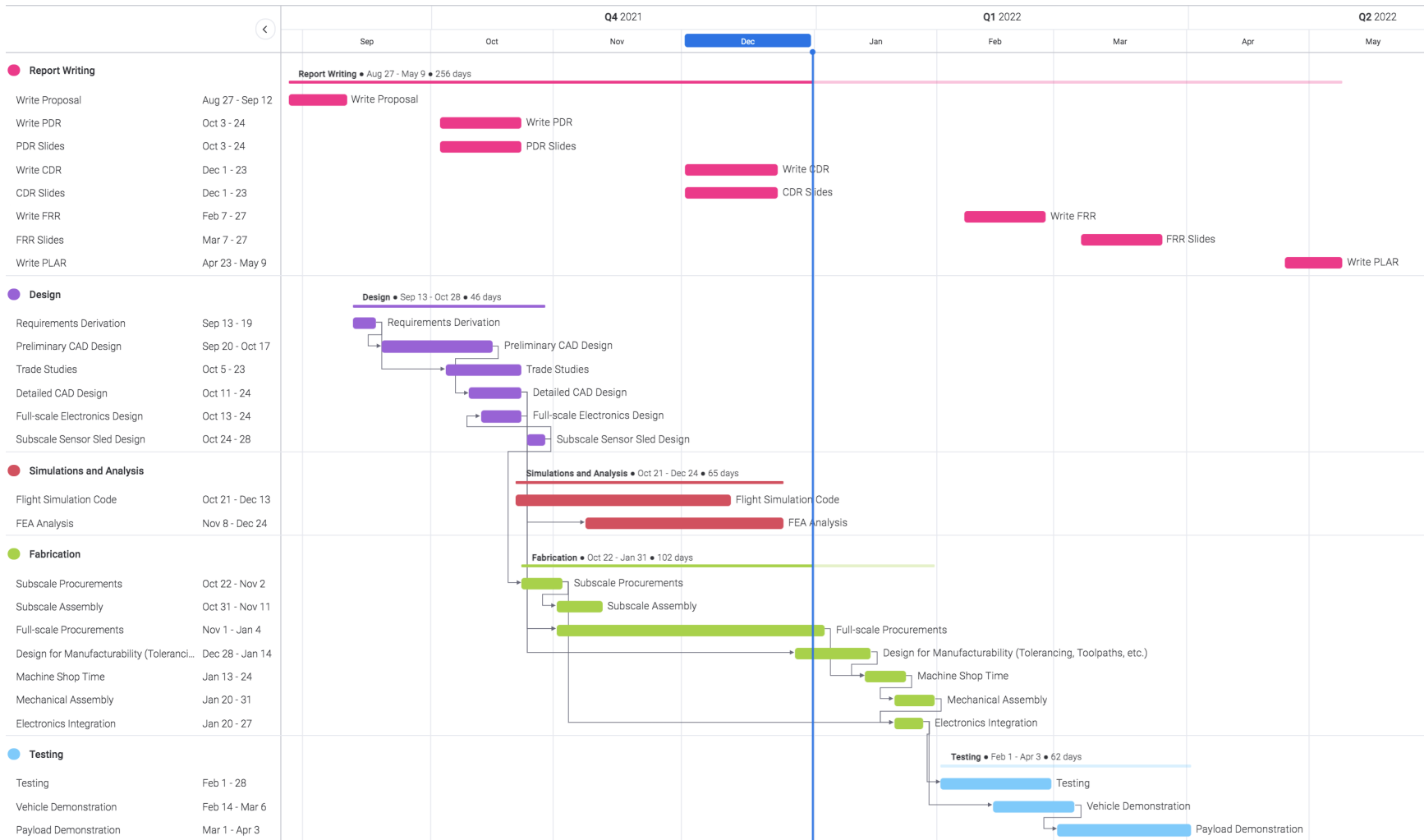


Figure 92: Recovery Gantt Timeline 2021-22

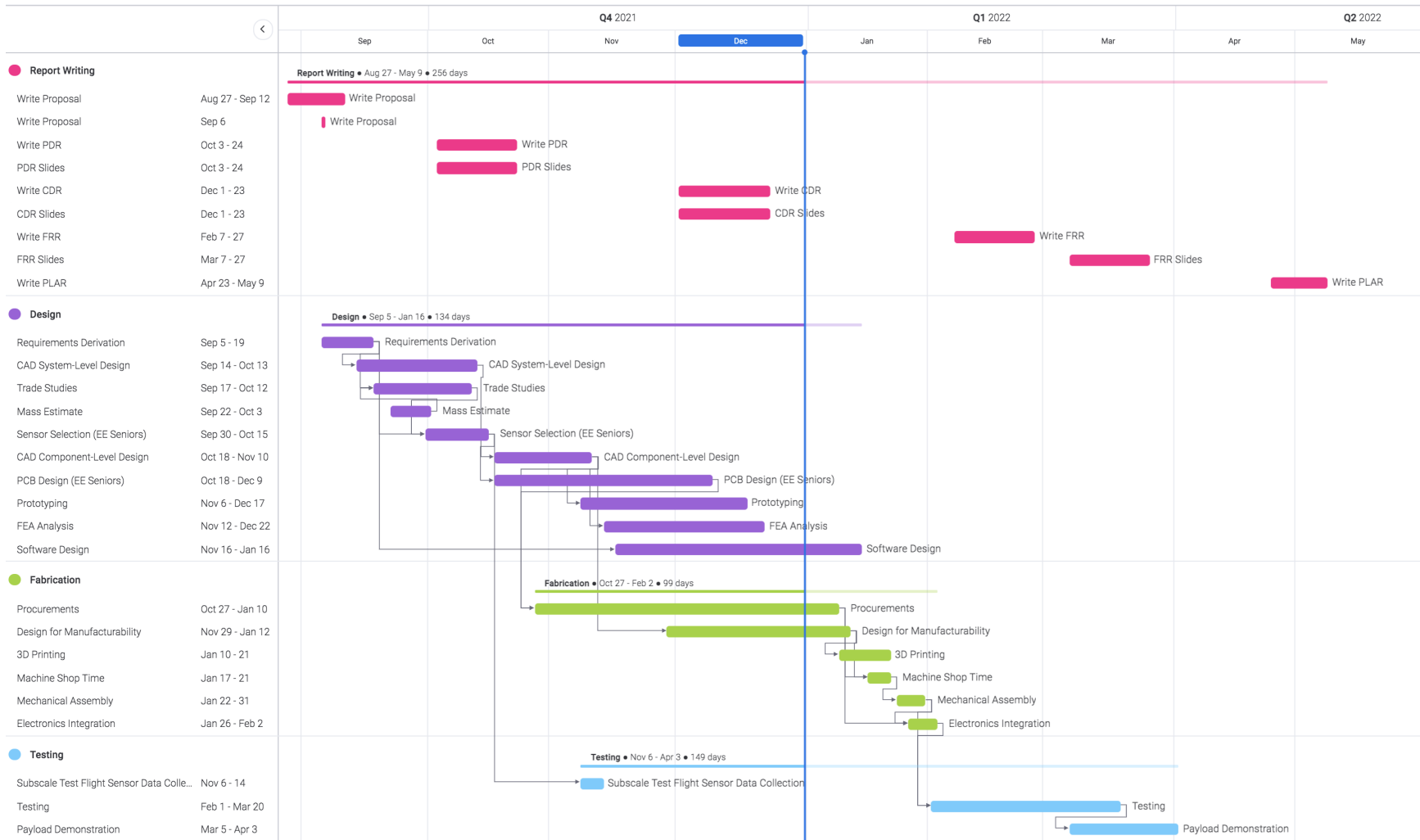


Figure 93: LVIS Gantt Timeline 2021-22

If the payload demonstration is not included in FRR, NDRT will submit an FRR addendum by the FRR addendum deadline ([NASA 2.19.2.3](#), [NASA 2.19.2.4](#), [NASA 2.20](#), [NASA 2.20.1](#), [NASA 2.20.2](#), [NASA 2.20.3](#)).

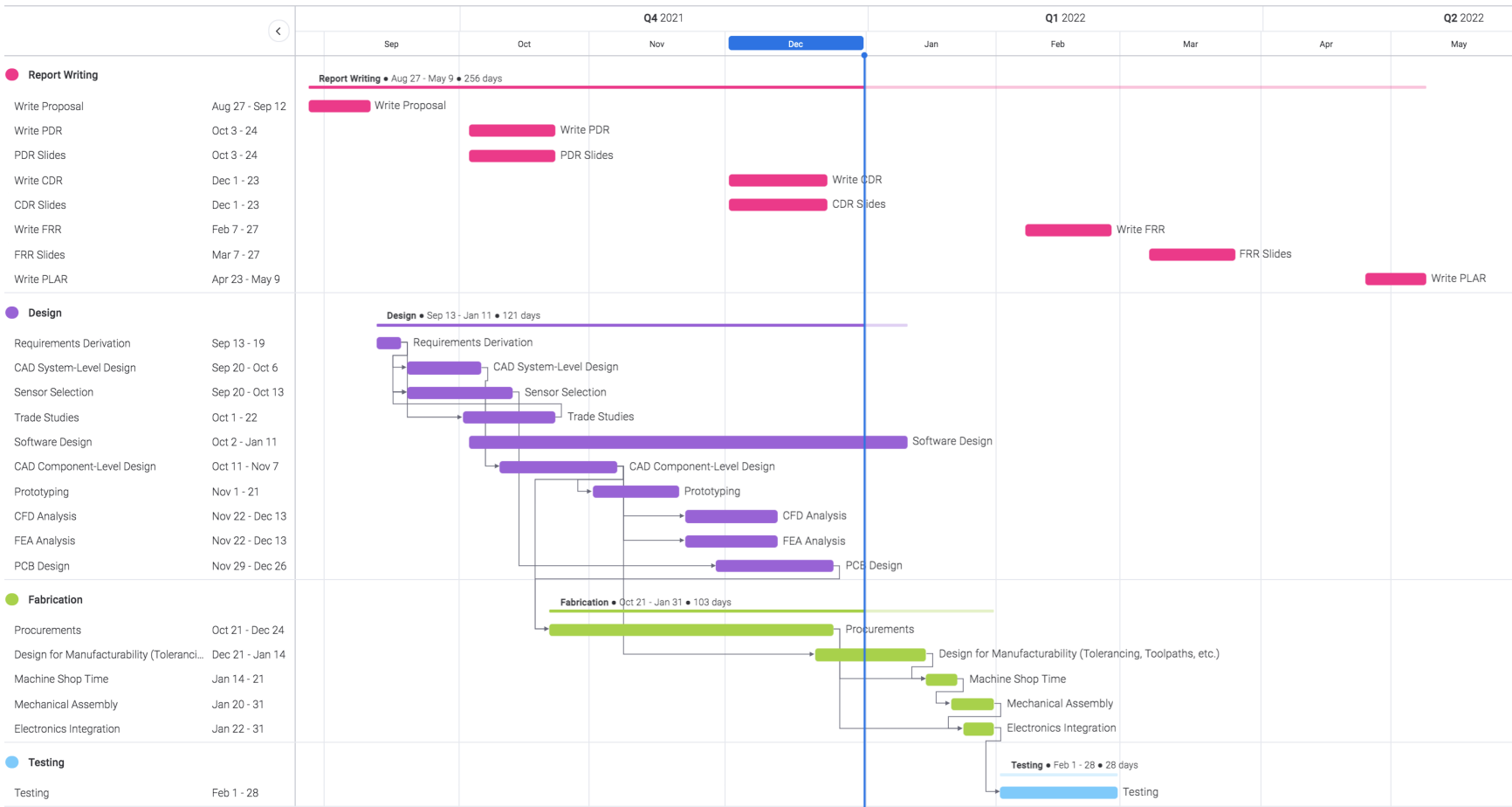


Figure 94: ACS Gantt Timeline 2021-22

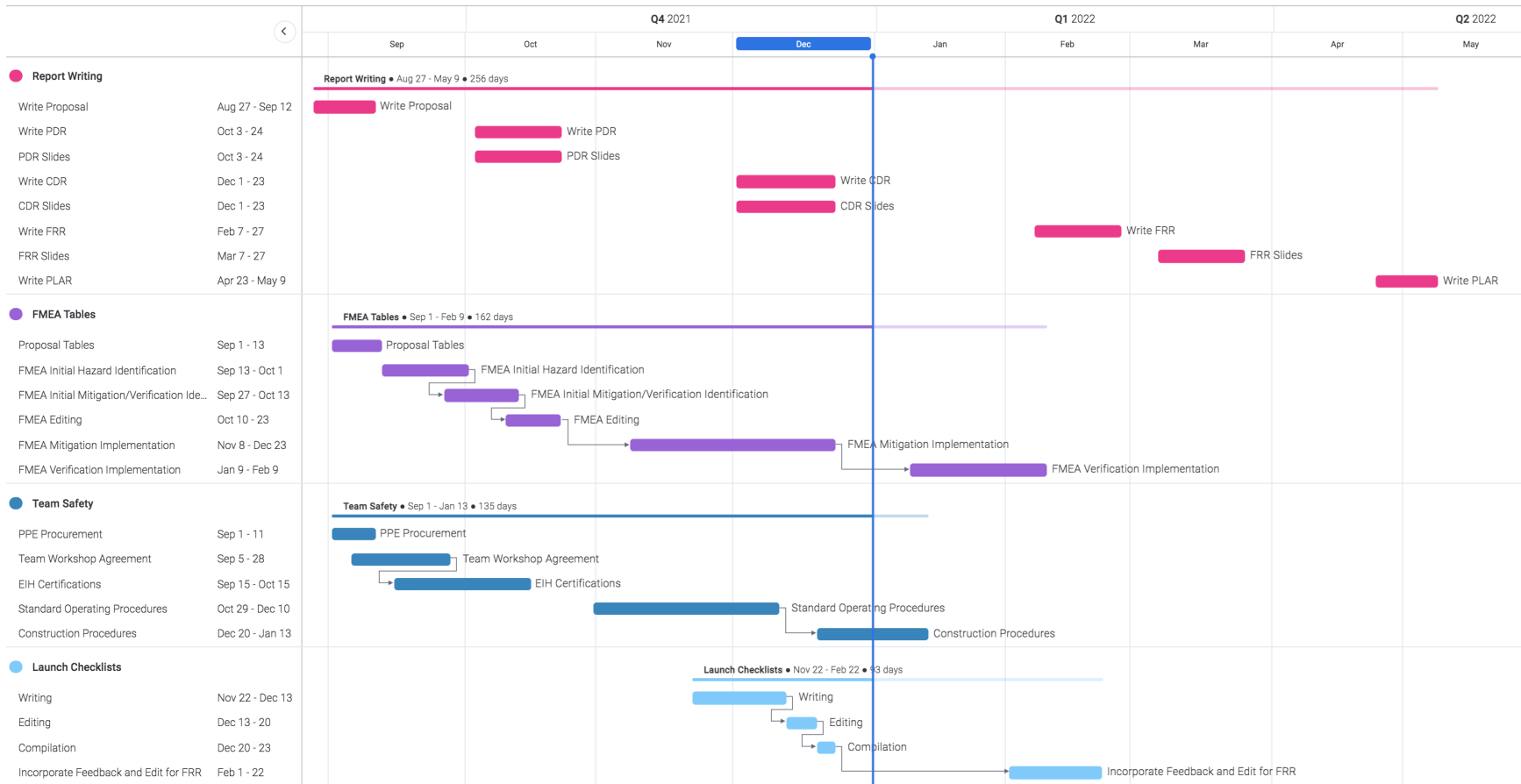


Figure 95: Safety Gantt Timeline 2021-22

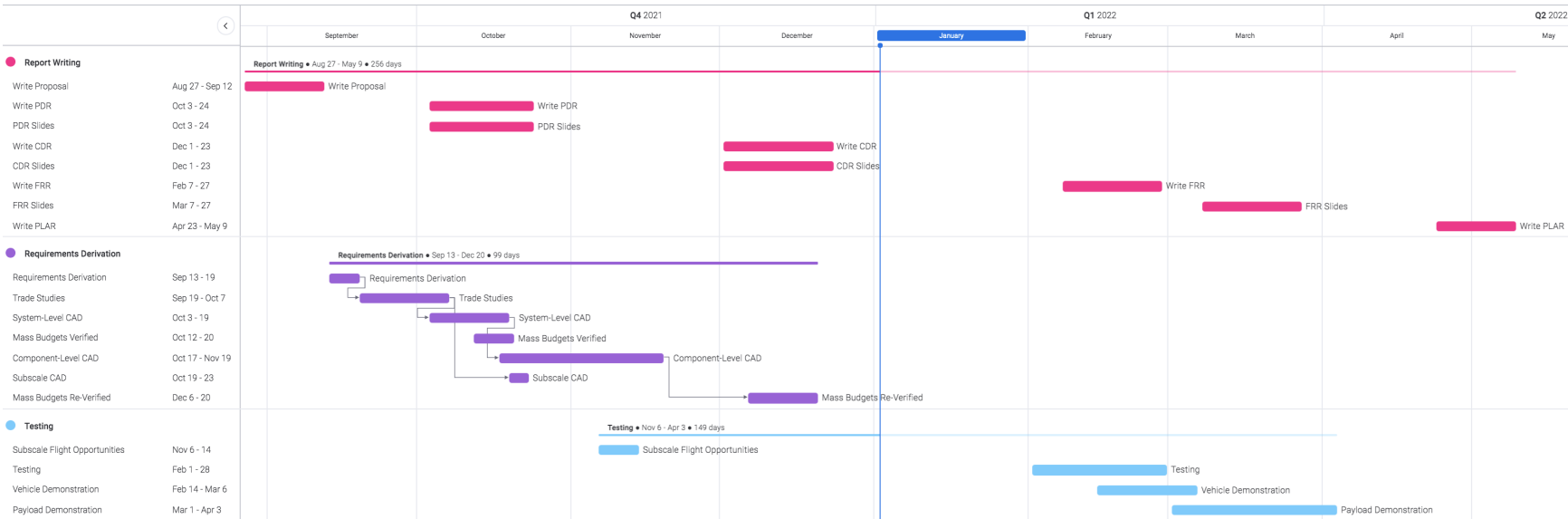


Figure 96: Systems Gantt Timeline 2021-22

## A Streamer Drift Experiment

**Objective:** Determine the drift reducing properties of a streamer compared to a parachute.

**Materials and Equipment Needed:**

1. Streamer test article
2. Parachute test article
3. GPS trackers (2) and batteries (2)
4. Subscale launch vehicle

**Test Setup:**

1. Prepare test articles by attaching GPS transmitters and batteries.
2. Follow all subscale Launch Rehearsal steps described in the [Launch Operating Procedures](#).

**Test Procedure:**

1. Insert test articles into payload bay of subscale vehicle so that they will be released at the apogee separation event.
2. Follow all steps described for subscale launch in the [Launch Operating Procedures](#).

**Analysis Procedure:**

1. Visually track test articles in the sky as they descend. Note any differences in descent rate or drift rate.
2. Visually locate, or use GPS trackers to locate, the test articles and launch vehicle.
3. Inspect launch vehicle and test articles for visible signs of damage from launch and ensure they are safe to touch. Be aware of the location of any Lithium-Polymer batteries.
4. Qualitatively inspect the differences in landing sites for the test articles and launch vehicle to verify accurate data readings.
5. Download GPS transmitter data and compare the drift rates of the test articles.

**Results:** Complete during subscale launch. The two test articles did not have matching descent rates, due to the difficulties in ascertaining a drag coefficient for the streamer. However, the launch vehicle and the streamer test article did descend with near identical velocities, including their drift rates. Upon landing, the streamer test article landed in a stream, causing the GPS transmitter to malfunction and all data was unrecoverable. However, since the launch vehicle descent rate was matched to the streamer, the drift reducing properties of the streamer could still be estimated more qualitatively. The launch vehicle landed within approximately 10 ft of the streamer. This distance was considered negligible and the streamer was determined to have near negligible benefits in reducing drift.

**Next Steps:** From the results of the experiment, the weights of the trade study to determine the drogue recovery device will be reevaluated and the trade study will be rerun using the new information.



## B MATLAB Hand Calculations Script

The following code is the `simplifiedescent.m` script that uses hand calculations to calculate the performance parameters of the vehicle.

```

%% simplifiedescent.m
% Calculate KE, descent time, and drift for given section masses and
% parachute parameters

% Updated 10/18 by Katherine -- added calculations for streamers
clear all; close all; %clc;
%% Inputs
[W,h,CdA,extra] = Input_Rocket();

% Velocity Wind
Vwind = 10; %mph

% Gravity
g = 9.81;
%% Conversion Factors
m2ft = 3.28084;
ft2m = 1/3.28084;
kg2lbm = 2.20462;
lbm2kg = 1/2.20462;
kg2slug = 0.0685218;
slug2kg = 14.594;
lbm2slug = 0.031081;
slug2lbm = 32.174;
oz2kg = 0.0283495;
mph2m_s = 0.44704;
mph2fts = 1.46667;
J2ft1b = 0.737562;
N21b = 0.22481;

%% Conversion Calculations
w = W.spent;
w1 = W.W1;
w2 = W.W2;
w3 = W.W3;
w4 = W.W4;

% Weights to Masses
m = (w * oz2kg);
m1 = (w1 * oz2kg);
m2 = (w2 * oz2kg);
m3 = (w3 * oz2kg);
m4 = (w4 * oz2kg);

% Altitude
h.apo = h.apo * ft2m;
h.main = h.main * ft2m;

% CdAs
CdAm = ((ft2m)^2)*(CdA.main+ CdA.drogue);
CdAd = CdA.drogue*(ft2m)^2;

% Density
rhod = mean([ISA(h.apo), ISA(h.main)]);
rhom = mean([ISA(h.main),ISA(0)]);

% Vwind
Vwind = Vwind * mph2m_s;

%% Under Drogue
% Ddrogue = 0.5*rho*Cdd*Ad*V^2;
% W = Ddrogue; % Drag is equal to weight at terminal velocity

% Terminal Velocity

```

```

vterm = sqrt((2*m*g)/(rhod*CdAd));

% Kinetic Energy Section 1
KE1d = 0.5 * (m1+m2) * (vterm).^2;

% Kinetic Energy Section 2
KE2d = 0.5 * (m3+m4) * (vterm).^2;

%% At Main Deployment
vmain = sqrt((2*m*g)/(rhom*CdAm));

% Kinetic Energy Section 1 Main
KE1m = 0.5 * m1 * (vmain).^2;

% Kinetic Energy Section 2 Main
KE2m = 0.5 * m2 * (vmain).^2;

% Kinetic Energy Section 3 Main
KE3m = 0.5 * m3 * (vmain).^2;

% Kinetic Energy Section 4 Main
KE4m = 0.5*m4*vmain^2;

%% At Main Deployment OPENROCKET
vmain_OR = 18.5*ft2m; % m/s

% Kinetic Energy Section 1 Main
KE1m_OR = 0.5 * m1 * (vmain_OR).^2;

% Kinetic Energy Section 2 Main
KE2m_OR= 0.5 * m2 * (vmain_OR).^2;

% Kinetic Energy Section 3 Main
KE3m_OR = 0.5 * m3 * (vmain_OR).^2;

% Kinetic Energy Section 4 Main
KE4m_OR = 0.5*m4*(vmain_OR)^2;

%% Total Time
deltad = h.apo - h.main;
Tdrogue = deltax/vterm;

deltam = h.main;
Tmain = deltax/vmain;

Ttotal = Tdrogue + Tmain;

%% Check That Deployment Height After 1 Second Delay is Still Above 500 ft
descent = vterm*1;
hdep_min = h.main - descent;

%% Drift
dfactor = extra.drift_factor;

driftm = Tmain* Vwind ;
driftd = dfactor * Tdrogue * Vwind;
drift = driftm + driftd;

%% CdA Min Calculation for Main
Mmax = max([m1, m2, m3, m4]);
KEmax = 75 * (1/J2ftlb);
Vmax = sqrt((2*KEmax)/Mmax);
CdAmin = (2*m*g)/((Vmax^2)*rhom);% - CdAd;

%% CdA Max Calculation for Drogue
Tmax = 90;
driftmax = 2500*ft2m;

```

```

Tdroguemax = Tmax - Tmain;

Vdroguemin = deltad/Tdroguemax;

CdAmax1 = (2*m*g)/((Vdroguemin^2)*rhod);

ddroguemax = driftmax - driftm;

Tdroguemin2 = ddroguemax/(Vwind);

Vdroguemin2 = deltad/Tdroguemin2;

CdAmax2 = (2*m*g)/((Vdroguemin2^2)*rhod);

if CdAmax1 < CdAmax2
    CdAmax = CdAmax1;
else
    CdAmax = CdAmax2;
end

% Input Cdd value
Cdd = 1.6;
radiusDrogue = sqrt(CdAmax/(Cdd*pi));
diameterDrogue = radiusDrogue*2;

%% Acceleration
% Force at main deployment = traveling at the speed at drogue (terminal
% velocity) but with CdA of the main deployment
F = 0.5*rhom*CdAm*vterm^2;
accel = F/(m*g)-1;

accel_pt = 12.3; % acceleration at peak thrust
peak_thrust = 3114;

%% CdA Min for Drogue
maxaccel = (1000/N21b)/((m1+m2+m3+m4)*g) - 1; % g
Fmax = (maxaccel+1)*m*g; % N

Vdroguemax = sqrt(2*Fmax/(rhod*CdAm));
CdAmin = (2*m*g)/((Vdroguemax^2)*rhod);

%% Calculate maximum section mass
m_max = 2*KEmax/vmain^2;

%% Forces
f_mainharness_main = (accel+1)*((m1+m2+m3+m4)*g);

f_pbaybulkhead_main = (accel+1)*(m1)*g;

f_PRMbulkhead_main = (accel+1)*((m2+m3+m4)*g);
f_PRM2bulkhead_main = (accel+1)*((m3+m4)*g);
f_SRMbulkhead_main = (accel+1)*(m4)*g;

f_motormount_pt = peak_thrust - m*g;
f_cr_pt = f_motormount_pt/3;

%% Convert to Standard
vterm = vterm * (m2ft);
KE1d = KE1d * J2ftlb;
KE2d = KE2d * J2ftlb;
KE1m = KE1m * J2ftlb;
KE2m = KE2m * J2ftlb;
KE3m = KE3m * J2ftlb;
KE4m = KE4m * J2ftlb;
KE1m_OR = KE1m_OR * J2ftlb;
KE2m_OR = KE2m_OR * J2ftlb;

```

```

KE3m_OR = KE3m_OR * J2ft1b;
KE4m_OR = KE4m_OR * J2ft1b;
vmain = vmain * (m2ft);
vmain_OR = vmain_OR*m2ft;
Vdroguemin = Vdroguemin *m2ft;
Vdroguemax = Vdroguemax * m2ft;

drift = drift * m2ft;
driftm = driftm * m2ft;
driftd = driftd * m2ft;
descent = descent * m2ft;
hdep_min = hdep_min * m2ft;

CdAd = CdAd*(m2ft)^2;
CdAm = CdAm*(m2ft)^2;
CdAmin = CdAmin *(m2ft)^2;
CdAmax = CdAmax * (m2ft)^2;
CdAmax1 = CdAmax1 * (m2ft)^2;
CdAmax2 = CdAmax2 * (m2ft)^2;
CdAmin2 = CdAmin2 *(m2ft)^2;
diameterDrogue = diameterDrogue * m2ft;

w_max = m_max*1/oz2kg;
mass_margin = abs((max([w1 w2 w3 w4])-w_max)/max([w1 w2 w3 w4]));

f_mainharness_main = f_mainharness_main*N21b;
f_pbaybulkhead_main = f_pbaybulkhead_main*N21b;
f_PRMbulkhead_main = f_PRMbulkhead_main*N21b;
f_PRM2bulkhead_main = f_PRM2bulkhead_main*N21b;
f_SRMbulkhead_main = f_SRMbulkhead_main*N21b;
f_motormount_pt = f_motormount_pt*N21b;
f_cr_pt = f_cr_pt*N21b;

```

The `simpledescent.m` script requires an input file that contains the parameters of the vehicle, contained in `Input_Rocket.m`, printed below.

```

%% Input_Rocket.m
% this is a function that contains all the info needed to run a sim for a
% certain rocket

% INPUTS:
% - n/a

% OUTPUTS:
% - W, W1, W2, W3, W4 in oz
% - important altitudes in ft
% - CdA for main, drogue, and rocket in ft^2

function [W,h,CdA, extra] = Input_Rocket()
%% Weights
%% Total Weight
W.W = 819; % oz
W.prop = 88.82; % oz
W.spent = W.W - W.prop; %ounces

% Payload Bay
w_nose = 28; % oz
w_pbay = 24.3; % oz
w_pbaycoupler = 20.3 +1.2; % oz plus epoxy
w_camera = 2; % oz
w_payload = 51.2; % oz
w_pbaybulk = 6.87 + 0.3; % oz plus epoxy
w_pubolt = 3;
w_ballast = 0;
W.W1 = w_nose + w_pbay + w_pbaycoupler + w_camera + w_payload + w_pbaybulk...
      + w_pubolt + w_ballast;

% Recovery Bay

```

```

w_rbay = 49.7; % oz
%w_module1 = 40; % oz estimate from PDR
w_main = 0;% 56.7; %oz
w_drogue = 0; %15.1; %oz
w_PRM = 50.6; %oz
w_rbaycoupler = 14.9 + 1.2; % oz plus epoxy
W.W2 = w_rbay + w_main + w_drogue + w_PRM + w_rbaycoupler; %+ w_module1;

% ACS Bay
w_acsbay = 42.4; % oz
w_acs = 75.8; % oz
w_acscoupler = 14.9 + 1.2; % oz plus epoxy
w_acsSRM = 36.1; % oz
%w_module2 = 28.1; % oz - estimate from PDR
w_acstether = 0; %16.4; % oz
W.W3 = w_acsbay + w_acs + w_acscoupler + w_acsSRM + w_acstether; %+ w_module2;

%Fin Can
w_fincan = 43.9; % oz
w_motormount = 14.9; % oz
w_finubolt = 3; % oz
w_cr = 3*(5.02 + 0.6); % oz plus epoxy
w_fcbulkhead = 6.87 + 0.3; % oz plus epoxy
w_fins = 41 + 3.6; % oz plus epoxy
w_motor = 79.89552; %+ 3.5 + 4; % oz % empty motor weight
w_tailcone = 4.73 +0.4; % oz
w_motorret = 3.5 + 0.4; % oz
W.W4 = w_fincan + w_motormount + w_finubolt + w_cr + w_fcbulkhead + w_fins ...
      + w_motor + w_tailcone + w_motorret;

W.total = W.W1 + W.W2 + W.W3 + W.W4 +16.4 + 15.1 + 56.7 +88.82; % mass verification

%% Important Altitudes
h.apo = 5300; % worst-case apogee
h.main = 592; % main deployment altitude

%% CdA Vals for Rocket and Main Parachute
% Tumbling Rocket
Lr = 132/12; % ft
Wr = 6/12; % ft
Cdr = .56;
CdA.tumble = Cdr*Lr*Wr;

% Ascending Rocket
diam_rocket = .5; %ft
Cdr = .45;
CdA.rocket = .25*Cdr*diam_rocket^2;

% Parachute / Streamer Parameters
streamer = 0; % if 1, streamer being used
if streamer==1
    Ld = 30; %ft
    Wd = 24/12; % ft
    Cdd = .09; % empirically determined for rocketman 100ft extreme streamer
    CdA.drogue = Ld*Wd*Cdd;
    dfactor = 0.75;
else
    Cdd = 1.6; % drogue
    Diameterd = 2; % drogue in feet
    CdA.drogue = Cdd*.25*pi*Diameterd^2;
    dfactor = 1;
end

Cdm = 0.97; % main

```

