NC STATE UNIVERSITY

# Tacho Lycos
# 2016 NASA Student Launch
# MAV CDR

High-Powered Rocketry Team

911 Oval Drive

Raleigh NC, 27695

January 15, 2016

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# 1. Summary of Critical Design Review

## 1.1. Team Summary

### 1.1.1. Team Name and Mailing Address

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Engineering Building III
911 Oval Drive
Raleigh, NC 27606

### 1.1.2. Name of Mentor, TRA Number, and Certification Level

| Alan Whitmore | James Livingston | Dr. Charles Hall |
|---|---|---|
| acwhit@nc.rr.com | livingston@ec.rr.com | chall@ncsu.edu |
| TRA Certification: 05945 | TRA Certification: 02204 | TRA Certification: 14134 |
| Certification Level: 3 | Certification Level: 3 | Certification Level: 3 |

## 1.2. Launch Vehicle Summary

### 1.2.1. Size and Mass

Table 1 Size and Mass Properties

| CDR | |
|---|---|
| Length | 102 in |
| Diameter | 5.5 in |
| Loaded Weight | 29.3 lbs |
| Center of Pressure | 76.3 in |
| Center of Gravity | 64.3 in |
| Stability | 2.18 Caliber |
| Apogee | 5569 ft |
| Max Velocity | 745 ft/s |
| Max Acceleration | 300 ft/s$^2$ |
| Recovery System | 1 Drogue/2 Main Parachutes |
| Motor | L1150R |

### 1.2.2. Motor Choice

The team has selected the AeroTech L1150R motor for the full-scale rocket. It has a specific impulse of 790.6 seconds and a burn time of 3.1 seconds. It is 20.87 inches long and has a diameter of 2.95 inches.

### 1.2.3. Recovery System

The vehicle will come down in two separate sections. A 1.5 foot drogue parachute will deploy at apogee, controlled by the aft avionics bay StratoLogger altimeters. This will separate the nosecone and forward airframe from the fin section and aft airframe. The drogue will be attached to an Advanced Retention Release Device (ARRD) in the forward airframe and to a bulkhead in the aft airframe. At 1,100 feet AGL, the Entacore altimeters in the forward avionics bay will trigger the ARRD to separate the nosecone and forward airframe from the aft airframe and fin section. Shortly after, at 1,000 feet AGL, the Entacore altimeters will trigger the sample section and nosecone to separate, releasing a 4 foot main parachute. A 5 foot main parachute will deploy at 700 feet between the aft airframe and fin section. This event will be controlled by the StratoLogger altimeters.

### 1.2.4. Rail Size

The launch rail will have a 1.5 square inch cross section and a length of 120 inches, which allows the vehicle enough distance to obtain a velocity of 63 feet per second as it leaves the launch rail.

### 1.2.5. Milestone Review Flysheet

The Milestone Review Flysheet can be found in Appendix A of this document. It can also be obtained from the Tacho Lycos website at www.ncsurocketry.com.

## 1.3. AGSE Summary

### 1.3.1. AGSE Title

The Autonomous Ground Support Equipment (AGSE) will be referred to as System To Orient Rocket on Mars (STORM).

### 1.3.2. Summarize Autonomous Procedure for AGSE

The system begins with the robotic arm. The sample will be placed in a predetermined position away from the AGSE. The robotic arm will move to the sample and grasp it with the gripper. After procuring the sample, the robotic arm will move it to the payload section where it will be securely enclosed by polyurethane foam. The robotic arm will then close the door and move a safe distance away from the rest of the system. The launch rail will then erect to 85 degrees from the horizontal. Once the launch angle is achieved, the igniter insertion system stepper motor will begin the procedure of raising the igniter into the vehicle’s motor.

# 2. Changes Made Since PDR

## 2.1. Changes made to Vehicle Criteria

Since the completion of the PDR, there have been a number of changes made to the launch vehicle design. The forward rail button on the vehicle's external airframe was moved 6 inches towards the tail of the rocket, placing it 18 inches from the tail instead of 2 feet. Furthermore, the airbrake surfaces were moved 1.6 inches towards the tail of the rocket to compensate for internal design changes.

Due to availability of supply, the 6 foot elliptic main parachute that was intended for the aft section has been changed to a 5 foot Irish Ultra parachute. The Irish Ultra has a higher drag coefficient, which allows for the smaller parachute diameter. This has an added benefit of a more-compact packing size.

The interior structure of the vehicle has altered in that the ejection charge bulkhead system and the airbrake system have been redesigned. The ejection charge bulkheads are no longer going to be epoxied in place. Instead, they will be secured with screws so that they are movable to allow for easier preparation prior to launch. This decrease in bulkhead security is anticipated to have negligible impact on system reliability. The airbrake system will now employ two, 8 millimeter linear guide rails with two linear bearings, one on each rail. Attached to each bearing will be a similar hinge system to the design in the PDR. These linear bearings will be moved with long metal rods attached to the linear actuator in a manner similar to the design in the PDR. The guide rails will ensure that the long metal rods attached to the linear actuator experience only axial loads during operation of the system. The rails will experience all of the lateral forces from the brakes and will deflect less than a millimeter.

## 2.2. Changes Made to AGSE Criteria

Since the PDR, there have been changes made to a few parts of STORM. The launch rail was extended another 5 inches to bring the overall length to 120 inches. This was done to give the vehicle more time on the rail and to increase the speed that the rocket would be leaving the launch rail to approximately 63 feet per second. The increase in speed was done to accommodate the NASA desired speed for launch rail exit of 60 feet per second.

The rotating sector gear that is used in the AGSE erection system has been increased from 7.5 inches to 8 inches. This change was required because the vehicle weight increased from previous estimates with the addition of epoxy and more airbrake components. The current estimated rocket weight is an overestimate that will not be exceeded in fabrication. With the 8 inch sector gear, the erection system has an overall factor of safety of 1.52 while with the 7.5 inch gear, the safety factor dropped below 1.5, which the team deemed unacceptable.

The plan for construction of the robotic arm has also changed. The HS 785HB servos in the shoulder, elbow and wrist joints have been replaced by HS 7950TH servos. Although smaller, the HS 7950TH servos are more powerful. *Figure 1* shows the two servos side by side with the new servo on the left. To fit the smaller servos into the current servo mounts, an adapter plate will be 3D printed to secure the new servos and to accommodate the altered screw hole pattern. *Figure 2* shows the original servo motor and motor mount. *Figure 3* shows the new 3D printed servo mount adapter plate. *Figure 4* shows the new servo mounted in the motor mount using the adapter plate. Operating the arm with the more powerful servos means that the gearing ratio can be reduced from 5:1 to 2:1. The gearing ratio can be changed because of the different sized servo motor and the thickness of the adapter plate.

Figure 1 New Servo (Left) Compared to Stock Servo (Right)

Figure 2 Stock Servo Fit in Motor Mount

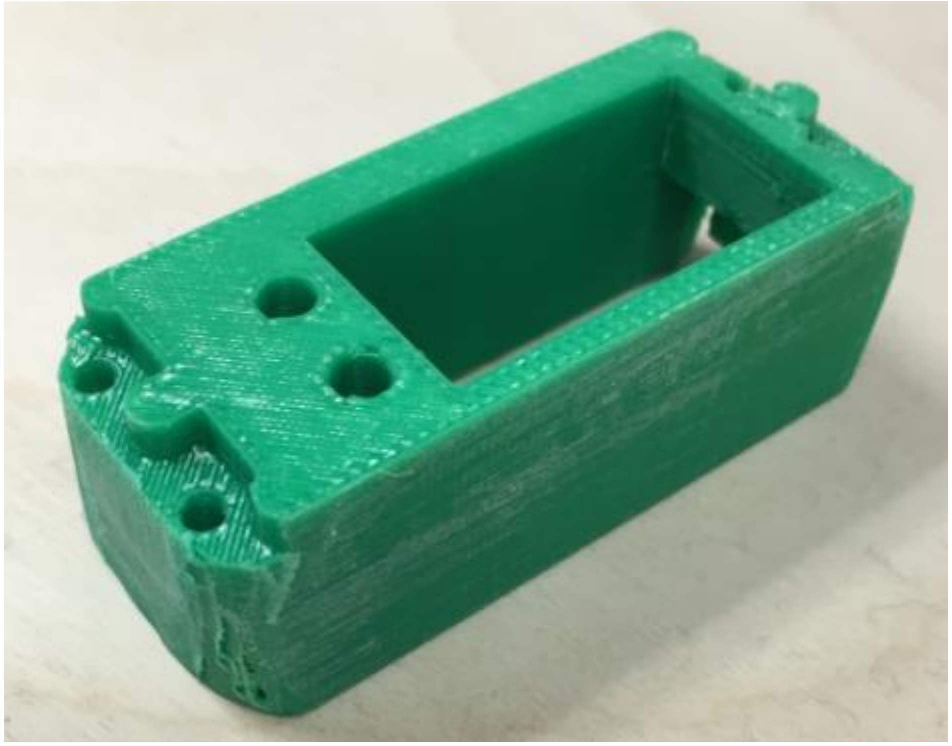


Figure 3 3D Printed Motor Mount Adapter

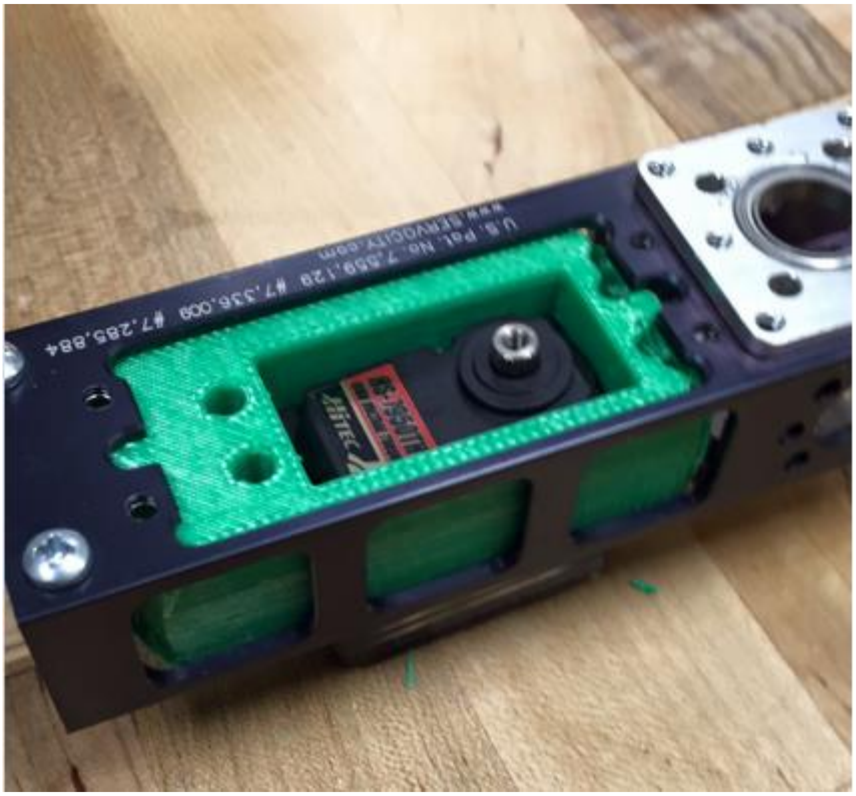


Figure 4 Motor Mount Adapter in Motor Mount

## 2.3. Changes Made to Project Plan

The budget now reflects more-exact prices for parts needed to assemble the vehicle and AGSE. The original funding plan was based off of numbers from the previous year but has now been updated with specific information obtained from other student organizations. There are still uncertainties in the funding plan for the spring 2016 semester as the Engineering Council has not appropriated the funds yet. The timeline has remained unchanged since the PDR.

# 3. Vehicle Criteria

## 3.1. Design and Verification of Launch Vehicle

### 3.1.1. Mission Statement, Requirements, and Mission Success Criteria

The primary mission of the NCSU Tacho Lycos team is to complete the criteria detailed in the NASA Student Launch Handbook. These requirements are to use an autonomous ground support equipment capable of inserting a sample, modeled as a PVC pipe, into a horizontal launch vehicle; raising the launch vehicle from an initial horizontal position to a near-vertical position; and finally inserting an igniter into the motor. When launched, the vehicle must bring the payload to 5,280 feet AGL. The basis of success for the team will be primarily founded on the completion of these criteria in a safe, efficient, and educational manner.

As defined by both NASA and the team, mission success is also achieved by designing a challenging and robust system. One requirement given by NASA is to complete all autonomous procedures in less than ten minutes. The team has set internal goals for times of various operations, which ensures that the ten-minute goal will be met with a significant cushion. Another requirement given by NASA is that the AGSE should have as little square footage and weight as possible. The team is working to keep the size and weight of the AGSE to a minimum while ensuring proper performance of the systems. Both the goals stated by NASA and the goals set by the team will be used when judging the success of the system.

### 3.1.2. Major Milestone Schedule

January 17 – Begin FRR writing

January 31 – Receive final vehicle design evaluation from NASA

February 1-3 – Finalize any changes to vehicle design criteria based on feedback

February 4 – Initiate vehicle manufacturing

February 17 – Complete full-scale rocket construction

February 18 – Complete all ejection tests

February 19-26 – Verify systems meet requirements and are operational

February 27 – Launch full-scale rocket

March 14 – Submit FRR

March 16 – Finish construction of AGSE

March 17-30 – Verify the abilities of the igniter and rocket ascension systems

April 1-6 – Test system as a whole

April 13 – Travel to Alabama for the competition and final launch

### 3.1.3. Review of System Design

#### 3.1.3.1. Subassemblies

#### 3.1.3.1.1. Nosecone Section

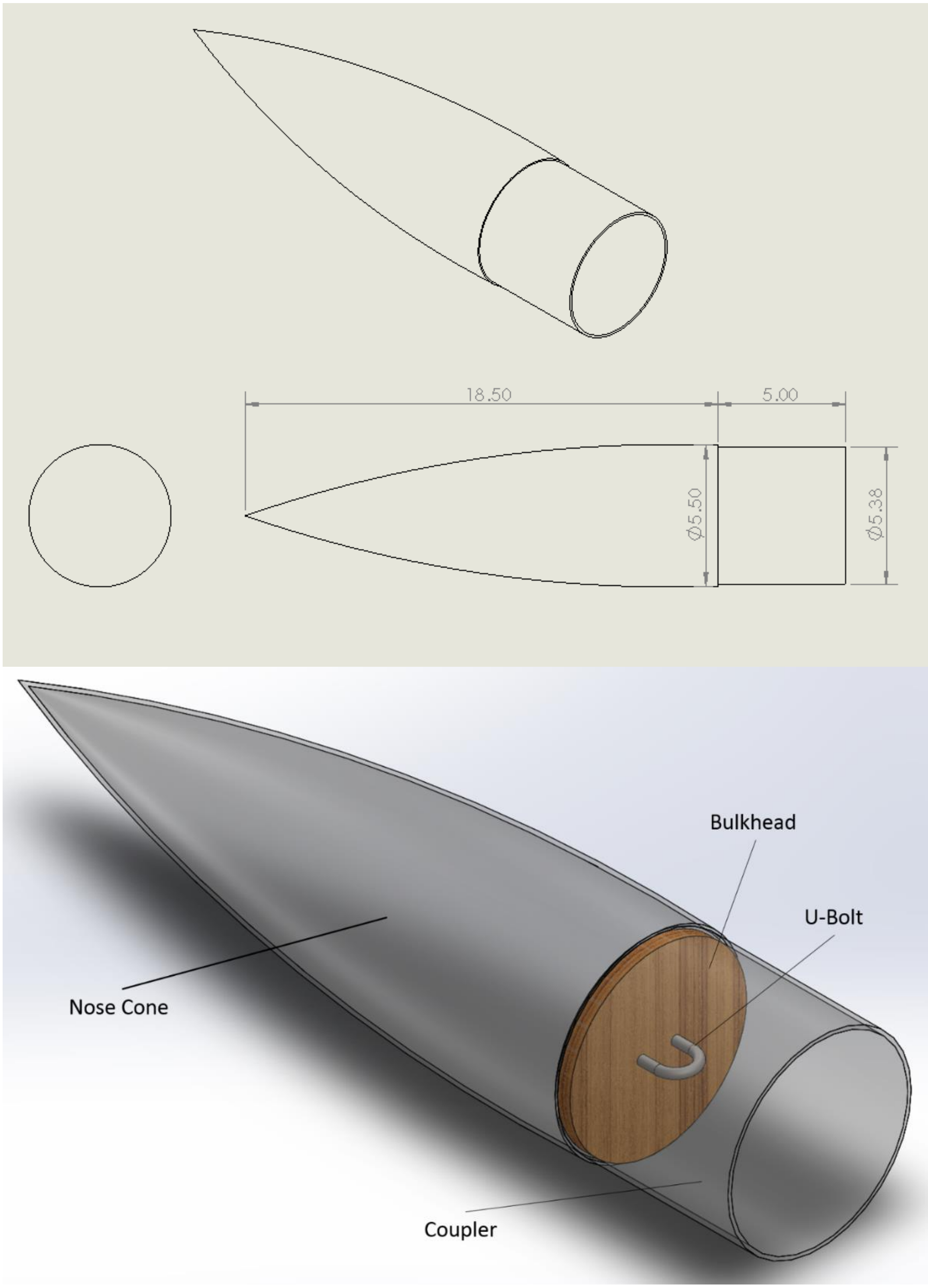



Figure 5 Nosecone Section Drawing and 3D Model

#### 3.1.3.1.2. Forward Airframe Section

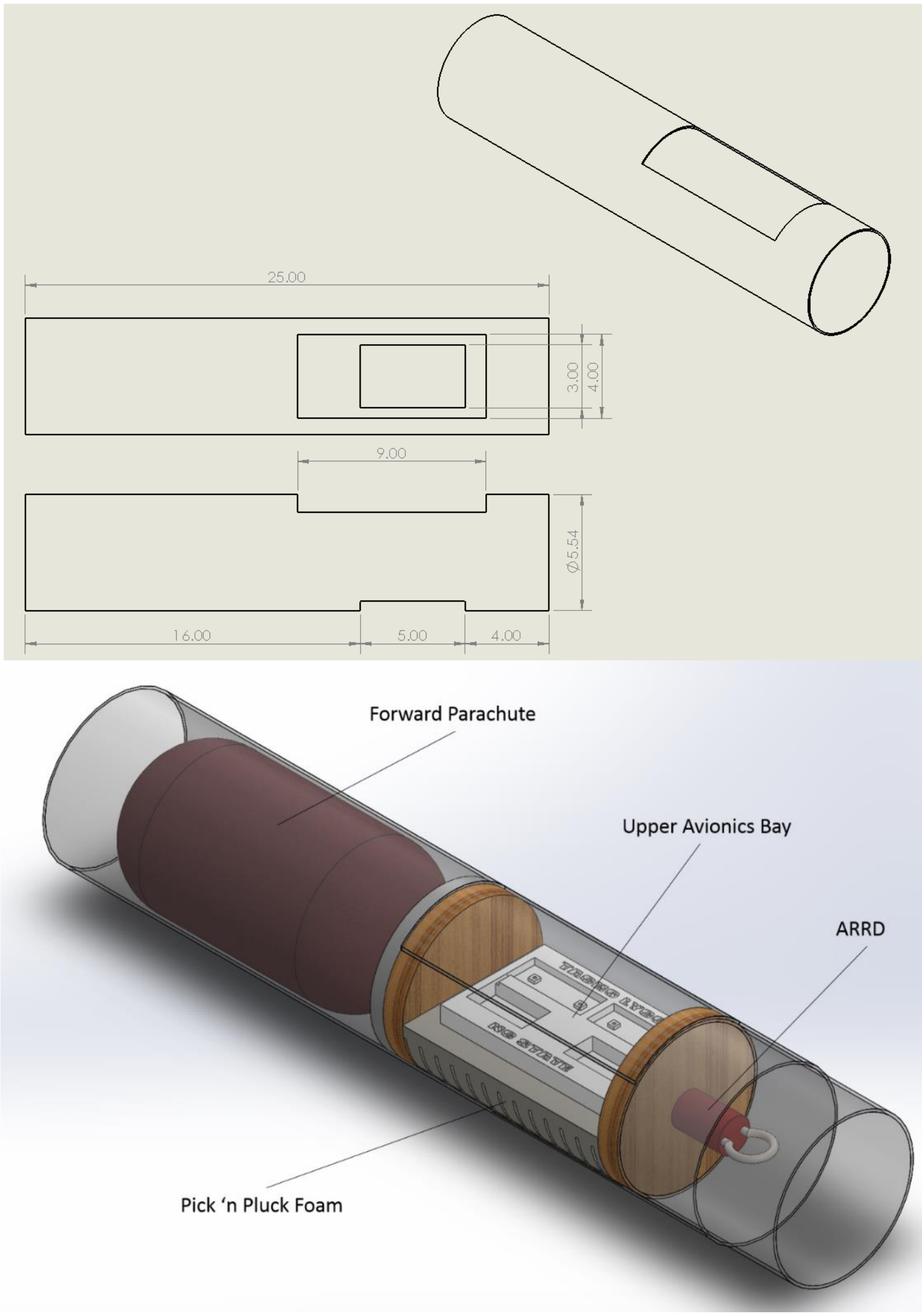
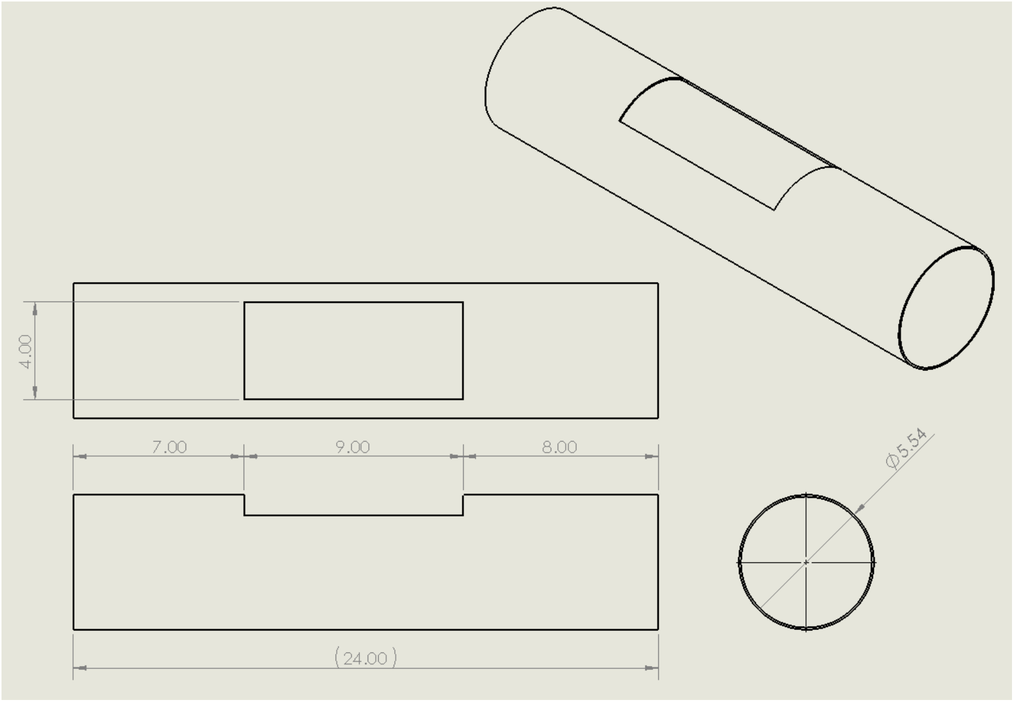



Figure 6 Forward Airframe Section Drawing and 3D Model

#### 3.1.3.1.3. Aft Airframe Section



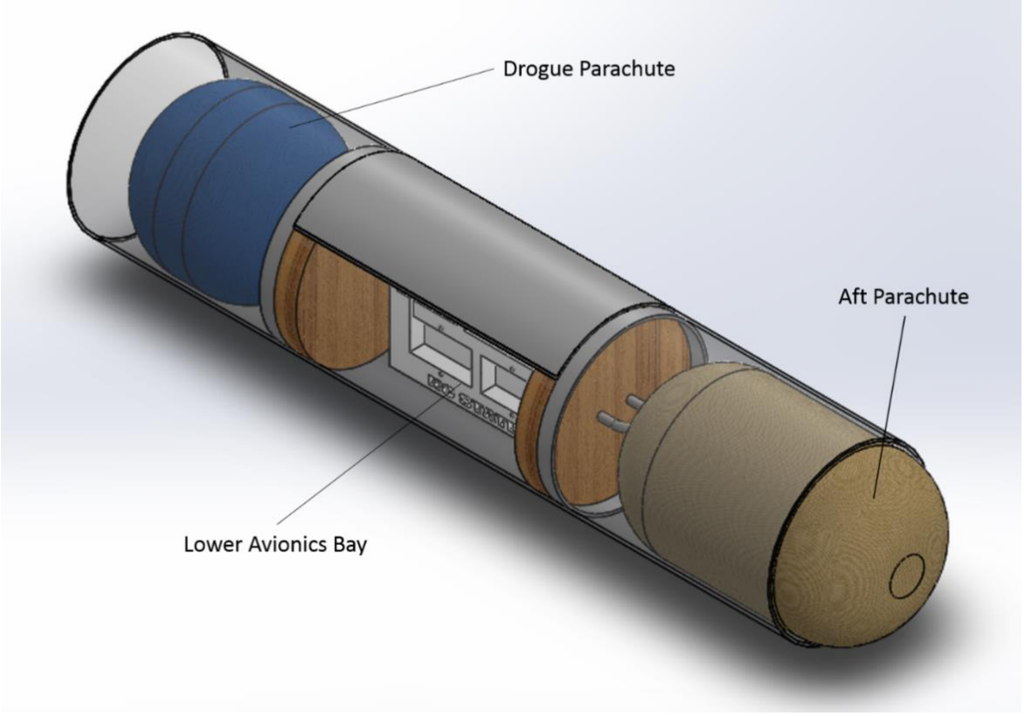




Figure 7 Aft Airframe Section Drawing and 3D Model

#### 3.1.3.1.4. Fin Section

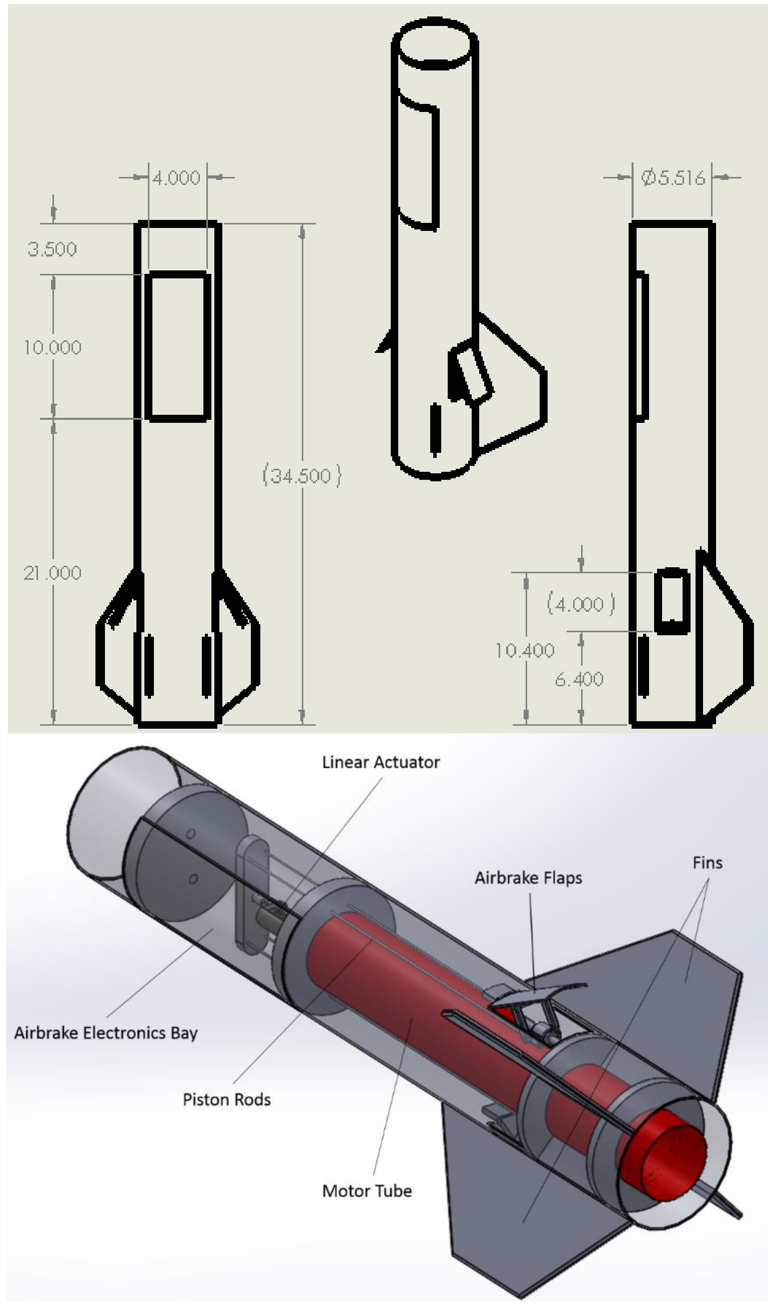



Figure 8 Fin Section Drawing and 3D Model

#### 3.1.3.2. Analysis and Model Results

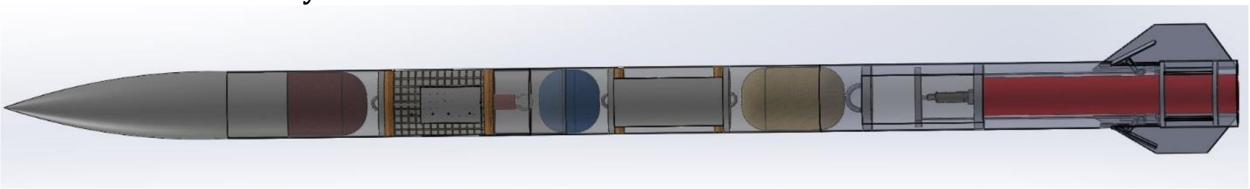


Figure 9 Full-Scale 3D Model of Launch Vehicle

The full scale rocket model was analyzed using computational fluid dynamics in the ANSYS Fluent software package. The vehicle was simulated at zero degrees angle of attack in two different configurations: airbrakes down and airbrakes up. Figure 10 shows the cross sectional area of the two configurations.

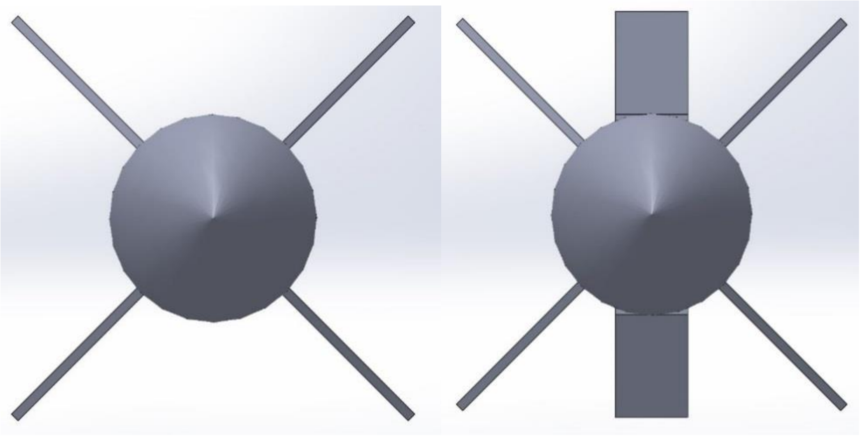


Figure 10 Cross Sectional Area of Simulated Configurations

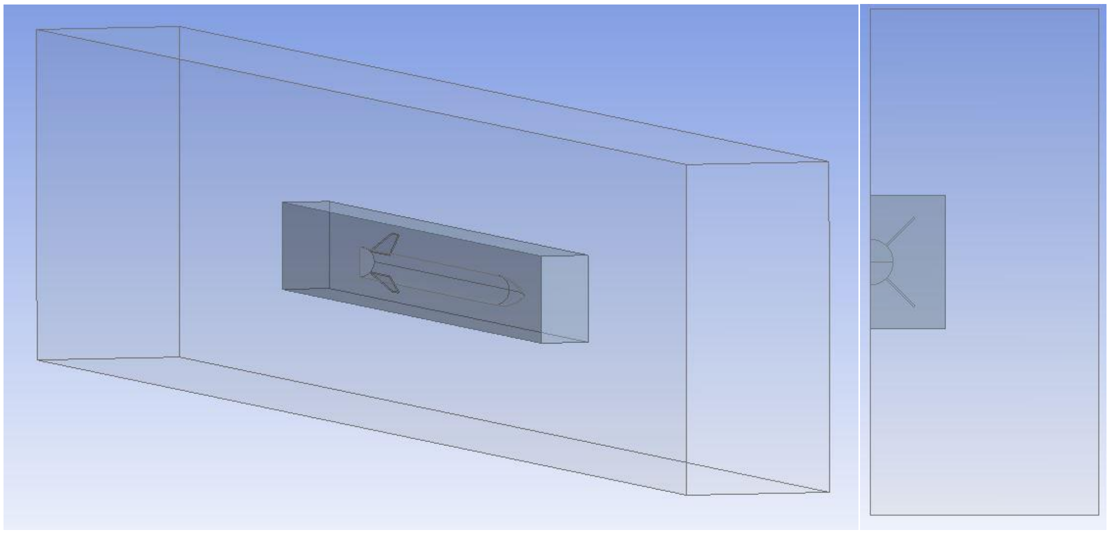


Figure 11 Inner and Outer Domain Model in ANSYS

In order to run the simulation, the vehicle faces were modeled as walls and the two domains were modeled as fluids. Two domains were used so that the model could be meshed finer close to the vehicle and coarser farther away. This was necessary to reduce the computational time required. To further reduce computational time, a symmetry plane was created that split the model in half. This resulted in a mesh that consisted of around 1.4 million elements for both configurations. The maximum element size for the outer domain was 3 inches, 0.75 inches for the inner domain, and 0.25 inches for the faces of the vehicle. Figure 12 shows the tetrahedral element mesh with the transitions between the vehicle, inner, and outer domains.

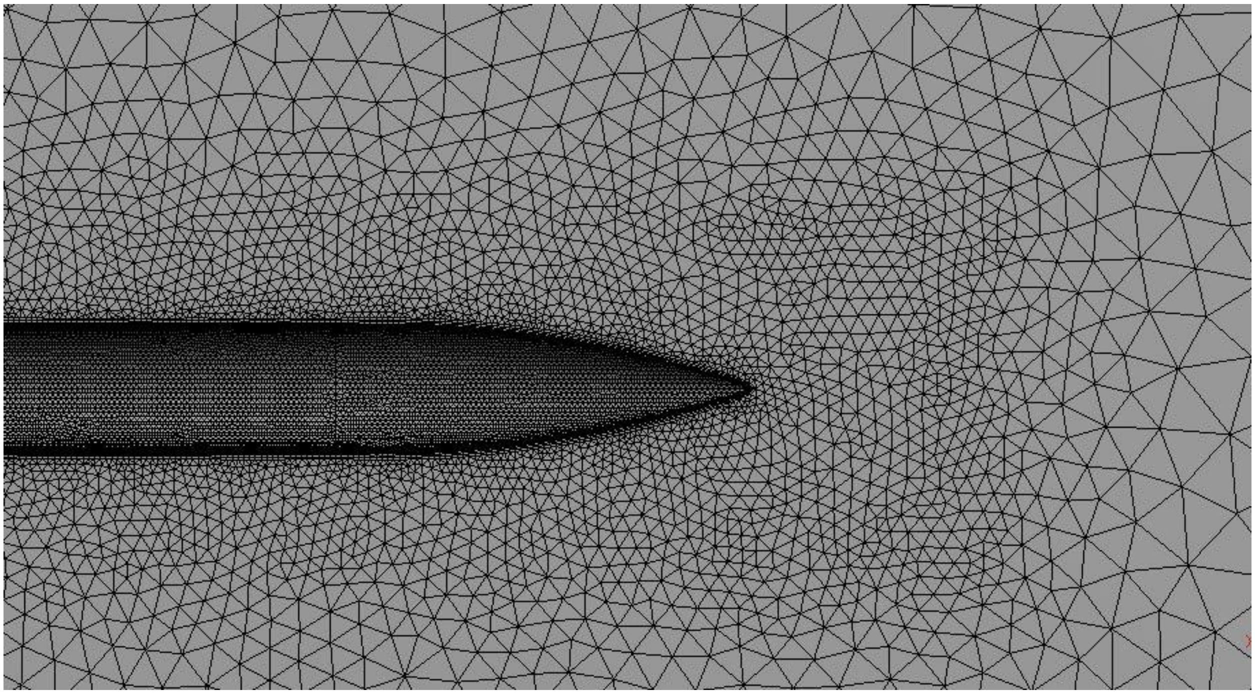


Figure 12 Mesh of the Model

The meshed model was then run using a realizable k-epsilon model, which is the most common turbulence model. The model used two transport equations to represent turbulent properties of the flow. Using this model allows the simulation to accurately represent realistic conditions. To further increase simulation realism, the reference values used were the cross sectional areas as shown in *Figure 10* and 102 inches for the length. With the simulation completely set up, hybrid initialization was used to obtain a starting point and 600 iterations was set as the limit for convergence. The residuals, drag coefficient, lift coefficient, and the moment coefficient were monitored to make sure they had an absolute convergence of 0.00001. All of the monitored cases converged by the 600 iteration limit which gave confidence in the results.

The results were then visualized in the ANSYS Fluent graphics solutions package. Figure 13 shows the pressure contour across the body of the vehicle. The high pressure zones at the tip of the nosecone and along the leading edge of the fins experienced 281 pounds per feet squared. The symmetry of the pressure contours along the vehicle invokes confidence in the aerodynamic design of the vehicle.

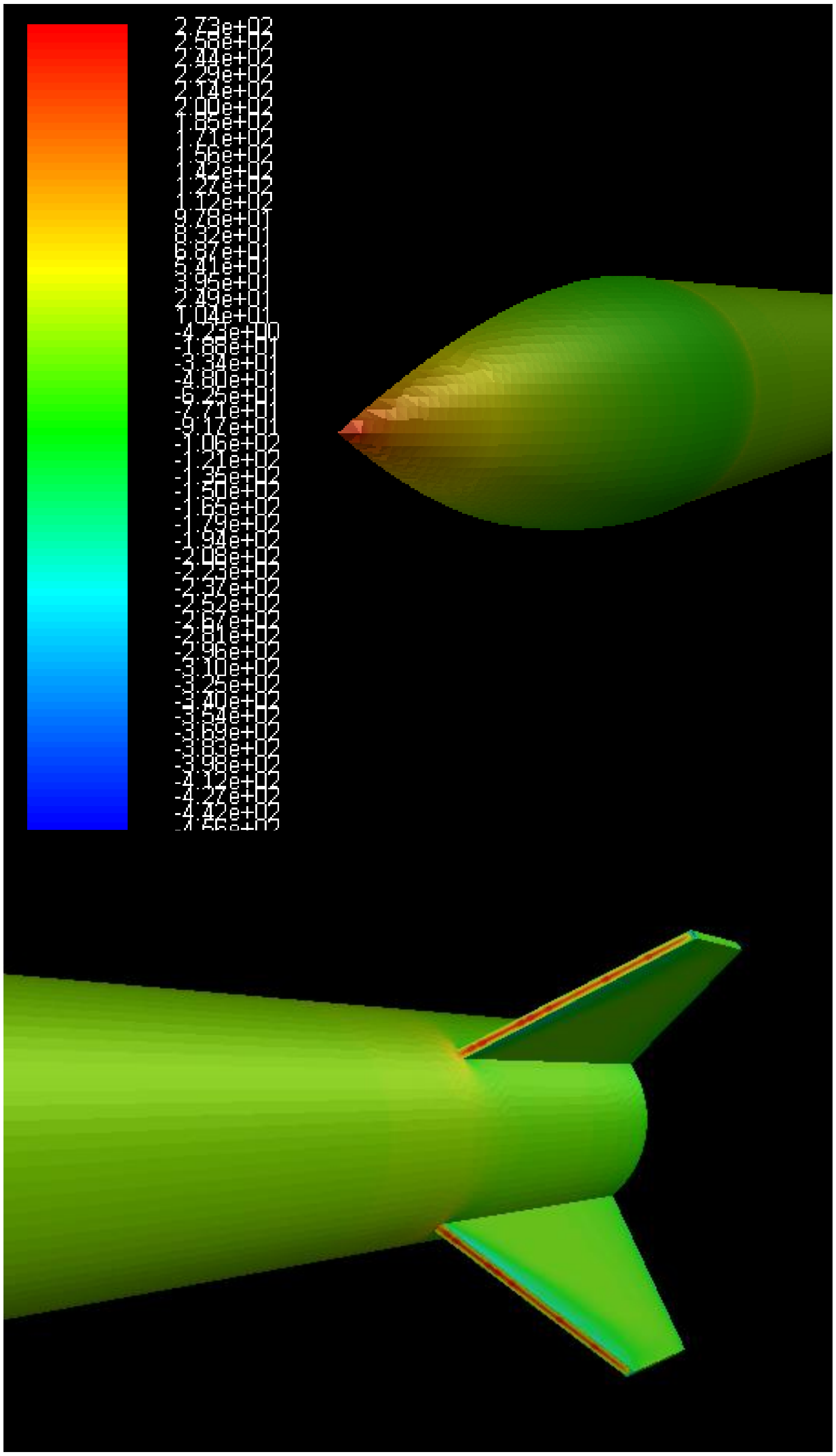



Figure 13 Airbrakes Undeployed Model of the Pressure Contour at 700 Feet per Second

The model was then analyzed again with a pressure contour along the body of the vehicle using the ANSYS Fluent post-processing software. *Figure 14* shows the resulting pressure contour; inspection of the results reveals that the pressure contour is the same as in the first analysis. As a result, the accuracy of the simulation was verified. In addition to the pressure contour, the model was analyzed with a volume rendering of the velocity streamlines along the body of the vehicle. As it can be seen in *Figure 15*, the velocity stayed fairly consistent at 700 feet per second except at the nose of the vehicle and the wake region. This result was anticipated and further verifies the accuracy of the simulation.

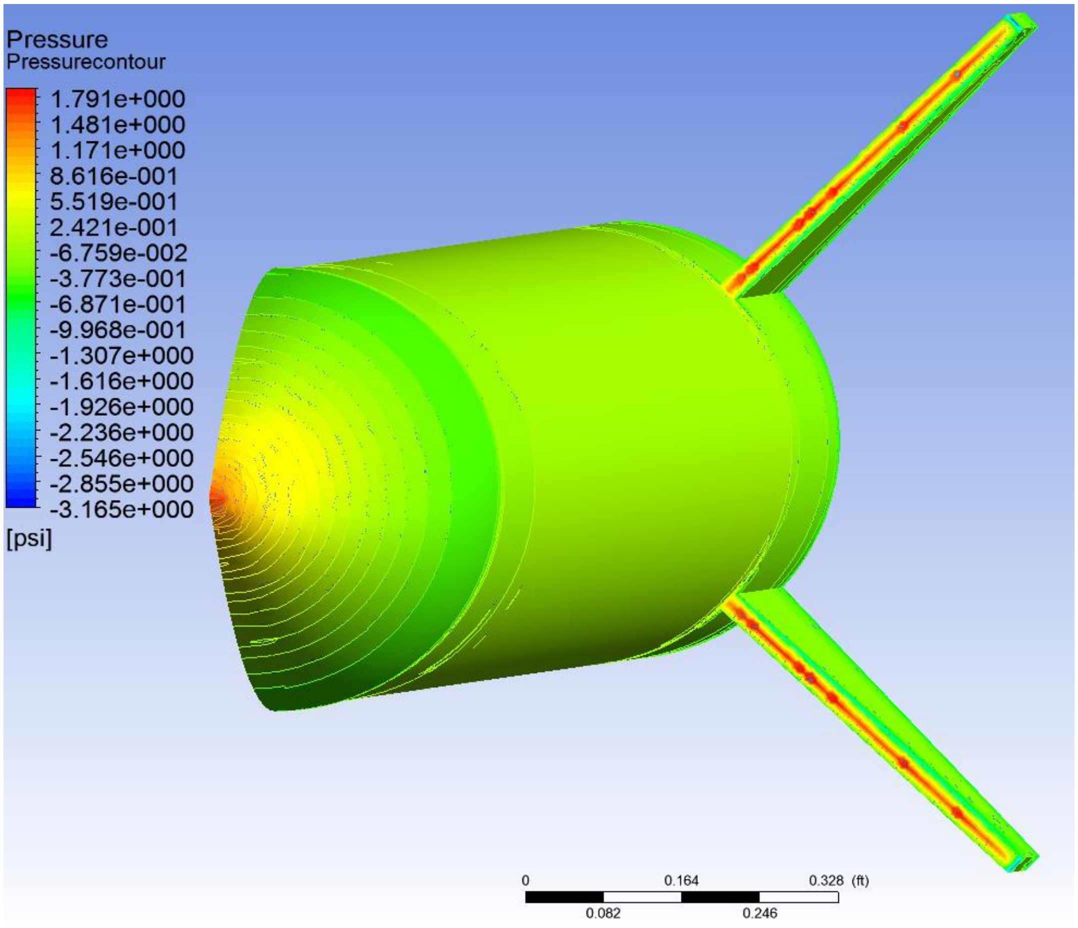



Figure 14 Airbrakes Undeployed Post-Processing Model of the Pressure Contour at 700 Feet per Second

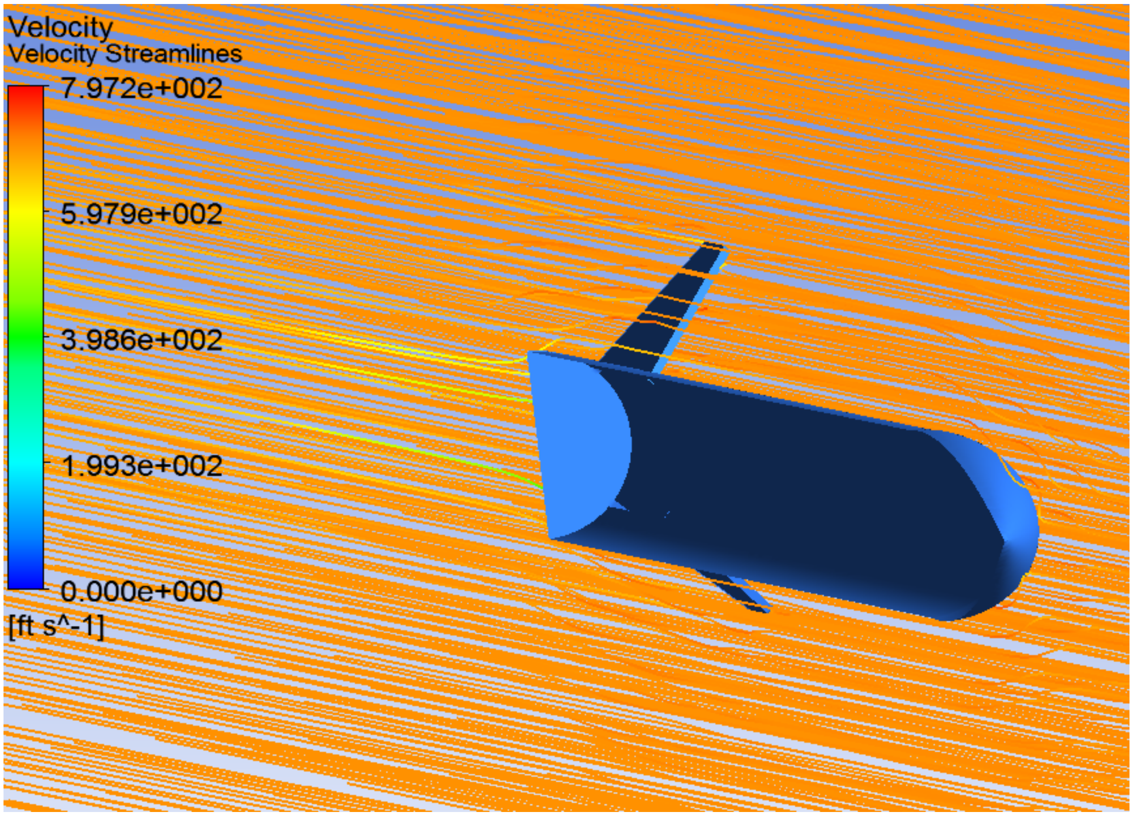



Figure 15 Airbrakes Undeployed Post-Processing Model of the Velocity Streamlines at 700 Feet per Second

These same three cases were then run for the airbrakes-up configuration of the model. These results can be seen in Figure 16, Figure 17, and Figure 18.

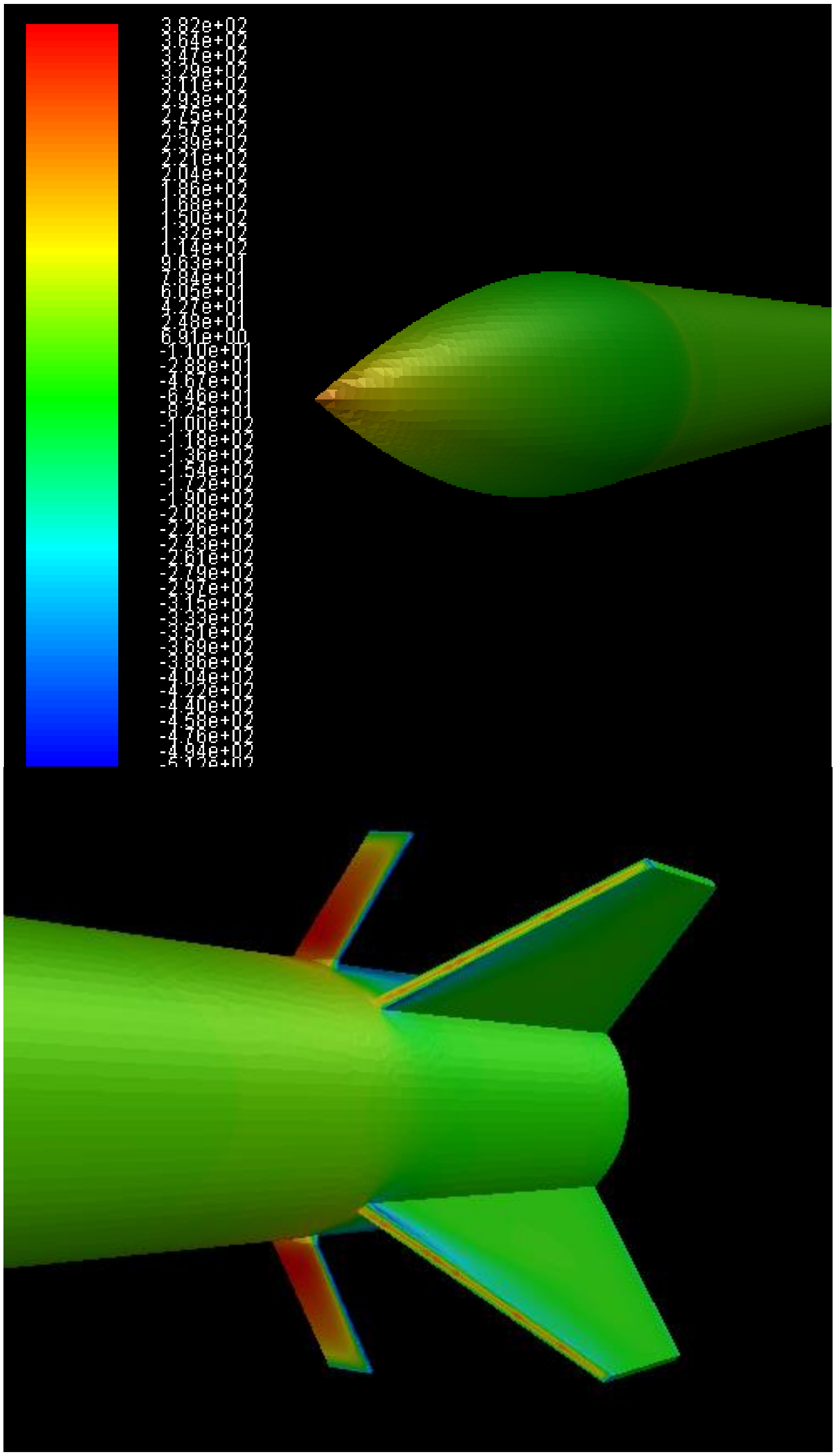



Figure 16 Airbrakes Deployed Model of the Pressure Contour at 700 Feet per Second

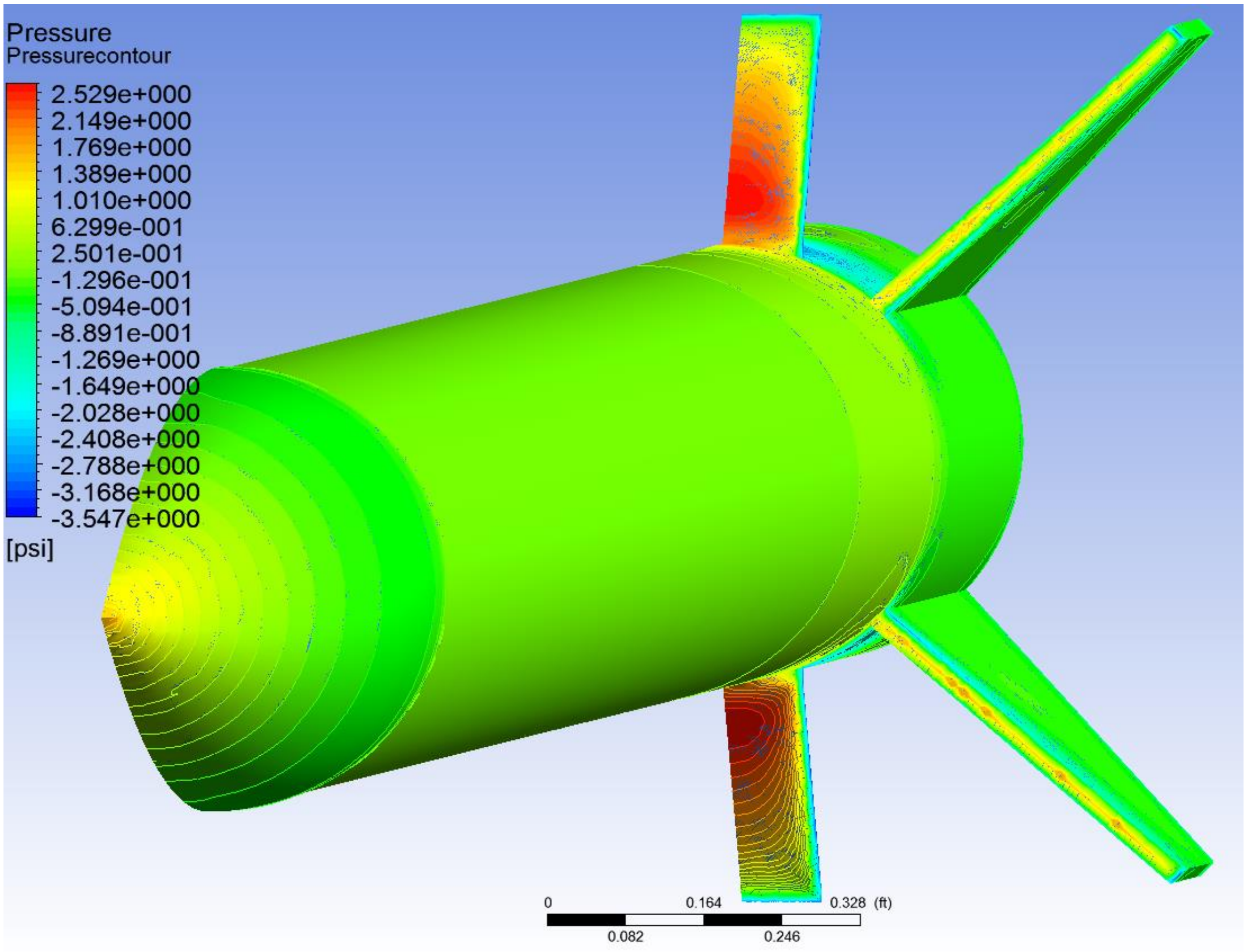



Figure 17 Airbrakes Deployed Post-Processing Model of the Pressure Contour at 700 Feet per Second

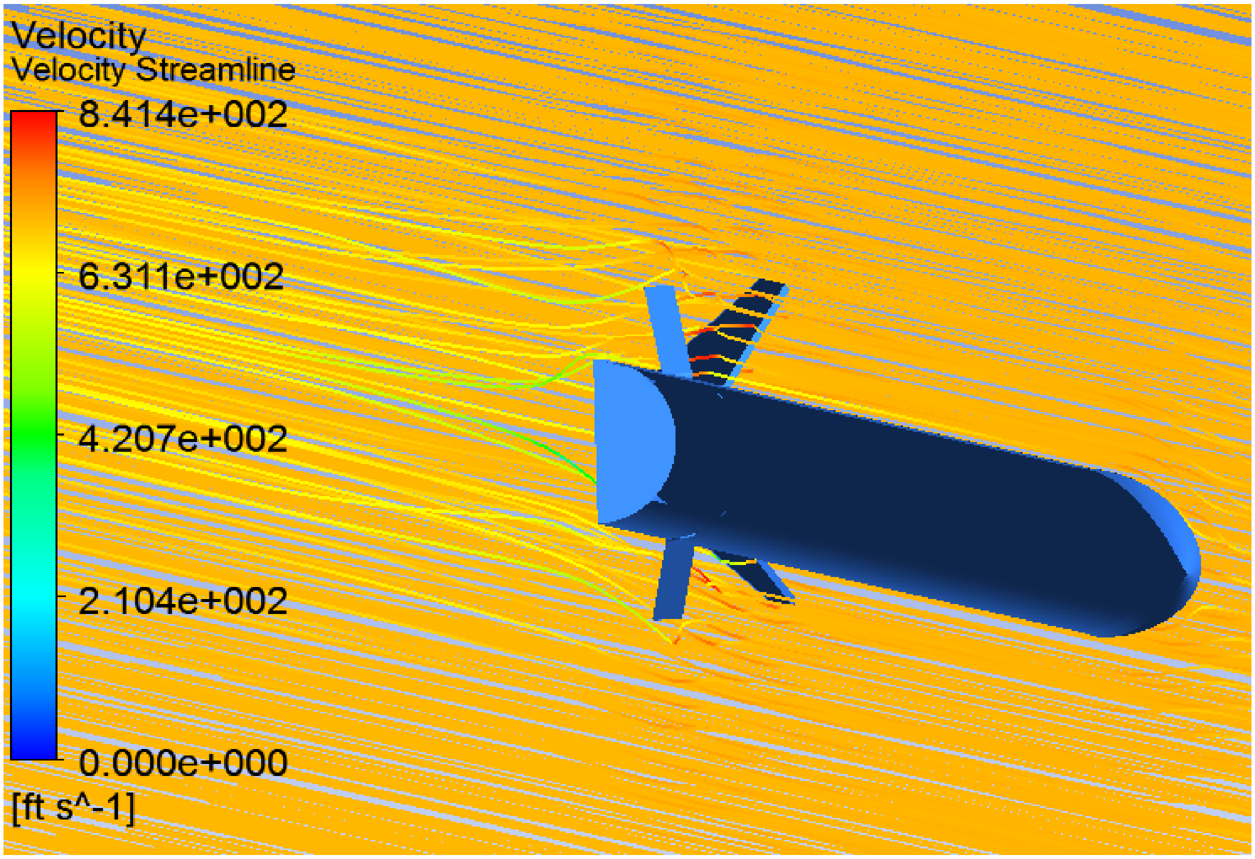



Figure 18 Airbrakes Deployed Post-Processing Model of the Velocity Streamlines at 700 Feet per Second

In addition to the visualizations from the post processing software, the ANSYS results also gave the drag coefficient, lift coefficient, and the moment coefficient of the vehicle. These coefficients can be seen in *Table 2* below.

Table 2 Coefficients from Fluent

| **Coefficients** | **Airbrakes Down** | **Airbrakes Up** |
|---|---|---|
| $C_D$ | 0.3848 | 0.54387 |
| $C_L$ | 0.001390 | -0.00003318 |
| $C_M$ | 0.00003330 | 0.00004478 |

The drag force experienced by the vehicle when the airbrakes are down is 22.67 pounds force and 44.58 pounds force when the airbrakes are engaged. The center of pressure was also calculated from the simulation results and the coefficients. The center of pressure was located 6.44 feet (77.28 inches) from the tip of the nosecone. This gives a static margin of 2.37 caliber. Barrowman's equation and OpenRocket gave a static margin of 2.19 caliber. This slight difference in the static margin can be attributed to the refinement of the Fluent model. The most accurate results come from a mesh with very small element sizes and that means more computational power required. Even though this model can be further refined to be more accurate, the results from the model give confidence in the design of the vehicle. As such, the cost of implementing more-refined computations is not justified for this analysis.

#### 3.1.3.3. Test Description and Results

Since the full-scale cannot be manufactured before the review of the CDR, the subscale provides a test of the full-scale design. The launch and results of the subscale launch are described in detail in Section 3.2 below.

#### 3.1.3.4. Final Motor Selection

The selected motor is the AeroTech L1150R. The motor has an average thrust of 247.40 pounds, a specific impulse of 790.60 seconds, and a burn time of 3.10 seconds. It is 20.90 inches long and has a diameter of 2.95 inches. The motor has a propellant weight of 4.60 pounds and a total weight of 8.10 pounds. This motor used the RMS 75/3840 motor casing with a rear motor retention.

### 3.1.4. Demonstrate Satisfaction of Requirements

**Deliver a Payload**

To deliver the payload sample, the sample must have a way to be secured within the launch vehicle. A SolidWorks model of the preliminary design is shown in *Figure 19* below. The door will be cut out from the fiberglass airframe in order to create an entrance for the payload to be inserted into the launch vehicle. The door will act on two hinges which will be have their own cutouts so that they will not be in the way of payload insertion. In order to keep the door closed, magnets will be attached to the airframe and the door. After the robotic arm inserts the payload, the arm will push the door shut and it will stay closed because of the magnetic contact. The payload will be inserted into a "Pick 'n Pluck" foam that is made out of polyurethane. This foam was chosen because it can be easily manipulated to hold the payload. In addition, the robotic arm should have minimal trouble of inserting the payload into the "Pick 'n Pluck" foam. This foam is also great at keeping packages secure due to its widespread use in high end camera bags and should have no problem of keeping the payload sample within the rocket. When all of the materials required for construction are received, testing of the foam and the magnetic locking system will occur. The other requirements and the means by which they were verified are outlined in Appendix D Vehicle Verification Matrix.

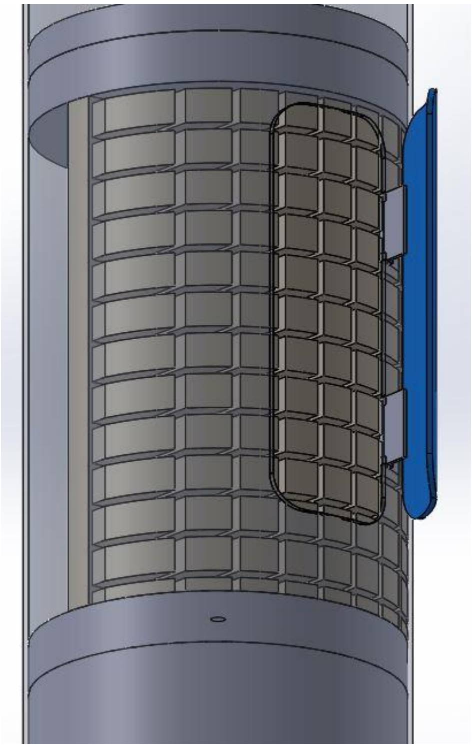


Figure 19 Preliminary Payload Compartment Model

### 3.1.5. Approach to Workmanship

Improper construction of the vehicle may lead to failure of the mission or loss of the vehicle entirely. Therefore, it is imperative that care is taken to uphold quality workmanship when the vehicle is being manufactured. The team believes that the quality of the workmanship is the foundation for success of the mission. To accomplish this mission, all senior members with experience in construction and design will be the primary contributors to manufacturing with guidance given to younger members whenever possible.

### 3.1.6. Planned Testing

The polyurethane “Pick ’n Pluck” foam’s ability to retain the payload needs to be thoroughly tested and verified as well as the robotic arm’s ability to precisely place the sample payload within said foam. As gravity assistance is prohibited, the arm will insert the payload into the compartment horizontally instead of from the top. The arm’s ability to close the payload door also needs to be verified. The payload door will be held shut with magnets, and the strength of these magnets will be tested to ensure that the payload door will successfully remain shut for the duration of the flight.

Wind tunnel testing will be used to experimentally determine the coefficient of drag of the rocket with the airbrakes open and closed. The tunnel will be run at various velocities, and the drag force will be found using a force balance. Using the airspeed and the drag force, the coefficient of drag can be found at each velocity. From this a trend will be interpolated and the data will determine at what point in the flight the airbrakes will be deployed to achieve the desired mile apogee. This data will be combined with the data from the ANSYS analysis of the rocket with airbrakes open and closed

### 3.1.7. Status and Plans of Remaining Manufacturing and Assembly

Currently, the team is waiting for the full complement of construction materials to arrive. The nosecone, airframe, coupler, and plywood have been acquired as well as all electronics required for the flight vehicle and AGSE. The 8020 rail and sheet metal for the AGSE and the 75 millimeter motor mount tube and parachutes for the launch vehicle have yet to arrive. All of the SolidWorks drawings required for laser cutting the fins, bulkheads, and centering rings have been completed. All construction consumables including but not limited to epoxy and screws have been acquired. Recovery hardware, including U-bolts, quick links, PVC blast caps, and terminal blocks, has also been acquired. Full scale and AGSE construction will commence after the submission of CDR.

### 3.1.8. Integrity of Design

#### 3.1.8.1. Suitability of Shape and Fin Style for Mission

For low altitude and subsonic flight the shape of fins are not of high importance. Nearly any reasonable shape is acceptable as long as the CP-CG relationship is maintained, and the stability margin is deemed sufficient. Trapezoidal fins are the fin shape to be used on the launch vehicle. An advantage of the trapezoidal fin shape is that the trailing edge is located forward of the end of the body tube. This protects the fins from damage when the tail section falls to the ground vertically as the body tube will impact before the fins, lessening the fins' impact significantly.

#### 3.1.8.2. Proper use of Materials

The bulkheads will be constructed with layers of 1/4 inch birch aircraft grade plywood, while the fins and centering rings will be constructed with layers of 1/8 inch birch aircraft grade-plywood. These components will be laminates using epoxy to bond the layers of plywood to create 3/4 inch thick bulkheads, 1/4 inch thick fins, and 3/8 inch thick centering rings. The layers of plywood used in each component will each be cut out from a larger sheet using a laser cutter.

A large, clean surface that is free of any debris will be covered with a plastic lining that is sized to accommodate the number of bulkheads needed. The size of the lining will be such that the desired quantity of bulkheads and fins take up half of the sheet’s size. This is so the lining can be folded in half over itself. Prior to placing the lining, thin strips of plumber’s putty will be place along the entire outer perimeter of the lining. The bulkheads and fins will then have the epoxy applied using a sponge to evenly spread over the bulkhead surface.

Once the bulkheads, fins, and centering rings have been cut out and have had epoxy applied between each layer, each component will be carefully placed on the lining. Sheets of peel ply will be cut to cover the items with approximately 2 inches of overhang along the entire edge. Breather will then be cut to the same size as the peel ply and placed directly over the peel ply. Strips of breather will be bridged from between each component all the way to the location of the vacuum tubing. This will ensure no air pockets remain trapped and an even pressure is applied at all points.

Plumber’s putty will then be placed adjacent to and along the entire previous putty lining on the inside edge, except for a one inch gap at the open end of the plastic lining fold. The vacuum tubing will then be inserted in this location and additional putty will be applied around the tubing to keep an airtight seal.

The vacuum will then be applied to a pressure of -20 inches of mercury for 8-12 hours minimum to allow the epoxy to cure.

The flight vehicle body tube will be constructed of 5.5 inch diameter fiberglass. Fiberglass offers greater strength than regular phenolic tubes or Blue Tube 2.0. It is highly resistant to abrasion and cracking which makes it unnecessary to add additional airframe reinforcements. This material has been used in multiple Tacho Lycos flights in previous years and has experienced no previous failures.

#### 3.1.8.3. Assembly Procedures, Attachments and Alignments, Connection Points, and Load Paths

To ensure the launch vehicle performs as designed for mission success, it must be constructed exactly as designed. Flight stability depends heavily on the vehicle's fin alignment. The axial alignment of the motor housing will affect fin alignment more than the construction or assembly of any other component, as this is where the fin tabs will be attached internally. The motor housing will be axially aligned by making use of the NCSU laser cutter to cut exact dimensions for centering rings. Centering rings will then be epoxied in place using a temporary piece of coupler to ensure that they are level. Once the fins are ready to be attached, the method suggested by the club's mentor and used during subscale construction will be implemented again for the full-scale. This involved placing two opposing fins in their respective slots at the same time and placing two pieces of tape over each fin. The fins were then positioned to a vertical alignment, and the tape was placed on the body tube to keep the fins' orientation. The two fins are then compared to a straight edge to ensure proper alignment. Epoxy was then applied to the joints on the inner and outer sides and allowed to cure before tape removal. This method has worked well for the team in previous builds and launches.

The full-scale vehicle will incorporate two coupler pieces to keep the forward airframe, aft airframe, and fin section connected and aligned properly. The coupler that will connect the forward and aft airframes will have a bulkhead flush with the forward surface. Screws will be externally inserted into this bulkhead to hold the coupler in place. The bottom half of this coupler piece and the aft airframe's body tube will have small holes drilled for shear pins to be inserted at 90 degree intervals. These shear pins will provide adequate connection until desired separation occurs from detonation of the black powder charges.

The second coupler will connect the aft airframe and fin section. This coupler will have its aft half permanently attached to the inside of the fin section by epoxy. The aft surface of the coupler will also be flush with a bulkhead fixed to the body tube with screws. This bulkhead will anchor the aft main parachute harness. The forward portion of the coupler and the aft end of the aft airframe will also use four shear pins inserted at 90 degree intervals.

#### 3.1.8.4. Motor Retention

To properly retain the motor, an Aero Pack 75 millimeter Retainer Kit was purchased from Madcow Rocketry. The motor housing will protrude past the aft-most centering ring. This will allow the threaded portion of the kit to be epoxied around the motor housing and flush to the centering ring. The motor is then inserted into the motor housing and the cap portion is simply twisted on. An example of this apparatus is seen in Figure 20.

Figure 20 Aero Pack 75mm Retainer

#### 3.1.8.5. Verification

For a complete verification of the integrity of vehicular design which includes the current status of each requirement, see the verification matrix in Appendix D.

#### 3.1.8.6. Mass Statement

The full-scale vehicle has a projected total weight of approximately 28 pounds as calculated by OpenRocket. In order to confirm the accuracy of OpenRocket, a SolidWorks mass model was created. This mass model uses SolidWorks material database in order to accurately predict the weight of the rocket as well as the center of gravity. The weight of the SolidWorks mass model is 26.94 pounds, which confirms the accuracy of the OpenRocket projected weight. The weight is expected to increase during the final build to no more than 32 pounds due to epoxy, paint, and other miscellaneous weights that are added during the build. The mass breakdown for the vehicle is shown in Table 3.

Table 3 Launch Vehicle Weight Breakdown

| Component | Weight (lbs) |
|---|---|
| Fiberglass | 9.10 |
| Nosecone | 1.79 |
| Centering Rings | 0.25 |
| Bulkheads | 2.43 |
| Fins | 0.98 |
| Motor Housing | 0.46 |
| Motor | 8.10 |
| U-bolts | 1.25 |
| Parachutes | 0.59 |
| Shock Cord / Recovery Harness | 0.59 |
| Avionics Hardware | 1.00 |
| Airbrake | 1.00 |
| Payload | 0.44 |
| | 27.98 |

### 3.1.9. Safety and Failure Analysis

The potential modes of failure and their effects are thoroughly described in Appendix B. The vehicle will be constructed and flown according to all NAR/TRA regulations. Furthermore, for safety, tasks such as the handling of the motor will only be done with advisor supervision or by the advisor(s) where appropriate. The team will also adhere to safety checklists outlined in this document to reduce this chance for mistakes or errors that could potentially put the team or other personnel at risk.

## 3.2. Subscale Flight Results

### 3.2.1. Flight Data

The launch on Saturday, November 28, 2015, and it was approximately 70 degrees Fahrenheit with clear skies and moderate winds. The Arduino telemetry system was recovered post-launch. The Arduino recorded data from a thermocouple which measured the temperature of the bottom of the motor casing. This data was gathered to develop a better understanding of thermal stresses endured by the motor casing during flight. Figure 21 shows the data recorded during the flight.

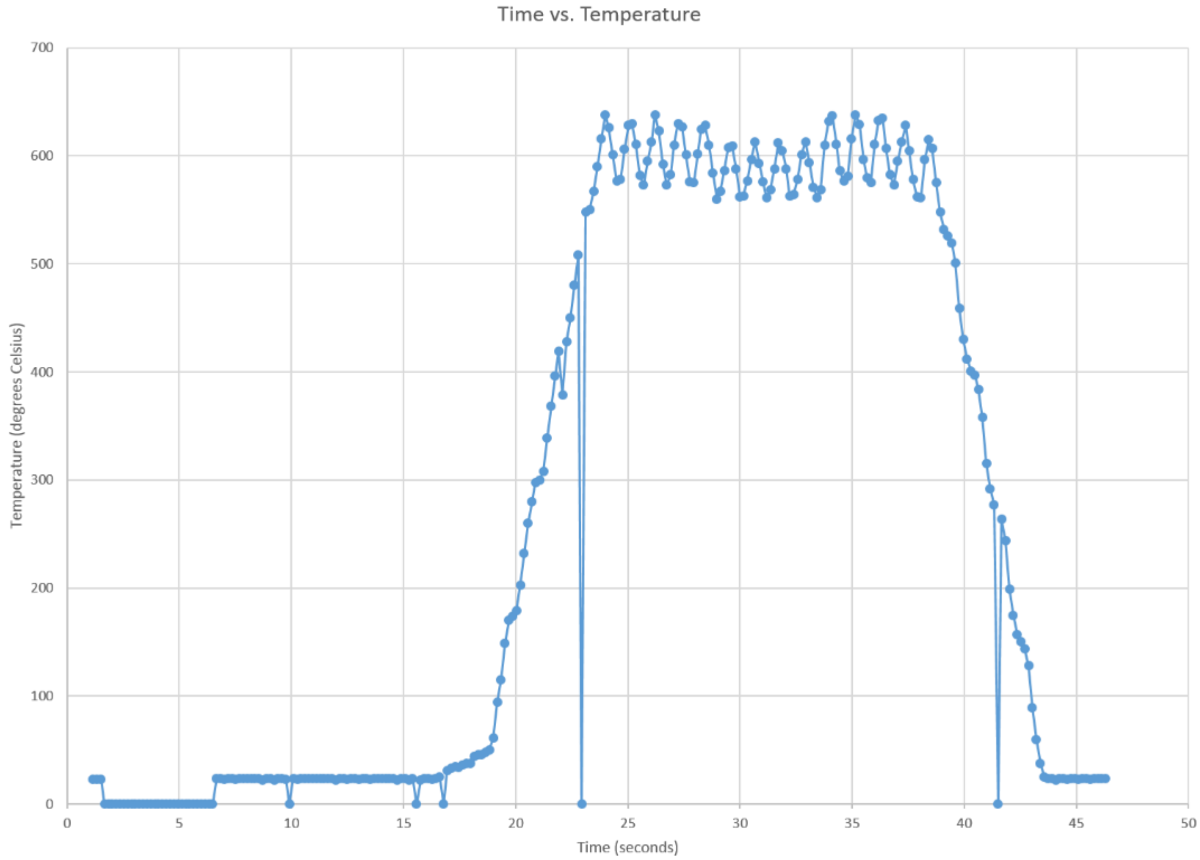



Figure 21 Subscale Temperature Experiment

### 3.2.2. Comparison to Simulation

The subscale vehicle was designed using OpenRocket, which produced flight simulations of a vehicle 72.25 inches long with a 4 inch diameter and weighed 163 ounces. The OpenRocket model had the CG 45.0 inches aft of nose tip and the CP at 54.2 inches aft of the nose tip, giving it a stability of 2.30 caliber. For the simulation, an I284W-10 motor was used. Standard atmospheric conditions were applied with an average wind of 5 miles per hour. The following are the predicted flight characteristics from the simulation: apogee at 1,798 feet, maximum velocity of 361 feet per second, maximum acceleration of 332 feet per second squared, time to apogee of 10.7 seconds, and total flight time of 66.8 seconds. These values are illustrated in *Figure 22*.

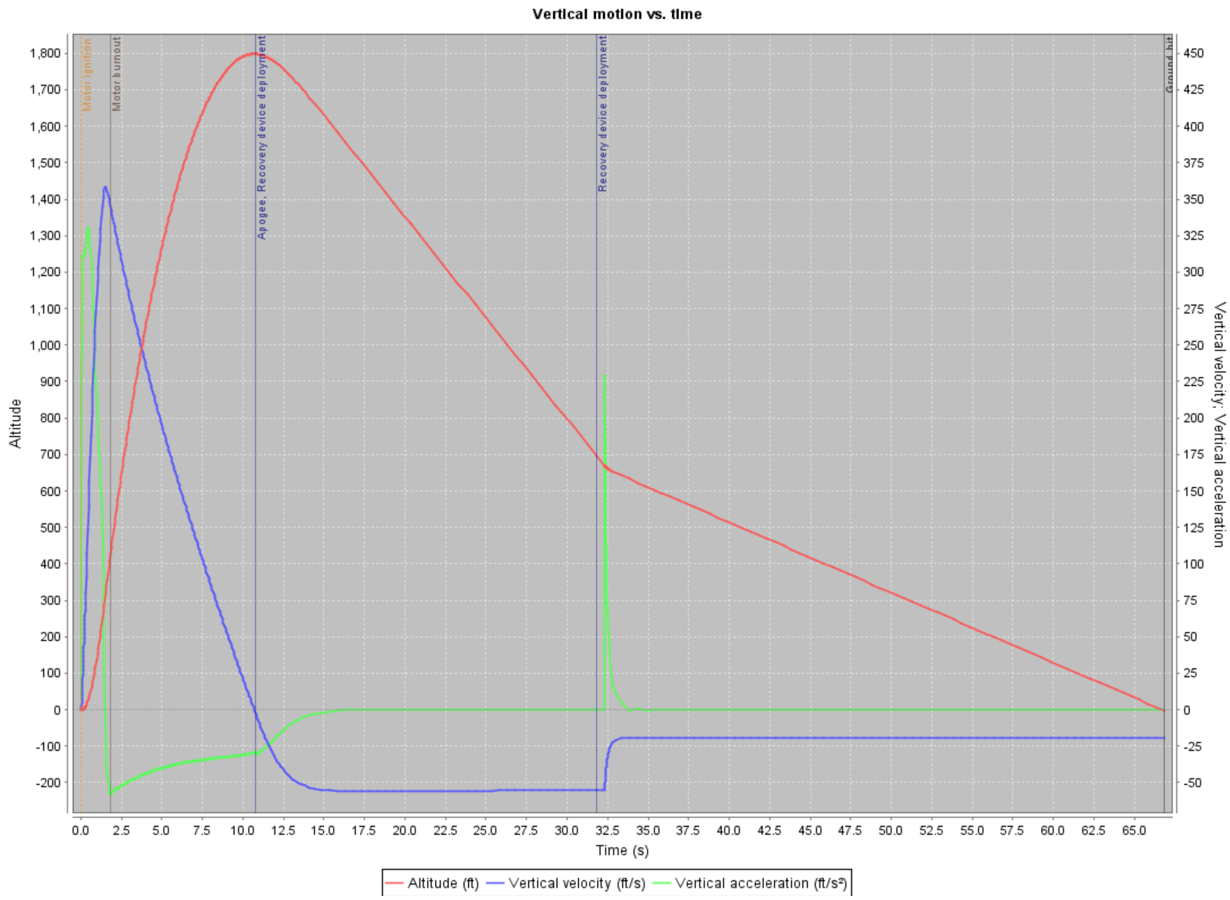



Figure 22 OpenRocket Subscale Flight Simulation

Actual CG at the field was found to be at 44.9 inches aft of the nose tip, leading to a static margin of 2.33 caliber. Shortly after liftoff, the subscale rocket weather cocked as can be seen in Figure 23. Rockets with a static margin greater than 2 have a higher tendency to weather cock than rockets with stability between 1 and 2, so this is not completely surprising. The weather cocking it experienced caused it to have a much lower apogee than projected. The subscale only achieved an apogee of 1,033 feet. In spite of the lower apogee, the drogue chute successfully deployed at apogee and the main chute deployed at 700 feet without issue as can be seen in Figure 24. Time to apogee was nearly an exact match, but total flight time was approximately 20 seconds less as a result of the reduced apogee. The maximum recorded velocity was also much lower as a result of the weather cocking; because the altimeter records vertical velocity instead of total velocity and the rocket was flying at such a severe angle, the recorded maximum velocity was approximately 115 feet per second lower than OpenRocket projected.

Figure 23 Subscale Flight

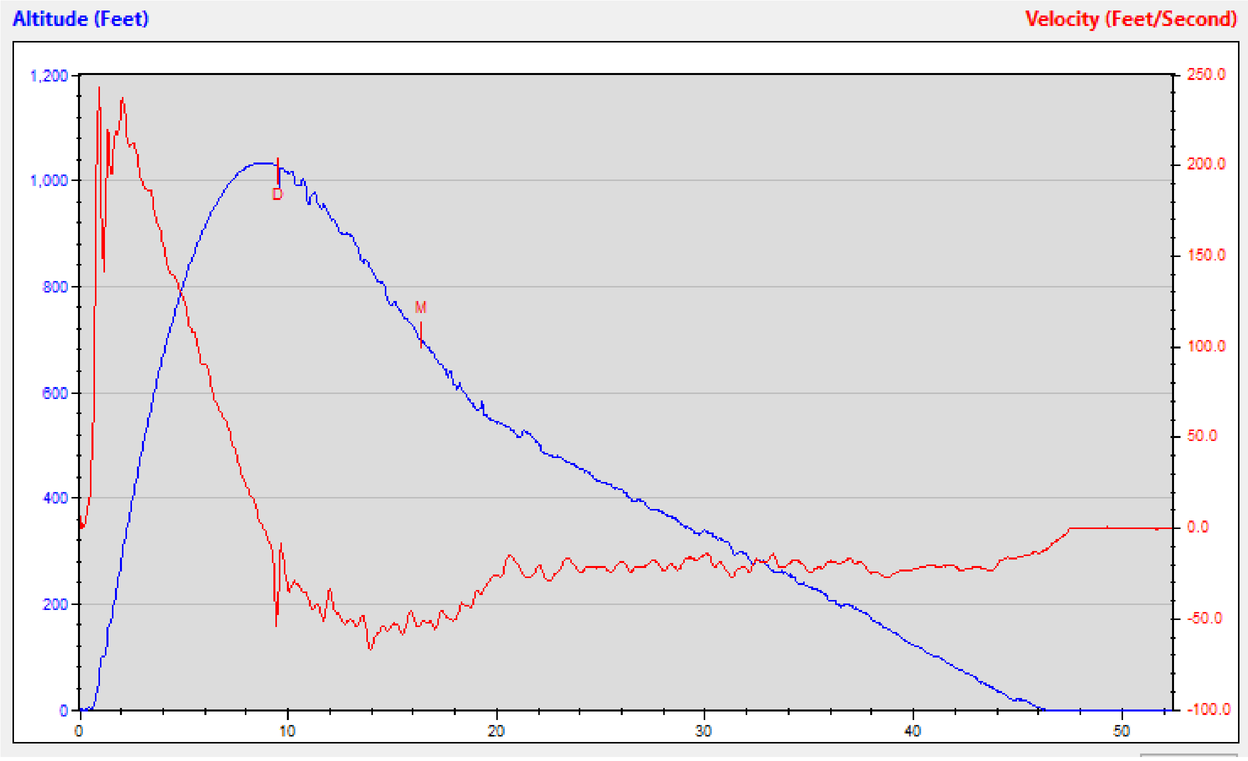



Figure 24 Subscale StratoLogger CF Data

### 3.2.3. How Subscale Impacted Full-Scale Design

When installing the ejection charges at the field prior to launch, the team had some difficulty installing the charges and e-matches in the confined space of the airframe. While this problem will be partially mitigated by the full-scale rocket's larger diameter, the team also decided to allow the bulkheads to be moveable. The initial design called for the bulkheads to be seated flush against sections of coupler as well as epoxied around the edges to adhere to the airframe. The epoxy around the edges is being replaced by six screws for each bulkhead that needs to be easily accessed. The sections of coupler will still be present to reinforce the bulkheads in the direction that the recovery harnesses will pull. These sections of coupler will also serve to ensure that the bulkheads are perfectly positioned to be screwed back into place. Using screws instead of epoxy will allow the bulkheads to slide and pivot back toward the center sections of their respective avionics bays for more ergonomic access. The access hatches will still be attached to the bulkheads with screws.

Due to the weather cocking problem experienced with the subscale, the team has decided to keep the static margin closer to 2.0 than the 15 percent overshoot the subscale was designed with.

## 3.3. Recovery Subsystem

### 3.3.1. Parachute, Harnesses, Bulkheads, and Attachment Hardware

The parachutes used for the main deployments will be a 60 inch Irish Ultra parachute and a 48 inch elliptical parachute, both purchased from FruityChutes. An 18 inch FruityChutes parachute will be used as the drogue parachute. The specifications of these parachutes can be seen in *Table 4*. The packing volume provided by the manufacturer is assumed to be an underestimate, so the parachute compartments have been designed to accommodate a larger packing size.

Table 4 Parachute Characteristics

| | **18 Inch Drogue** | **48 Inch Main** | **60 Inch Main** |
|---|---|---|---|
| **Type** | Classic Elliptical | Classic Elliptical | Iris Ultra |
| **$C_d$** | 1.5-1.6 | 1.5-1.6 | 2.2 |
| **Parachute Material** | 1.1 oz Rip-Stop | 1.1 oz Rip-Stop | Standard Nylon Toroidal |
| **Line Material** | 400 lb Spectra Lines | 400 lb Braided Nylon | 400 lb Flat Nylon |
| **Swivel Rating** | 600 lb | 1500 lb | 1500 lb |
| **Weight** | 1.16 oz | 7.3 oz | 10.9 oz |
| **Advertised Packing Volume** | 6.4 $in^3$ | 37.2 $in^3$ | 60.9 $in^3$ |

The recovery harnesses will consist of 25 foot long, flat, 1 inch Kevlar rated for 2000 pounds. The loops for recovery hardware are sewn using Tex 90 Kevlar thread. Having 25 foot long harnesses makes each harness three times the length of the total rocket. Once the ARRD separates the forward and aft sections, the harnesses will be approximately seven times the length of the forward sections and approximately five times the length of the aft sections.

The bulkheads will be fabricated from 3/4 inch thick aircraft plywood. Each bulkhead will be seated flush with a section of coupler epoxied to the airframe in the direction that the recovery system will pull for reinforcement. The thickness of the bulkheads serves both to ensure that they will not fracture under stresses from recovery system deployment and to ensure that there is sufficient area to screw access hatches into.

The bulkheads will each have 2 inch U-bolts mounted on them for the recovery harnesses to attach to. The harnesses will attach to the parachutes and U-bolts using quick links. All hardware will be purchased from Lowes.

### 3.3.2. Electrical Components

The altimeters used to control the recovery system will be a StratoLogger CF, a StratoLogger SL100, and two Entacore AIM 3.0's. Each will be independently powered by a 9 Volt battery and controlled with its own switch. For each of the altimeters, a battery snap will be connected to the power terminals on the altimeters and attached to the battery. For power activation, an electrical switch will be wired using 18 gage wire to connect to the switch terminals. The switch will be mounted such that the mechanical button that is pressed to activate power is protruding to the outside of the vehicle.

The StratoLogger altimeters' main and drogue terminals will be wired to 2x4 terminal blocks that will be mounted to the bulkheads that enclose the aft altimeter bay. The drogue wiring will go to the forward bulkhead, and the main wiring will go to the aft bulkhead. Each terminal block will be screwed into its respective bulkhead. One side of the terminal blocks will be wired to the altimeters, and the other side will be wired to the e-matches used to detonate the ejection charges.

The Entacore altimeters' A and B terminals will be wired to the aft and forward bulkheads of the forward avionics bay, respectively. On the aft bulkhead, the altimeters will be wired to the ARRD, which attaches to the bulkhead with its own nut and bolt assembly. The B terminals will be wired to a 2x4 terminal block on the forward bulkhead. One side to the terminal block will be wired to the altimeters, and the other side will be wired to the e-matches used to detonate the ejection charges.

A Big Red Bee (BRB) GPS Unit will be attached to each separating section of the rocket (two total). This will allow for live viewing of the GPS coordinates of each independently falling section. The power unit for each BRB is self-contained and will broadcast information for at least 3 hours before losing power.

### 3.3.3. Drawings of Recovery System

The vehicle will come down in two separate sections. A 1.5 foot drogue parachute will deploy at apogee as shown in Figure 25 below. This will separate the nosecone and forward airframe from the aft airframe and fin section. The drogue will be attached to an Advanced Retention Release Device (ARRD) in the forward airframe and to a bulkhead in the aft airframe. At 1,100 feet AGL, the ARRD will separate the nosecone and forward airframe from the aft airframe and fin section. Shortly after, at 1,000 feet AGL, the forward airframe and nosecone will separate, releasing a 4 foot main parachute as shown in Figure 26 below. A 5 foot main parachute will deploy at 700 foot between the aft airframe and fin section as shown in Figure 27.

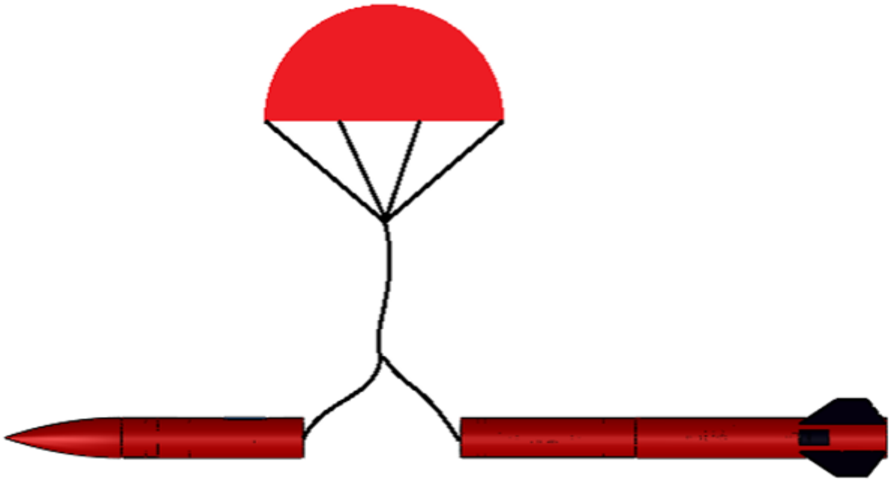


Figure 25 Recovery System at Apogee

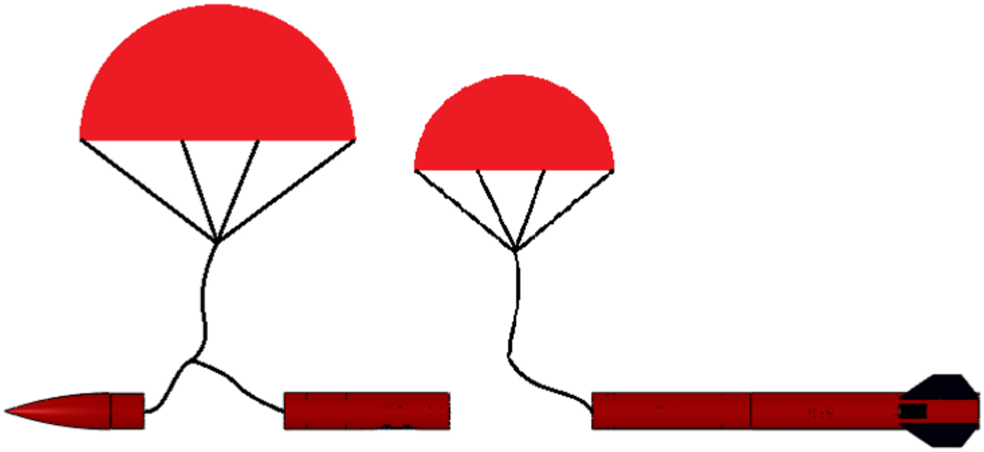


Figure 26 Recovery System at 1000 ft AGL

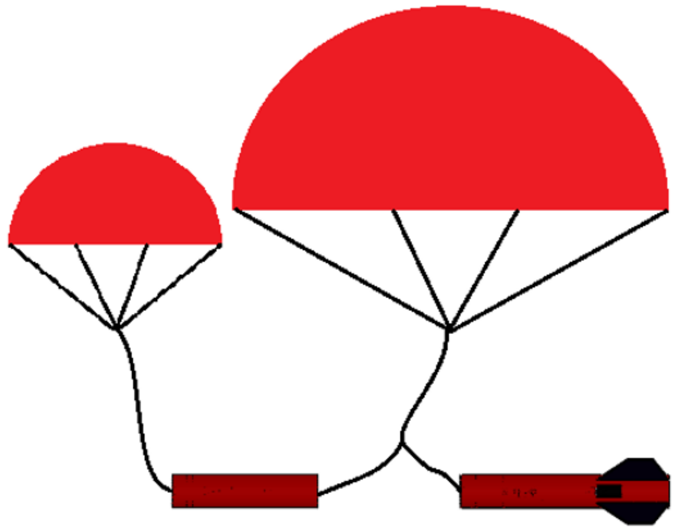


Figure 27 Recovery System at 700 ft AGL

### 3.3.4. Electrical Schematics

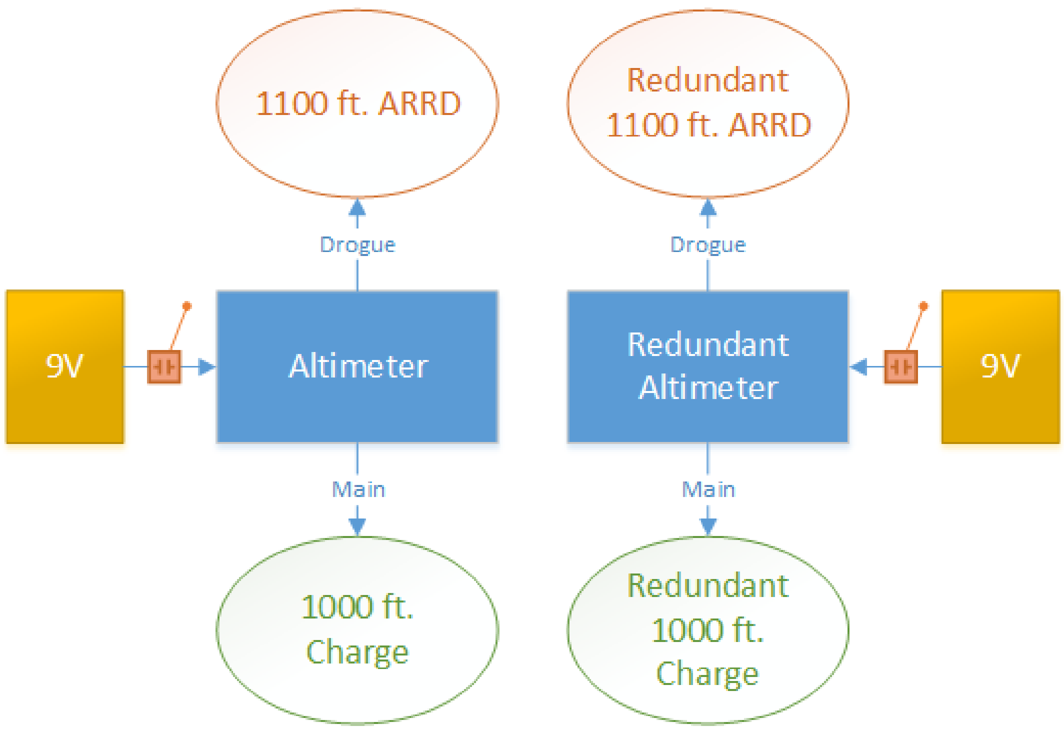



Figure 28 Forward Avionics Diagram

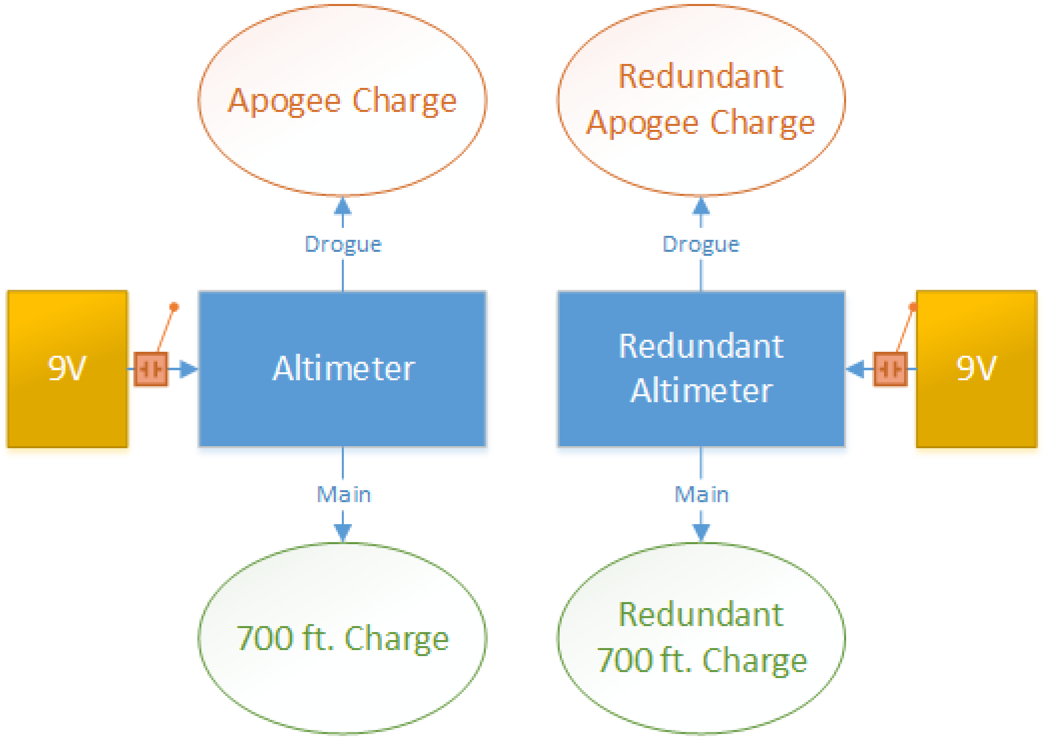



Figure 29 Aft Avionics Diagram

The airbrake system will be driven by a Firgelli P16-50-22-12-P linear actuator. The actuator will provide sufficient response speed and loading capabilities to control the airbrake system. The actuator also allows simple connection and control to Arduino via PWM and USB connection through Firgelli's Linear Actuator Control board (LAC). The entire system is compact, lightweight, and will fit well within the section that will house it. An Arduino Mega 2560 will use an Adafruit BMP180 barometric pressure sensor to measure current pressure to calculate altitude. The Arduino will use the data to determine when to deploy the airbrakes to achieve the target apogee. The LAC board accepts analog 0-3.3 volt, 4-20 milliamps; digital 0-5 volt pulse width modulation (PWM), 1-2 millisecond standard RC; or USB to control the actuator. It has been determined that using PWM will be the simplest way for the Arduino to communicate with the LAC. The team will be using Arduino-C to program the airbrake control system. The schematic below shows the relationship between the electronics used in the airbrake system.

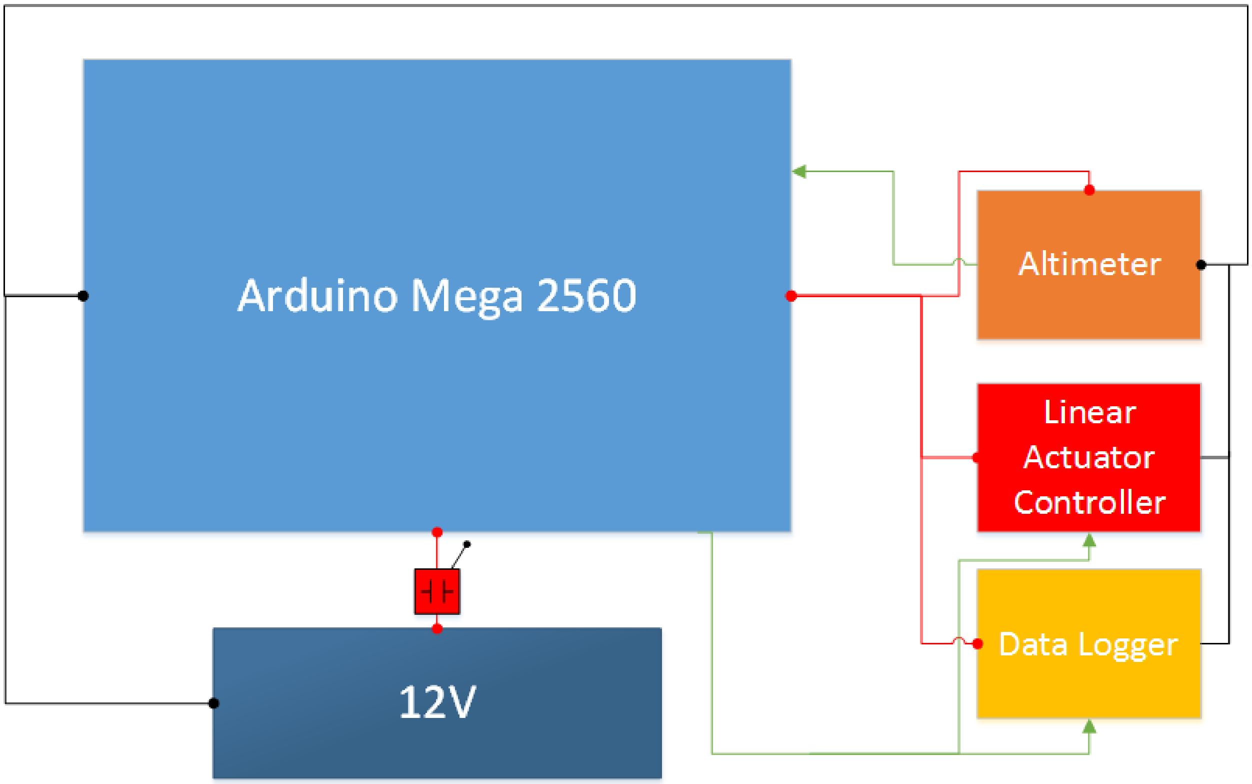



Figure 30 Airbrake Actuator Diagram

### 3.3.5. Kinetic Energy

A MATLAB program was written to determine the parachute sizes required to keep the velocity and kinetic energy to acceptable levels. The MATLAB program assumed the drag coefficient of the parachutes to be 1.55 for the elliptic 18 inch drogue and 48 inch main parachutes and 2.2 for the 60 inch Irish Ultra parachute. Air density was assumed to be standard sea level and was set at 0.002377 slugs per cubic foot. The velocity was calculated using the following equation:

$$V = \sqrt{\frac{2D}{C_D \rho A}}$$

Equation 1

Where D equals the weight of the vehicle, $C_D$ equals the drag coefficient, ρ represents the air density, and A gives the area of the parachute.

The kinetic energy KE was found using:

$$KE = \frac{1}{2} m V^2$$

Equation 2

Where m is the mass of the rocket and V is the velocity found above. These results were then plotted against different parachute sizes to determine the ideal size required to keep the vehicle reusable while also keeping the drift distances within acceptable limits.

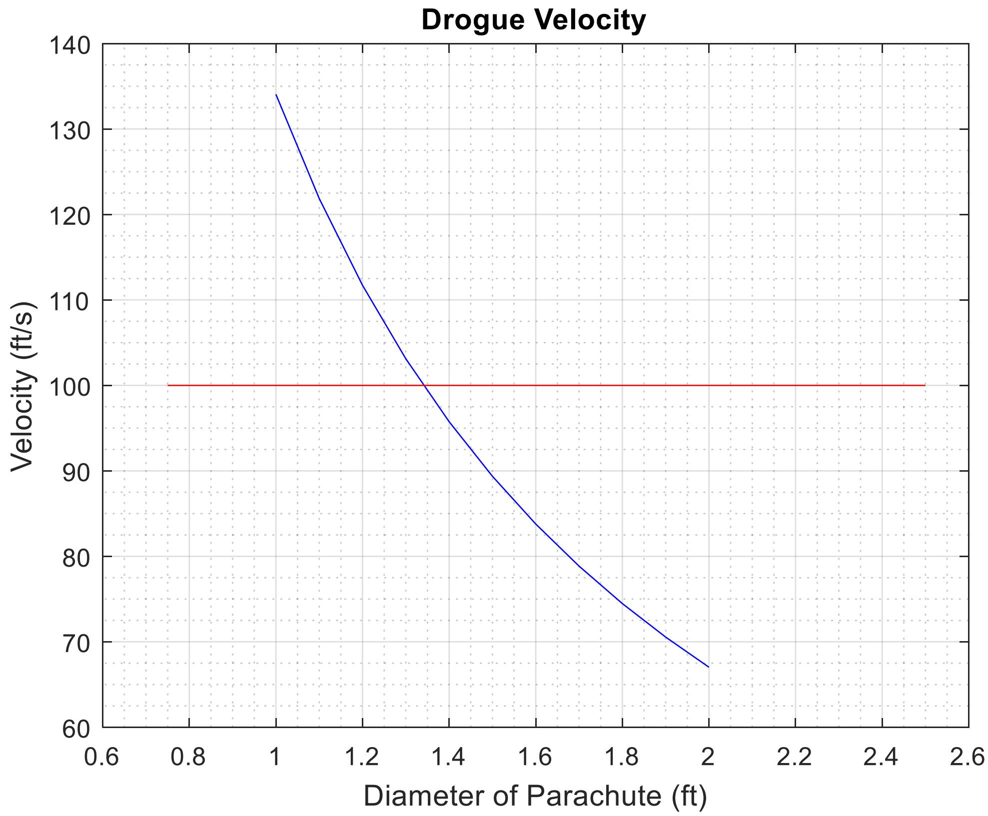



Figure 31 Vehicle Velocity under Drogue

Under the club mentor's guidance, 100 feet per second was chosen as the maximum velocity the vehicle will fall under the drogue. Using that requirement, an 18 inch drogue parachute was chosen to deploy at apogee. Figure 31 above shows the parachute diameters required to slow the parachute down to 89 feet per second. The rocket weight, after propellant burn, was used to calculate these values.

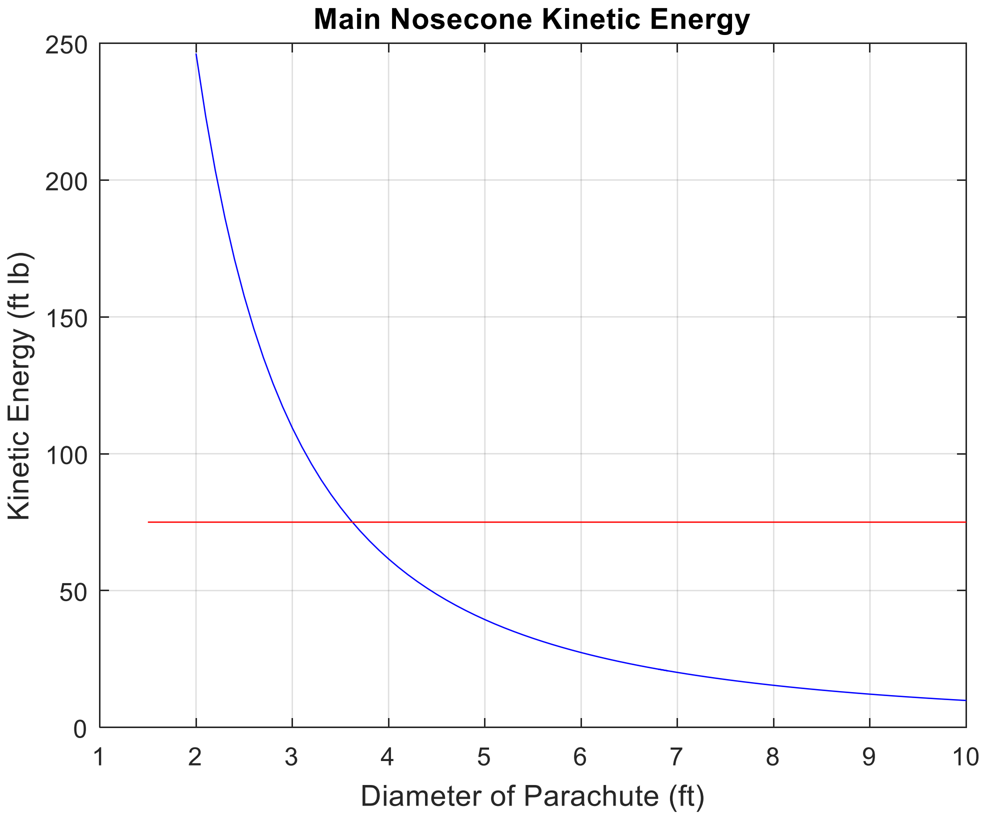



Figure 32 Forward Section Kinetic Energy

At 1,000 feet, the main parachute will deploy from the nosecone and payload section of the vehicle. This section must hit the ground with a kinetic energy below 75 foot-pounds. In order to accomplish this, a 4 foot main parachute was chosen, as shown in Figure 32. This will slow the forward section down to 20 feet per second. The rocket weight, determined after ARRD separation, was used to calculate these values.

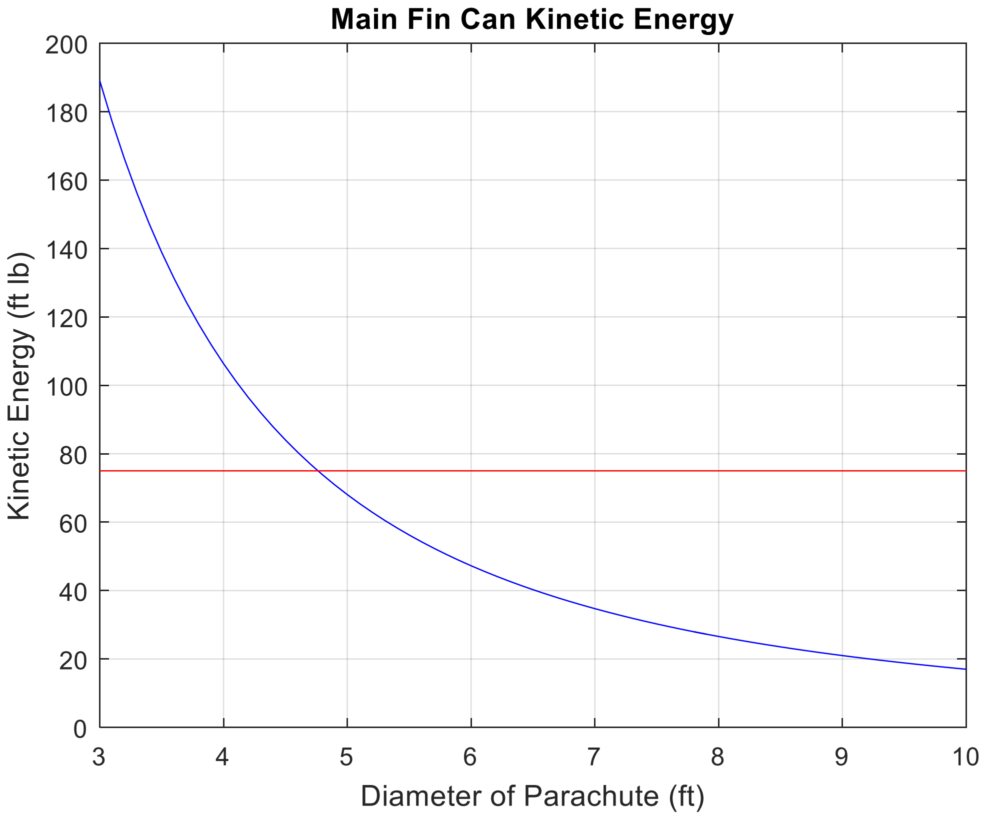



Figure 33 Aft Section Kinetic Energy

Once the fin section reaches 700 feet AGL, the main parachute will come out of that section. This section also has the requirement to land with less than 75 foot-pounds of kinetic energy. Using Figure 33 above, a 5 foot diameter parachute was chosen to allow the fin section to also land safely to allow for reusability. This parachute will slow the fin section down to 17 feet per second. The rocket weight, determined after separation and propellant burn, was used to calculate these values.

#### 3.3.6. Test Results

Ejection tests were performed to verify compete separation would occur in flight for the subscale vehicle. The amount of black powder required to separation was found using the following equation found in *Modern High-Power Rocketry 2:*

$$grams\ of\ black\ powder = \pi d^2 h * 0.007$$

Equation 3

Where d and h are the diameter and height of the compartment, respectively. The equation showed that the drogue parachute compartment required 0.8 grams of black powder and the main required 1.0 gram of black powder. Testing showed that the calculated charges were sufficient to separate the sections. The team prefers a separation with enough energy to extend the recovery harnesses sufficiently to ensure full deployment of the parachutes. Upon inspection, the 0.8 gram charge used to separate the drogue compartment was deemed insufficiently energetic to ensure full deployment due to the tape used to secure the charge within the blast cap. The charge size was increased by 0.1 grams until the team was satisfied with the deployment. The final charge size was determined to be 1.0 gram.

Release tests were run to ensure a safe and guaranteed separation of the ARRD during descent. Tests were conducted to determine the amount of black powder necessary to cause successful separation. Tests were conducted by mounting the device to a stationary test stand and filling the explosive cavity with varied amounts of black powder. Differing weights, 5 pounds, 10 pounds, and 15 pounds, were hung from the eye-bolt to determine if the amount of black powder needed for separation was proportional to the weight hanging from the device. Tests began with 0.1 grams of black powder for each of the weights to determine if more was needed for successful separation of the ARRD with plans to increase black powder by increments of 0.1 grams until separation. Successful separation occurred with 0.1 grams of black powder unnecessary and demonstrating that only 0.1 grams of black powder was necessary to separate the ARRD at any weight.

### 3.3.7. Safety and Failure Analysis

For a safe and successful launch, the vehicle and all its components must reach ground-level intact and without causing harm to any individuals or the environment. To ensure that no individuals are harmed, several factors must be accounted for. When preparing the black powder charges for placement, a maximum of two individuals will handle the vehicle and charges at any time. A third individual will read from a checklist to ensure that steps are taken in the correct order and verify when actions are complete. This process will be important make sure that power is not supplied to the altimeters during setup as to not accidentally detonate a charge prematurely. This will be accomplished by keeping the switches in the off position and only connecting the e-matches to their terminals as the last item before the vehicle is finally assembled.

Once the vehicle has been launched, every team member will be required to watch the flight path of the vehicle to the best of their abilities. If the vehicle doesn't leave a perceivable smoke trail or visual contact with the vehicle itself is lost, it must be verbally acknowledged for all present to hear. Continual scanning of the sky will be conducted as to regain contact with the flight vehicle. If the vehicle maintains visual contact throughout the whole flight, or visual contact is regained, its location must be made apparent to all present and the vehicles flight path will be followed to the ground.

In the event that the recovery system doesn't work as designed, failure analysis will be conducted to determine the cause. Initial failure analysis will be conducted at the launch site once the vehicles landing site has been reached and the power has been properly disabled. The initial analysis will be an examination of parachutes. This includes their condition (intact, damaged, tangled etc.), the state of deployment (whether they fully ejected from their compartment, snagged another piece of the vehicle), and whether they remained connected to the vehicle (shock cord condition). The next item to exam will be the connecting harnesses and attachment hardware. Quick links, U-bolts, and bulkheads will be examined to visually confirm whether their structural integrity was compromised during the flight in some way. The next item will be the black powder charges which will be visually analyzed to determine whether they were detonated or remained inactive during the flight. Wiring connections will then be checked to see if a possible disconnection occurred due to inflight forces or other variables. Lastly, a two-part examination of flight data will be analyzed. Once the charges have been properly discarded, power will be resupplied to the altimeters. At the initial startup of the altimeters, audible beeps will be emitted and counted to determine the flight data of the last flight recorded. This will be supplemented by a more in-depth evaluation by connection to a program that reveals altitude, velocity, acceleration, and voltage supply to the altimeters during the previous flight.

## 3.4. Mission Performance Predictions

### 3.4.1. Mission Performance Criteria

The first objective to accomplish is the altitude requirement of 5,280 feet AGL. Based on the simulations and calculations, the L1150R motor is sufficiently powerful to carry the vehicle past the goal at the current projected weight. The additional drag provided by the airbrakes will lower the apogee to the target.

One of the altimeters has to be designated as the officially scored competition altimeter. All of the altimeters will be calibrated carefully to ensure accuracy and programmed to read the correct altitude for the elevation at the launch site.

The launch vehicle must be recoverable and reusable. The vehicle will be constructed from sturdy materials which will easily withstand the gentle landing. The staged recovery system will ensure that the landing is low force. The two, independent sections will each contain a GPS tracking unit to aid in the recovery of the vehicle after landing.

The vehicle shall have a maximum of four independent sections. These sections at landing will be the nosecone, forward airframe, aft airframe, and fin section.

The launch vehicle will be limited to a single stage. The vehicle will be flying on a single stage L1150R motor.

The launch vehicle shall be capable of being prepared for flight at the launch site within 2 hours. Through proper use of a launch checklist and rehearsed assembly of the vehicle, the team will be able to prepare the vehicle for flight within this time constraint.

The launch vehicle shall be capable of remaining in launch-ready configuration at the pad for a minimum of 1 hour without losing the functionality of any critical on-board component. Each electrical component will be independently powered by either a fresh 9 volt battery or a fully charged LiPo battery to minimize the drain on each battery thereby increasing its life. Furthermore, the altimeters will have switches which will not be activated until the vehicle is in launch configuration on the pad, which will further decrease the drain on the batteries.

The launch vehicle shall be capable of being launched by a standard 12 volt direct current firing system. The standard igniter used to ignite the motor being used to launch the vehicle can be triggered by a standard 12 volt direct current firing system.

The launch vehicle shall use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP). This motor shall not exceed 5,120 Newton-seconds of total impulse (L-class). The vehicle will be flown on an AeroTech L1150R motor, which is approved and certified by the National Association of Rocketry (NAR) and has a total impulse of 2517 Newton-seconds.

### 3.4.2. Flight Profile Simulations

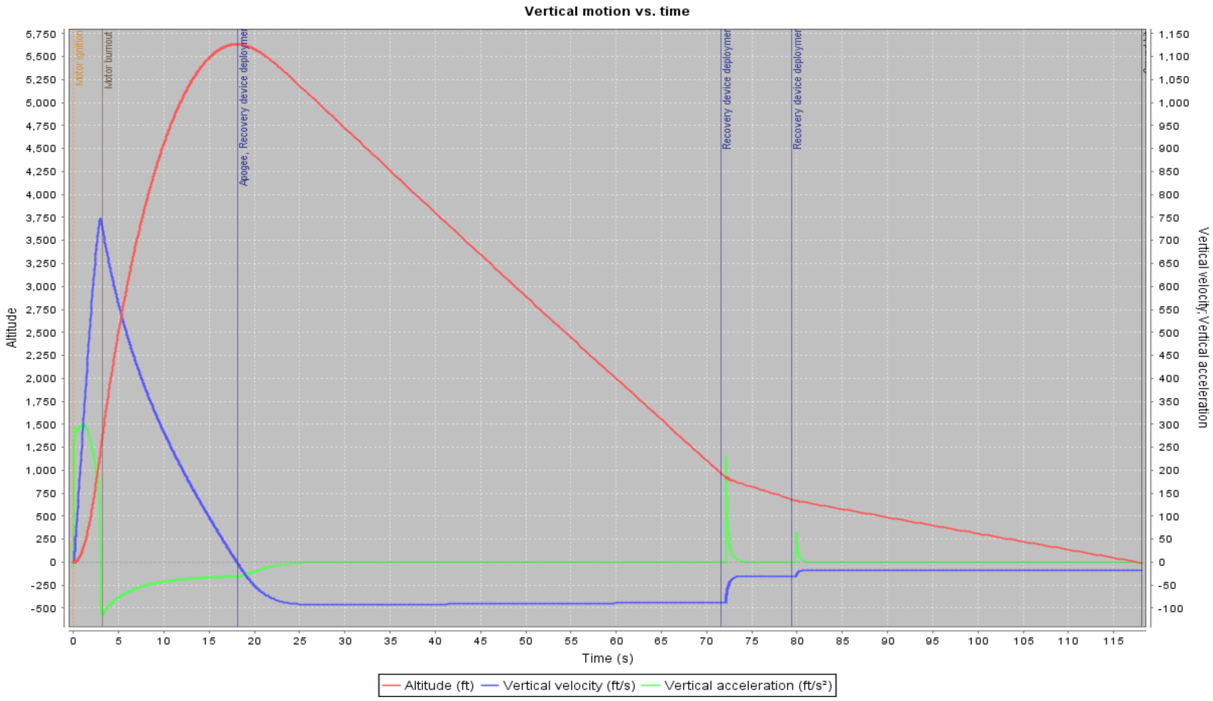



Figure 34 OpenRocket Flight Simulation of Full-Scale

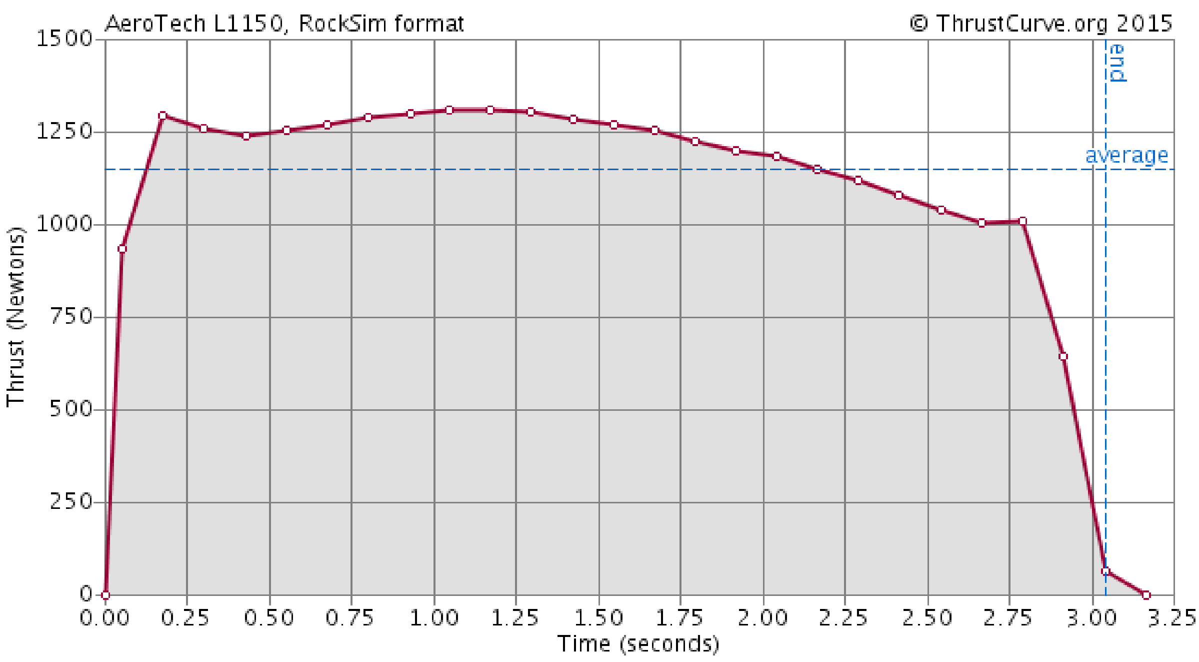



Figure 35 L1150R Thrust Curve

### 3.4.3. Thoroughness of Analysis

The analysis of the rocket so far has included many different calculations and computer analyses. The rocket was originally created with OpenRocket which gives a calculation of centers of pressure and mass, static margin, and stability. The team then used Barrowman's Equation to confirm the center of pressure calculation. With Computational Fluid Dynamics, the coefficients of drag, lift, and moment were able to be determined along with another confirmation of the center of pressure. This CFD analysis was also done with the experimental flaps extended. A SolidWorks model was created of the rocket and from it a mass model was made. All of these analyses together prove the thoroughness of the team's evaluation of the rocket.

### 3.4.4. Stability Margin

From OpenRocket software, the simulated CG and CP locations were 63.32 and 74.54 inches aft of the tip of the nose. This makes for a stability margin of 2.03 caliber at takeoff which satisfies the minimum value of 2.00 recommended by the NASA reviewers during the PDR presentation. As the motor burns out and the CG is moved farther forward, the stability will increase to 2.93 caliber. The overall rocket with CG and CP locations marked can be seen in Figure 36.

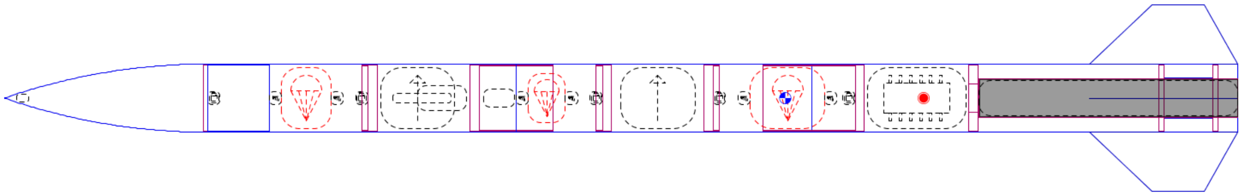


Figure 36 OpenRocket Depiction of Full-Scale Rocket

## 3.5. Integration of Experimental Airbrake System

### 3.5.1. Integration Plan

Integration of the airbrake system will occur partially during construction of the rocket. In particular, the shaft mounting flanges will need to be precision mounted on the forward centering ring prior to its incorporation into the rocket. The airbrake flaps themselves will also be cut out of the body tube prior to any other work on the fin section. This will decrease the likelihood of damage to other components, as well as make it easier to construct in the middle of middle of the body tube. After the fins, motor tube, and centering rings have been mounted in the fin section, both of the 8 millimeter shafts will be inserted into their respective mounting flange. With the shafts in their proper locations, the linear bearings (each with a 3D printed "attachment point") will be slid onto their respective shaft. The engine block can then be slid into the body tube until it rests on top of the motor tube, and all four of the piston rods will be slid through their respective holes in the engine block. This will allow the engine block to be rotated until each rod is exactly in line with its respective hole in the two attachment points. Once the engine block has been rotated into the desired location, it will be permanently installed in body tube. When the engine block has been fixed in its location, the 3D printed actuator mount can be installed on the forward face. This will allow the Firgelli linear actuator to be installed, along with it the plate that will be used to direct its forces down to each airbrake. Each of the four piston rods will then be attached to this plate and their respective holes in the attachment points. After all of this is achieved, the hinges can be mounted to both the body tube and each airbrake flap, and the 3d printed “pivot points” can be attached to both attachment points and the flaps, connecting the entire system.

The process is shown in Figure 37 through 40.

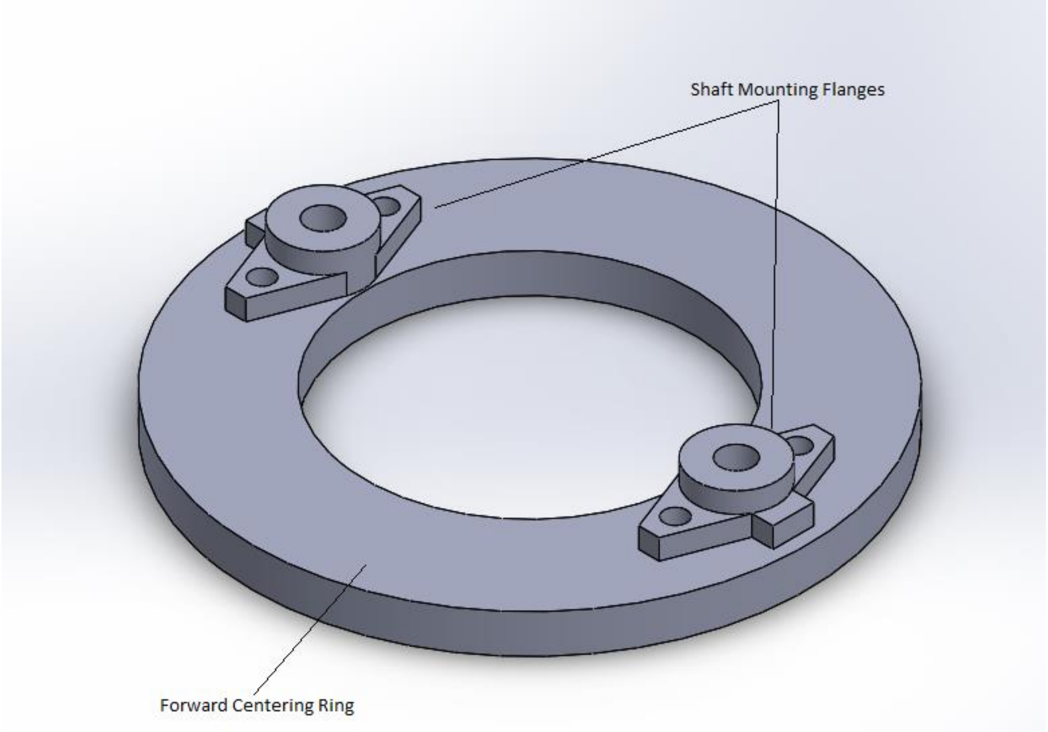



Figure 37 Attaching Shaft Mounting Flanges to the Forward Centering Ring

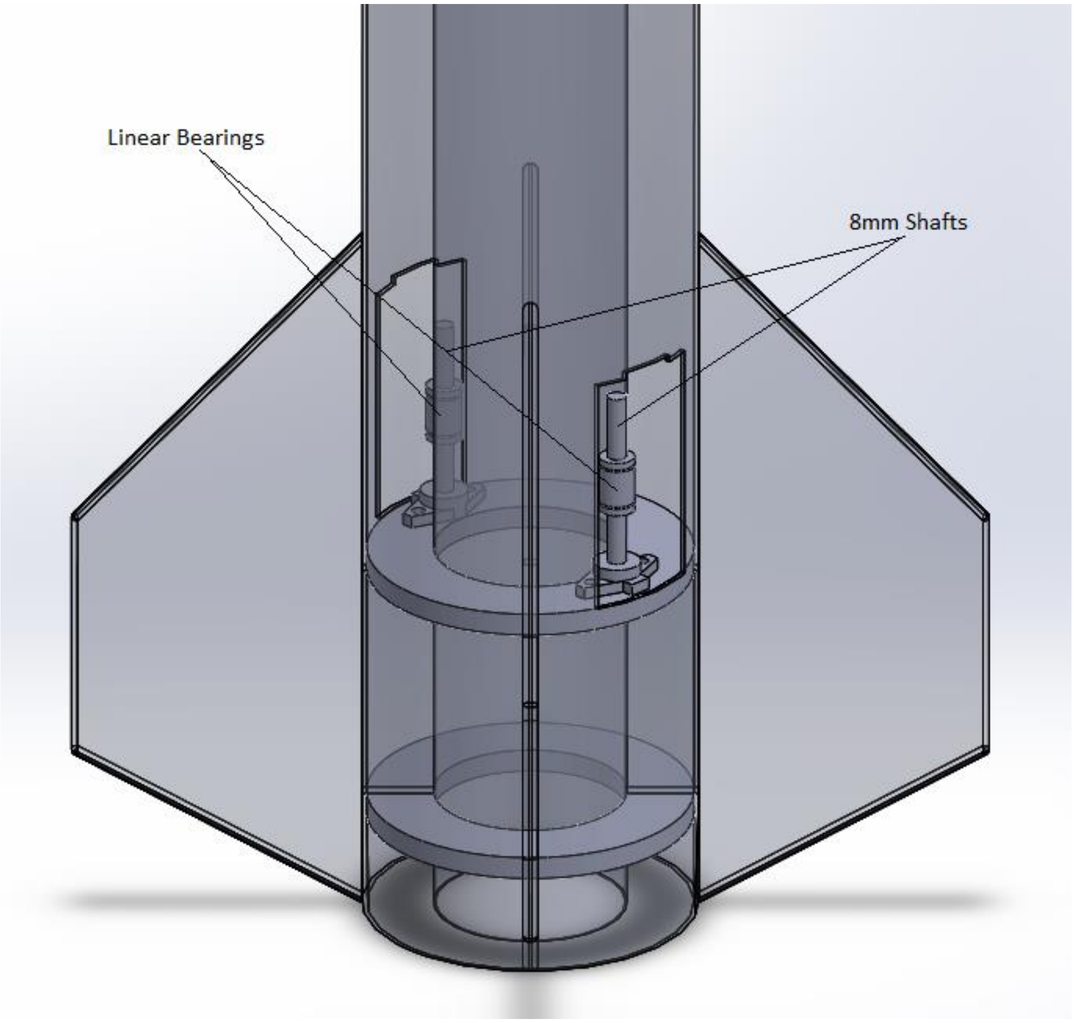



Figure 38 Mounting of 8mm Shafts with Linear Bearings in Flanges

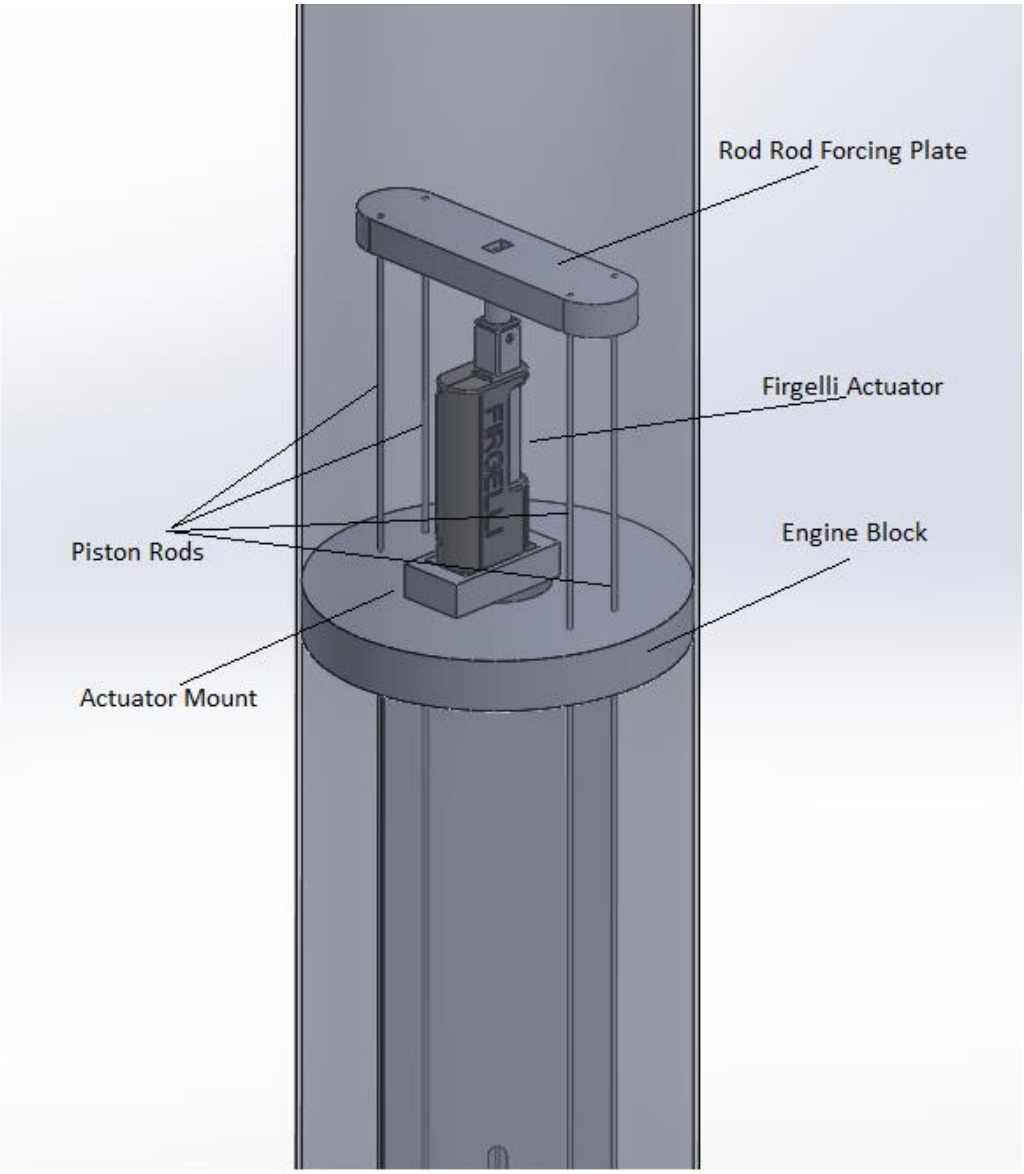



Figure 39 Placement and Mounting of Engine Block and Upper Actuating Components

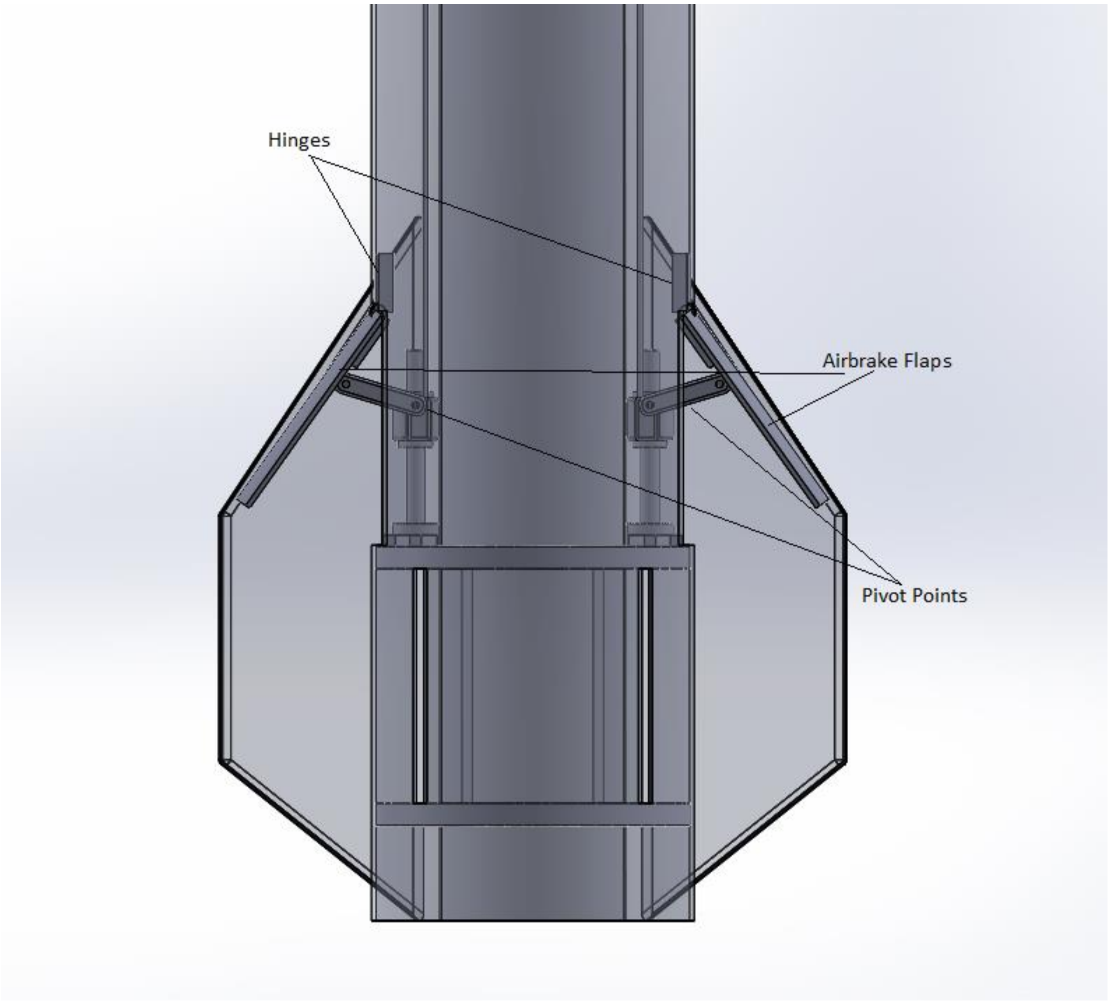



Figure 40 Placement of Airbrake Flaps and Attached Components

### 3.5.2. Compatibility of Elements

All of the components in the airbrake system were specifically designed to function together to achieve the goal of slowing the rocket down effectively. When parts were not available commercially, they were designed to be 3D printed. All components will fit in the small space that is available and were designed to be both effective in the task that they serve and efficient in volume and weight.

### 3.5.3. Simplicity of Integration Procedure

Each step in the integration of the airbrake system will be relatively simple. While it is true that the airbrake system's components are all contained in a tight environment, careful integration planning as well as the cut outs for each airbrake and the access hatch on the fin section will ensure the risk of errors during construction of the system is kept to a minimum.

## 3.6. Launch Concerns and Operating Procedures

### 3.6.1. Final Assembly and Launch Preparations

#### 3.6.1.1. Recovery Preparation

1. Retrieve nosecone
2. Ensure that screws that attach bulkhead to nosecone are tightened
3. Retrieve forward airframe
4. Remove access hatch from forward airframe with four screws
5. Carefully pull avionics bay from forward airframe making sure not to pull out wiring
6. Check that altimeter switches are in the off position
7. Insert two fresh batteries into each of the battery trays
8. Connect battery snaps on each battery
9. Insert avionics sled back into avionics bay making sure no wires are crossed and the sled is oriented with the sled facing the correctly marked position
10. Attach e-match wiring to terminal block 1 and ensure the wires are secured
11. Insert primary main black powder charge into cap 1 on top of forward airframe avionics bay
12. Insert e-match into cap 1
13. Insert wadding into cap 1 and cover cap 1 with blue painter's tape
14. Repeat steps 10-13 with redundant main black powder charge into cap 2 on top of forward airframe avionics bay in terminal block 2
15. Replace access hatch and
16. Assemble ARRD
17. Unscrew base then push piston up to remove toggle
18. With screwdriver push piston out; remove the ball bearings careful not to dislodge spring. Remove cartridge from base.
19. Place ball bearings in red anodized body
20. Place shackle and toggle assembly into red body; push piston into body up to the end of the threads
21. Place black powder into cartridge; fill cavity. Place 2 e-matches through hole
22. Place blue painter's tape over the end of the cartridge to retain black powder
23. holding base and body; screw together by turning red body until firmly seated
24. Grasp body and base assembly and firmly pull toggle to ensure correct fit
25. Insert e-matches into terminal blocks 3 and 4
26. Insert forward airframe avionics bay into forward airframe
27. Reattach access hatch to forward airframe
28. Retrieve aft airframe
29. Remove all four screws from aft airframe access hatch and remove access hatch
30. Carefully pull aft airframe avionics bay from aft airframe making sure not to pull out wiring
31. Check that altimeter switches are in the off position
32. Insert two fresh batteries into each of the battery trays

33. Connect battery snaps on each battery
34. Insert avionics sled back into avionics sled back into avionics bay making sure no wires are crossed
35. Attach e-match wiring to terminal block 5 and ensure the wires are secured
36. Insert primary main black powder charge into cap 3 on bottom of aft airframe aft bulkhead
37. Insert e-match into cap 3
38. Insert wadding into cap 3 and cover cap 3 with blue painter's tape
39. Repeat steps 26-29 with redundant main lack powder charge into cap 6 on bottom of aft airframe aft bulkhead in terminal block 6
40. Attach e-match wiring to terminal block 7 and ensure the wires are secured
41. Insert primary drogue black powder charge into cap 5 on top of forward bulkhead of aft airframe
42. Insert e-match into cap 5
43. Insert wadding into cap 5 and cover cap 5 with blue painter's tape
44. Repeat steps 31-34 with redundant drogue black powder charge into cap 5 on top of forward bulkhead of aft airframe
45. Replace access hatch on aft airframe and tighten all four screws
46. Retrieve the 48" main parachute and the shock chord for the nosecone and forward airframe
47. Remove the rubber band from the parachute
48. Attach quick link with no blue tape on shock chord to the bottom of the nosecone
49. Have another person verify that the quick link is secure
50. Insert Kevlar sheet protector and parachute into forward airframe
51. Attach quick link with blue tape to the forward airframe
52. Have another person verify that the quick link is secure
53. Insert nosecone and parachute assembly into the forward airframe making sure that the shear pins are aligned with v's
54. Install four (4) shear pins into the forward airframe to connect nosecone to the forward airframe
55. Retrieve the 18" drogue parachute and shock chord for the forward and aft airframes
56. Remove the rubber band from the parachute
57. Attach quick link with blue tape to forward bulkhead of aft airframe
58. Have another person verify that the quick link is secure
59. Insert Kevlar sheet protector and parachute into aft airframe
60. Attach quick link with blue tape to lower bulkhead of forward airframe
61. Have another person verify that the quick link is secure
62. Insert forward airframe into aft airframe making sure the shear pins are aligned with v's
63. Install four (4) shear pins into the aft airframe to connect forward and aft airframes
64. Retrieve 60" main parachute and the shock chord for the fin section
65. Remove rubber band from the parachute
66. Attach quick link with no blue tape to bottom bulkhead of aft airframe
67. Have another person verify that the quick link is secure

68. Insert Kevlar sheet protector and parachute into aft airframe
69. Attach quick link with blue tape to bulkhead in fin can section
70. Have another person verify that the quick link is secure
71. Insert mid-section assembly into fin section making sure the shear pins are aligned with v's
72. Install four (4) shear pins into fin section to connect aft airframe to fin section
73. Unscrew all four screws from fin section access hatch and remove access hatch
74. Install LiPo battery for electronics bay
75. Replace access hatch on fin section and tighten all four screws
76. Check CG location and verify static margin after inserting motor

#### 3.6.1.2. Motor preparation Forward Closure Assembly

1. Apply a light coat of Synco Super Lube or other grease to all threads and all O-rings.
2. Chamfer both inner edges of the delay insulator with fingernail
3. Assemble the RMS-Plus delay element, delay insulator, aft delay spacer and delay O-ring
4. Insert the forward delay spacer into the delay cavity until it is seated against the forward end of the cavity
5. Apply a light film of grease to the inner circumference of the delay cavity (but not the forward end of the cavity)
6. Insert the delay charge assembly into the delay cavity, O-ring end first, until it is seated against the forward delay spacer. Case Assembly
7. Install the propellant grains into the liner
8. Push the liner assembly into the motor case until it is approximately equally recessed from both ends of the case
9. Place the forward insulator (1" O.D. fiber washer) into one end of the case, seated against the liner assembly
10. Place the greased forward (3/32" thick X 1" O.D.) O-ring into the forward insulator end of the case until it is seated against the forward insulator
11. With the motor case held in a horizontal position, thread the previously assembled forward closure assembly into the forward end of the motor case by hand until it is seated against the case
12. Place the aft insulator (1" O.D. fiber washer) into the aft (nozzle) end of the motor case, seated against the liner assembly
13. Insert the larger end of the nozzle into the aft end of the case and against the aft insulator
14. Place the greased aft (1/16" thick X 1" O.D.) O-ring into the aft end of the motor case, seated in the groove between the nozzle and the case
15. Thread the aft (gold) closure into the aft end of the motor case by hand until it is seated against the case

#### 3.6.1.3. Setup on launcher

1. Carry assembled rocket to launch pad  Slide rocket launch lugs onto 15-15 launch rail
2. Erect rocket to vertical position and verify its angle into wind and away from spectators
3. Flip red switch on forward airframe and verify continuity
4. Flip black switch on forward airframe and verify continuity

5. Flip red switch on aft airframe and verify continuity
6. Flip black switch on aft airframe and verify continuity

#### 3.6.1.4. Igniter Insertion

1. For full-scale test launch, a certified individual will insert igniter
2. During flight in Huntsville, igniter will be inserted using the automatic insertion system

#### 3.6.1.5. Troubleshooting

1. Check to ensure that correct launch pad is live
2. Check for continuity between control booth and launch pad
3. Check igniter is fully installed
4. Check connections on igniter
    a. Check connections are not in contact with each other
    b. Ensure igniter leads are securely wrapped around alligator clips
5. Check that altimeters are turned on
6. Check for correct beeps from altimeters

#### 3.6.1.6. Post-flight inspection

1. Ensure that all black powder charges have blown
2. Turn off all four (4) altimeters
3. Inspect vehicle for cracks or other signs of physical damage
4. Inspect parachutes for tears
5. Inspect parachute chords for fraying and tangling
6. Inspect shock chords for fraying
7. Ensure all non-consumable pieces are accounted for (hardware, ARRD parts)
8. Ensure rocket is ready to launch again in the same day

## 3.7. Safety and Environment (Vehicle and AGSE)

### 3.7.1. Updated Analysis of Failure Modes

Refer to Appendix A for the Failure Mode Effects and Criticality Analysis (FMECAs).

### 3.7.2. Updated Listing of Personnel Hazards

While competing in the NASA Student Launch project, there are many hazards that team members have to consider in order to keep safety at the forefront. From the laboratory to the launch pad, there are potentially harmful tools, materials, and chemicals. Before using any of the power tools in the laboratory, the safety officer gives a demonstration on the correct procedure for to use the tools safety. The team members are then supervised until they are proficient on the lab tools. The correct personal protective equipment (PPE) must also be worn by team members depending on the tools, materials, or chemicals they are working on. Team members must also follow the Material Safety and Data Sheets (MSDS) when handling any hazardous materials and chemicals. Table 5 and

Table *6* contain a personnel safety matrix for construction and launch pad.

Table 5 Construction Personnel Hazards

| Safety Concern | Mitigation | Confidence |
|---|---|---|
| **Drill Press** | All personnel in the lab space are notified before powering on the drill press. Safety glasses and earplugs are to be worn by persons operating the press. Precise set up of the drill press and retention of the material being drilled will ensure the press is operated smoothly and within operating limits. | The drill press is a safe piece of machinery. Team members are trained on how to use the press safety and are supervised until proficient. Proper PPE will be worn at all times during operation. |
| **Band Saw** | All personnel in the lab space are notified before powering on the band saw. Safety glasses and earplugs are to be worn by persons operating the band saw. Saw calibration and setup are checked prior to use. Only select materials and thickness will be used on the band saw. | Proper setup (tightness and alignment of band) is the most important part of safe operation of the band saw. Team members are trained on the band saw and supervised until proficient. Proper PPE will be worn at all times during operation. |
| **Belt Sander** | All personnel in the lab space are notified shortly before powering on the belt sander. Safety glasses and earplugs are to be worn by persons operating the belt sander. | The belt sander will be checked for proper tightness before use. Proper PPE will be worn at all times during operation. |
| **Manual Mill** | For any items that need the manual mill, the team goes to the director of the Mechanical Engineering Shop. The director of the shop is a professional machinist hired by NC State. | The shop director ensures the safety of his lab and helps teach those concerns to team members. All shop procedures are followed when the manual mill is used. |

| | | |
|---|---|---|
| **Chop Saw** | For any items that need the chop saw, the team goes to the director of the Mechanical Engineering Shop. The director of the shop is a professional machinist hired by NC State. | The shop director ensures the safety of his lab and helps teach those concerns to team members. All shop procedures are followed when the chop saw is used. |
| **Black Powder** | Black powder is handled in an isolated location, premeasured, and placed into vials before taking it out to the launch site. The black powder is stored separately in a safe environment away from potential ignition sources. | Black powder is one of the more dangerous substances handled by the club, so extreme caution is taken when handling. There is minimal chance for problems with black powder. |
| **Epoxy** | Epoxy is applied in ventilated areas. Persons using epoxy wear gloves and eye protection. | Safety procedures and observers ensure epoxy is a minimal safety concern in the lab. |
| **Power Supply** | Power supplies are left unplugged when not in use. They are not used near water and cords are inspected for bare wires before use. Circuitry is checked prior to use to ensure they can handle the applied loads. | Relatively low power uses with stringent safety requirements ensure proper use and safety when using electrical equipment. |
| **Soldering Iron** | Soldering irons are left unplugged when not in use. They are not used near water and cords are inspected for bare wires before use. User ensures proper spacing during operation. | Primary concerns with soldering irons focus around electrical safety and minimizes misplacement of the heat source. Keeping these two risks in check ensures the safety of the equipment operation. |

Table 6 Launch Personnel Hazards

| Safety Concern | Mitigation | Confidence |
|---|---|---|
| **Assembly of Rocket Motor** | The rocket motor is carefully carried from the car to the rocket assembly point. During assembly, all points specified by the manufacturer's instructions are followed step by step while our mentor, Alan, supervises. | Assembling the rocket motor is a critical procedure to ensure the safety and success of the launch. Special attention to manufacturer as well as advisor's instructions ensures the motor ignites and burns properly. |
| **Handling of Vehicle** | Two hands are used to transport each component when taking the rocket from the car to the assembling area. Electronics and blast caps are armed and filled shortly before launch. | Cautious handling protects the rocket from falls that could damage components and harm the launch. |
| **Launch Vicinity** | Monitoring the location of everyone that is in attendance on the launch site and preventing them from getting to close will be a simple task by giving warnings prior to launch. | Having set distances specified by launch officials mitigates this concern. |
| **Location** | Launches are only done at locations specified by the North Carolina Rocketry Association or NASA Student Launch. | The team is confident in these organizations to choose proper locations for launches. |

### 3.7.3. Environmental Concerns

#### 3.7.3.1. NAR Environmental Regulations

The NAR High Power Rocket Safety Code document addresses the following environmental regulations:

Flight Safety. I will not launch my rocket at targets, into clouds, near airplanes, nor on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site, and will not put any flammable or explosive payload in my rocket. I will not launch my rockets if wind speeds exceed 20 miles per hour. I will comply with Federal Aviation Administration airspace regulations when flying, and will ensure that my rocket will not exceed any applicable altitude limit in effect at that launch site.

The team will fulfill this regulation by only launching at approved launch sites and with approved payloads. The team will comply with all FAA regulations and will not launch into winds greater than 20 miles per hour.

Launch Site. I will launch my rocket outdoors, in an open area where trees, power lines, buildings, and persons not involved in the launch do not present a hazard, and that is at least as large on its smallest dimension as one-half of the maximum altitude to which rockets are allowed to be flown at that site or 1500 feet, whichever is greater.

The team will fulfill this regulation by only launching at approved launch sites.

Launcher Location. My launcher will be 1500 feet from any inhabited building or from any public highway on which traffic flow exceeds 10 vehicles per hour, not including traffic flow related to the launch. It will also be no closer than the appropriate Minimum Personnel Distance from the accompanying table from any boundary of the launch site.

The team will fulfill this regulation by only launching at approved launch sites and by placing the accompanying table at least the Minimum Personnel Distance from the boundary of the launch site.

Recovery System. I will use a recovery system such as a parachute in my rocket so that all parts of my rocket return safely and undamaged and can be flown again, and I will use only flame-resistant or fireproof recovery system wadding in my rocket.

The team will fulfill this regulation by including two commercial parachutes in the rocket and by testing the rocket airframe to the expected impact loads. Only flame resistant wadding will be used in the rocket.

Recovery Safety. I will not attempt to recover my rocket from power lines, tall trees, or other dangerous places, fly it under conditions where it is likely to recover in spectator areas or outside the launch site, nor attempt to catch it as it approaches the ground.

The team will fulfill this regulation by only flying at approved launch sites where there are no power lines, tall trees or dangerous places to have to retrieve the rocket from. No one will attempt to catch the rocket as it approaches the ground.

#### 3.7.3.2. Environmental Impact on the Vehicle

The environment can play a significant impact in preventing a safe and successful vehicle launch. In order to understand and mitigate key environmental risks, Table 7 was created for the team to understand different scenarios and how to reduce the impact of these risks.

Table 7 Environmental Hazards

| Safety Concern | Hazard | Mitigation |
|---|---|---|
| **Cloud Cover** | NAR Safety Codes prevent launch into cloudy conditions. | Make sure to check the weather forecast before launching and have a backup launch day in case of inclement weather |
| **Rain, Snow or Hail** | NAR Safety Codes prevent launch into cloudy conditions. Wet conditions can damage electrical components on the rocket or the ASGE. Hail impacts can dent or damage the rocket and AGSE | Make sure to check the weather forecast before launching and have a backup launch day in case of inclement weather. In case of precipitation bring a tarp to put over the rocket. In case of hail stow the rocket under a protective shelter like a picnic shelter or inside the trunk of a car. |
| **High Winds** | NAR Safety Codes prevent launch into winds greater than 20 miles per hour. For winds less than 20 miles per hour the rocket may drift into an inaccessible area | Make sure to check the weather forecast before launching and have a backup launch day in case of inclement weather. If possible launch at a time during the day where there is the least amount of wind |
| **Bodies of Water** | The rocket can fall into the water and the electronics could be damaged. The rocket may fall into a deep body of water and cannot be recovered. | Make sure to launch in an area free from rivers, ponds, large puddles and the ocean. If the rocket falls into a body of water remove it as quickly as possible and disconnect the batteries from the electronics. Make |

| | | |
|---|---|---|
| | | sure to test electronic components before using them again |
| **Cold Temperatures** | Cold temperatures cause the batteries to discharge more quickly and cause the fiberglass body tube and fiberglass nosecone to shrink | Check to make sure the flight batteries and AGSE batteries are functional before launch. Check that the fiberglass body tube can still be separated by the black powder charge |
| **High Humidity** | Black powder charges become moist and don't ignite. Altimeters become uncalibrated in a high temperature high humidity atmosphere. | Store black powder in a cool, dry environment, check the calibration of the altimeters before launch |
| **UV Exposure** | Adhesives on the rocket can weaken. The body tube may warps or electrical components on the AGSE may become damaged | Limit the exposure of the rocket and AGSE to direct sunlight. Visually inspect the rocket and AGSE before launch |
| **Road, Concrete of Hard Surfaces** | Rocket is damaged because of an impact with a hard surface | Make sure to launch in an area that has soft surfaces for the rocket to land on |
| **Trees or other Vegetation** | The parachute may become tangled in a tree or can be ripped while being retrieved from a tree. The rocket can get stuck in a tree or other piece of vegetation, or may become damaged from an impact with a tree. | Make sure to launch in an area that is clear of trees or other objects that the rocket or parachute could impact |
| **Ground Support Crew** | Members of the ground crew may become injured by falling rocket parts or by being too close to the rocket at takeoff. | Make sure that all crew members remain alert and vigilant during the duration of the rocket launch and recovery. All crew should maintain a safe distance from the rocket at launch. |

#### 3.7.3.3. Vehicle's Impact on the Environment

The rocket has the potential to impact the environment in multiple ways. The most unavoidable impact would be the pollution caused by the combustion products of the motor. This impact cannot be mitigated without entirely scrubbing the launch. Another environmental impact would occur if there was any debris caused by a failed or damaged rocket. If not all collected/recovered after the completion of the launch, any material would become litter. Fire is a possible environmental impact that could occur if either the motor casing (being hot after full burn of the motor) comes in contact with something flammable or if the rocket impacts something while still under power. This risk is being mitigated by choosing a long enough descent and by ensuring that the rocket leaves the launch pad at a velocity high enough to prevent it from going off course. The final possible environmental impact would be any damage caused by collision with the rocket. This risk is being mitigated by using redundant charges for each parachute as well as redundant altimeters to lower the risk of the parachutes not deploying.

# 4. AGSE Criteria

## 4.1. Testing and Design of Payload Equipment

### 4.1.1. Design at System Level

**AGSE Configuration**

In Figure 41 below, the AGSE/Full-Scale Vehicle combination is shown. The important components are labeled. The AGSE base, legs, and launch rail pivot supports will be built from 1.5 inch square t-slot aluminum framing. Using t-slot aluminum greatly reduces the component weight as compared to steel and will reduce manufacturing complexity (no welding required). The chosen launch rail is extruded 6105-T5 aluminum from 80/20 Inc. with a 1.5x1.5 inch t-slot cross-section and 120 inch length. For the given rocket weight and rail length, the bending moment at the rail hinge was determined to be approximately 160 foot-pounds. Using the moment of inertia provided by the manufacturer, the maximum bending moment in the launch rail was determined to be 4110 pounds per square inch. The yield stress for 6105-T5 aluminum given by the manufacturer is 35,000 pounds per square inch, so the expected loading is well within the limit. The vehicle's rail buttons will be matched to fit the launch rail cross-section. The blast plate, mounted to the launch rail, will be water-jetted from a piece of thin steel plate. Steel was chosen over aluminum for the blast plate due to the high heat exposure during launch.

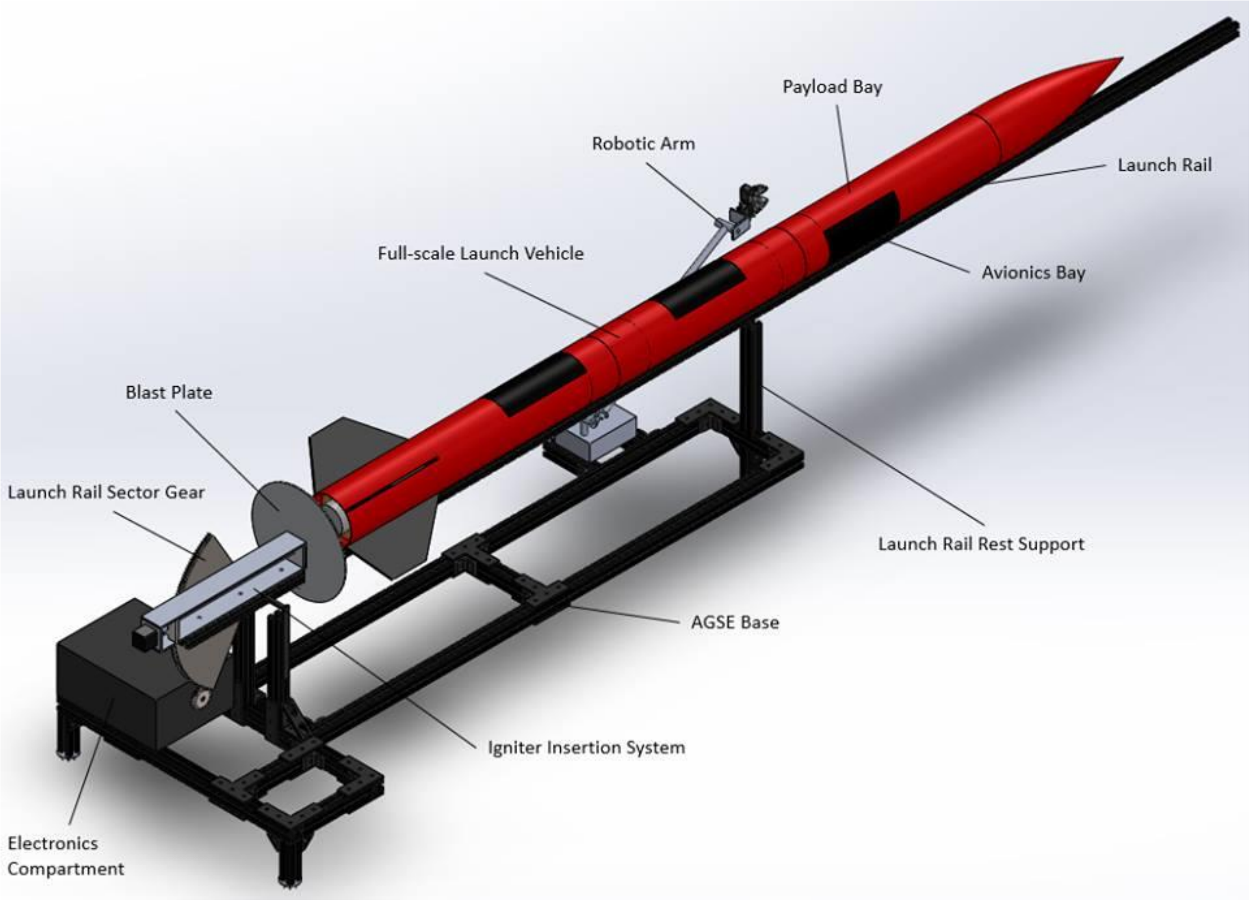



Figure 41 AGSE and Full Scale Vehicle

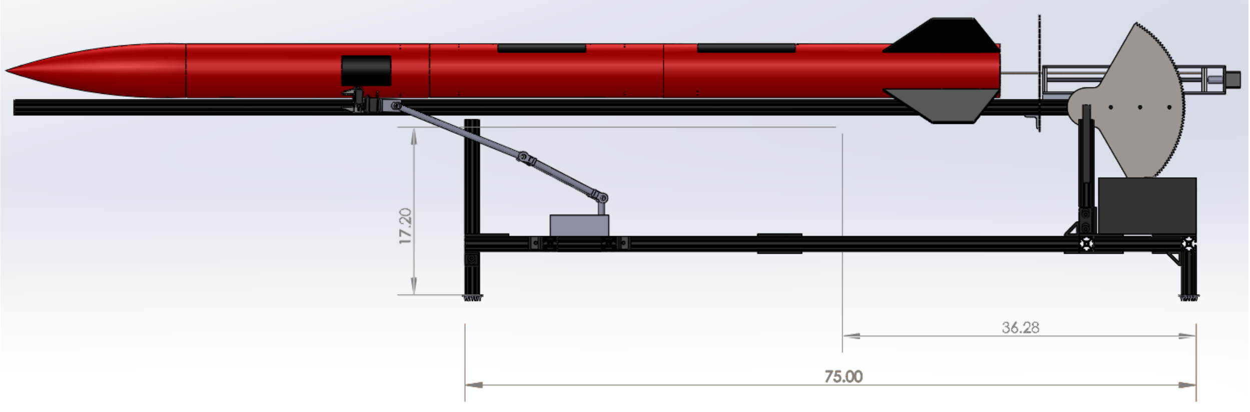



Figure 42 AGSE and Vehicle CG Location (Horizontal)

Figure 42 above and Figure 43 below show the CG locations for the horizontal and raised orientations. In the horizontal position, the CG is 36.28 inches from the back of the AGSE, 17.20 inches above the ground and 2.16 inches to the left of the centerline. In the raised position, the C.G moves closer to the back of the AGSE being 13.51 inches from the back. In addition, the CG moves up to 39.59 inches above the ground. The low, centralized location of the CG will ensure that the AGSE remains stable in the horizontal configuration. For the vertical position, while the CG is considerably higher than in the horizontal position, the team has confidence in the stability the rear legs and spiked feet provide for the AGSE. Table 8 below shows the AGSE component weights and the total AGSE weight of 81.9 pounds.

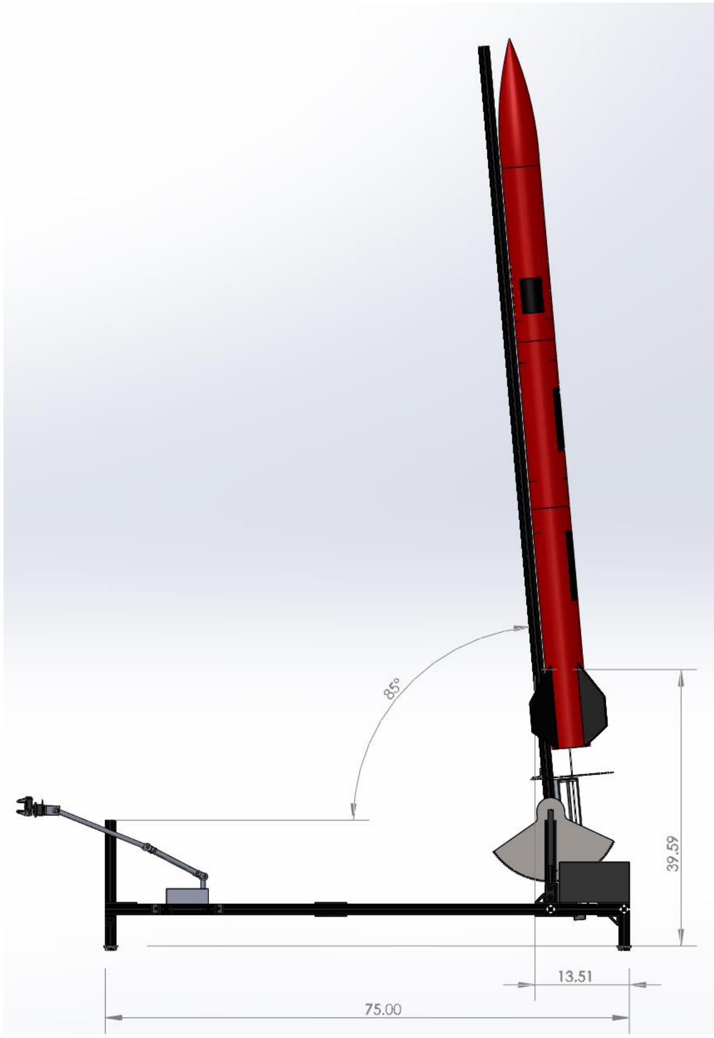



Figure 43 AGSE and Vehicle CG Location (Vertical)

Table 8 AGSE Component Weights

| Element | Weight (lbs) |
|---|---|
| Base | 40.5 |
| Legs | 1.8 |
| Launch Rail and Blast Plate | 17.4 |
| Electronics Box | 13.4 |
| Insertion System | 6.4 |
| Arm Assembly | 2.4 |
| | 81.9 |

**AGSE Base**

In order to give confidence in our AGSE base, Finite Element Analysis (FEA) was used to simulate realistic loading applications. The ANSYS Mechanical Static Structural software package was the tool used to determine the equivalent stress and the total deformation of the AGSE Base. To begin the analysis, two SolidWorks models of the AGSE Base were created and imported into the ANSYS software. These two models represent two configurations of the AGSE, the launch rail in the horizontal position and the launch rail in the fully erect position. These models can be seen in *Figure 44* and *Figure 45* below with a fine tetrahedron mesh already applied. The number of elements in the mesh is significantly lower than the mesh from the ANSYS Fluent analysis on the rocket. Only 2000 elements were needed because static structural analysis is simpler than fluid dynamic analysis and does not require a 1.5 million element mesh to obtain realistic results.

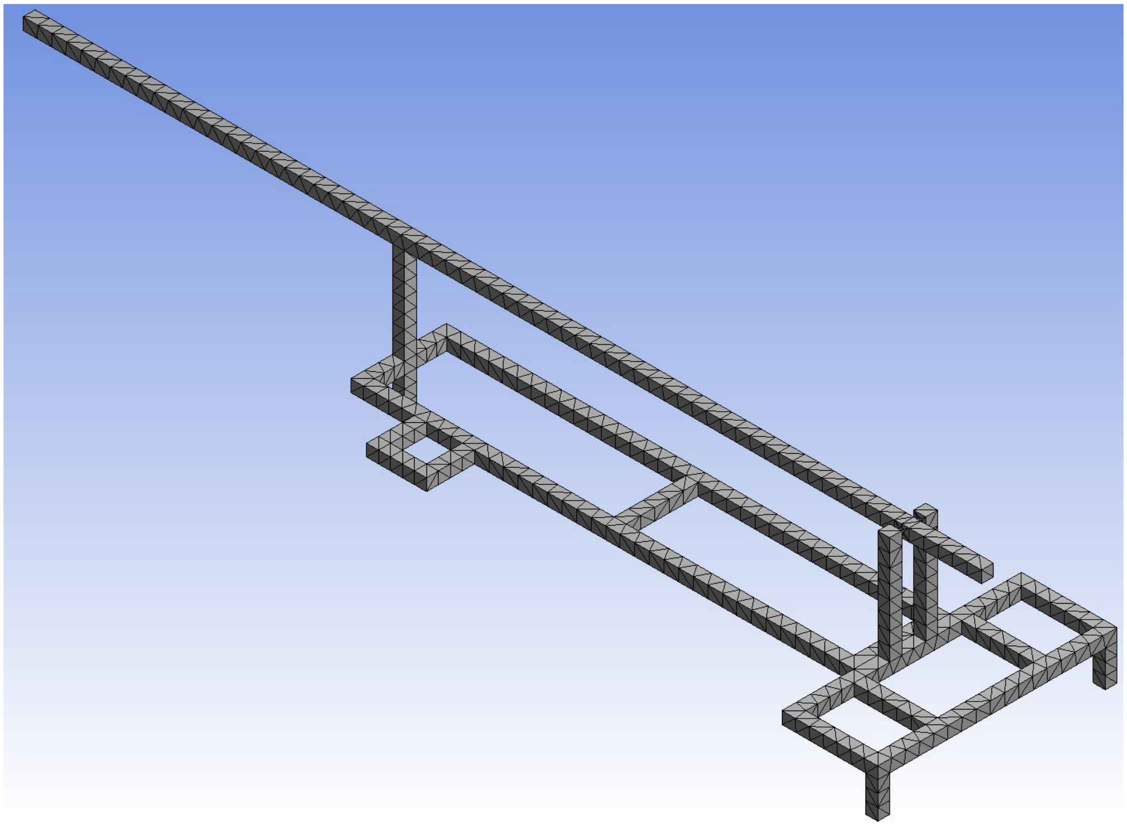


Figure 44 AGSE Model Mesh in the Horizontal Position

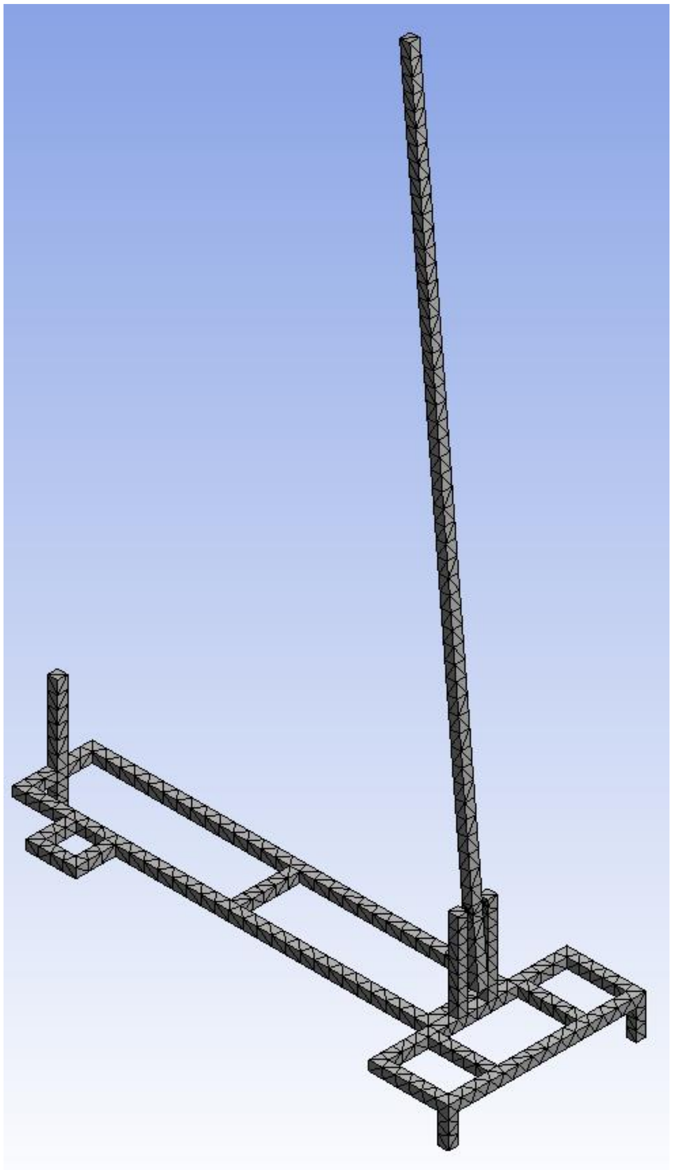


Figure 45 AGSE Model Mesh in the Fully Erect Position

In order to simulate realistic loading conditions, point forces equivalent to the weight of the launch rail, rocket, and the sector-shaped gear were applied at their respective center of mass locations along the top face of the launch rail. In addition, fixed support boundary conditions were applied on the bottom faces of the feet to simulate the spiked feet in the ground on Mars. The solving software was then applied to loading setup and the deformation and equivalent von-Mises stress contours were solved for. Figure 46 shows the stress contour of the AGSE in the horizontal position. The max stress of 436 pounds per square inch occurred at the pivot location of the launch rail. Other high stress locations are shown at the top of the AGSE where the launch rail rests on the support beam and in the middle of the launch rail where the vehicle is located. A figure of the deformation was not created because the max deformation was only 0.02 inches which occurred at the tip of the launch rail.

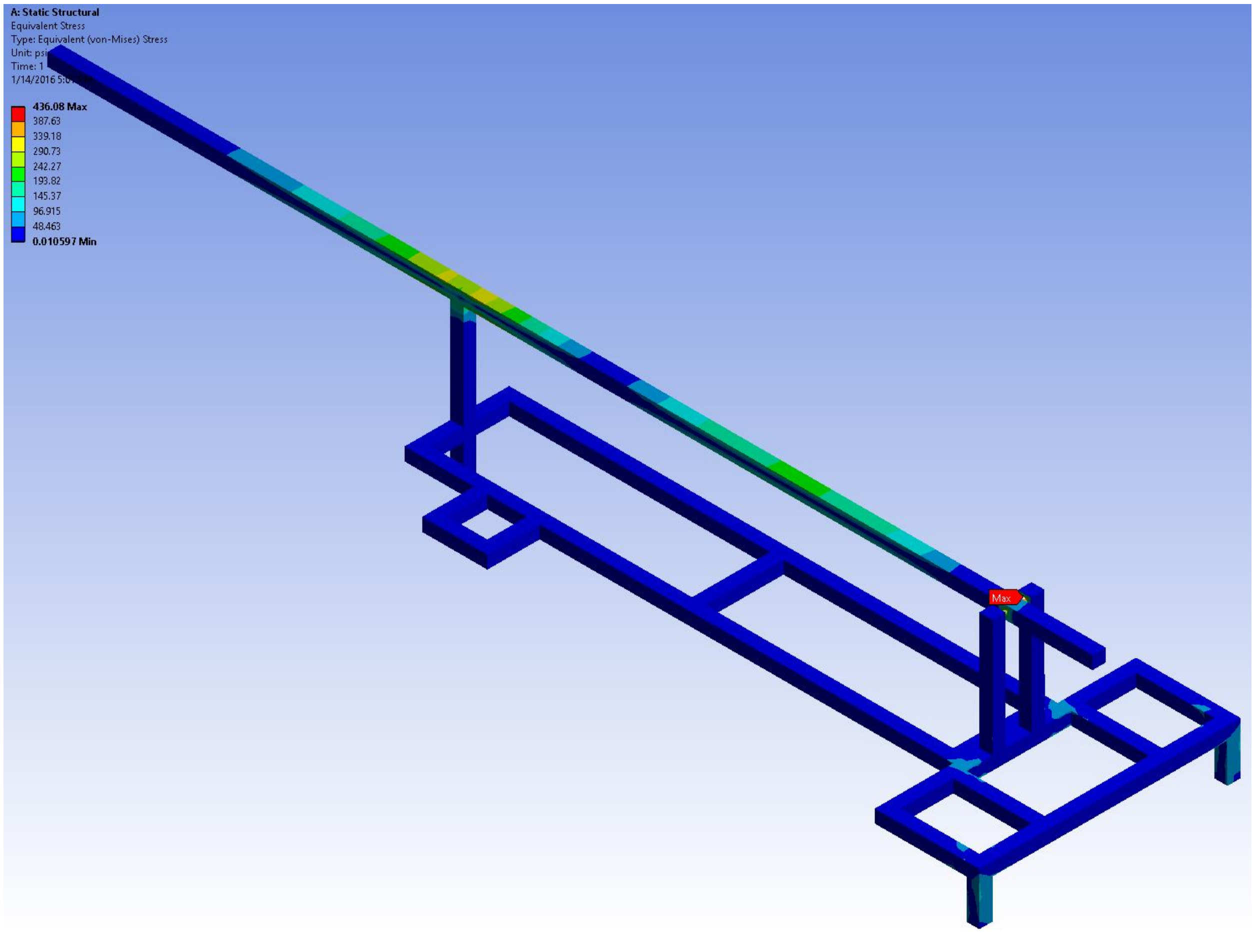



Figure 46 AGSE Model Equivalent von-Mises Stress Contour in Horizontal Position

As with the stress analysis in the AGSE horizontal position, the fully erect position model was given the same loading and boundary conditions to simulate a realistic scenario. *Figure 47* and *Figure 48* below show the results of the starting conditions. The maximum equivalent von-Mises stress was 3081.3 pounds per square inch and was again located at the pivot point of the launch rail. This higher stress value makes sense because now the load of the rocket and the launch rail are acting straight down on the pivot section. However, 6101-T5 aluminum has a yield stress of 35,000 pounds per square inch so failure at the pivot location is highly unlikely. The max deformation is 0.416 inches and is located at the tip of the launch rail. While this deformation is fairly significant, it does not significantly influence the final launch angle of 85 degrees from horizontal. These results give us confidence in the material selection and design of the AGSE.

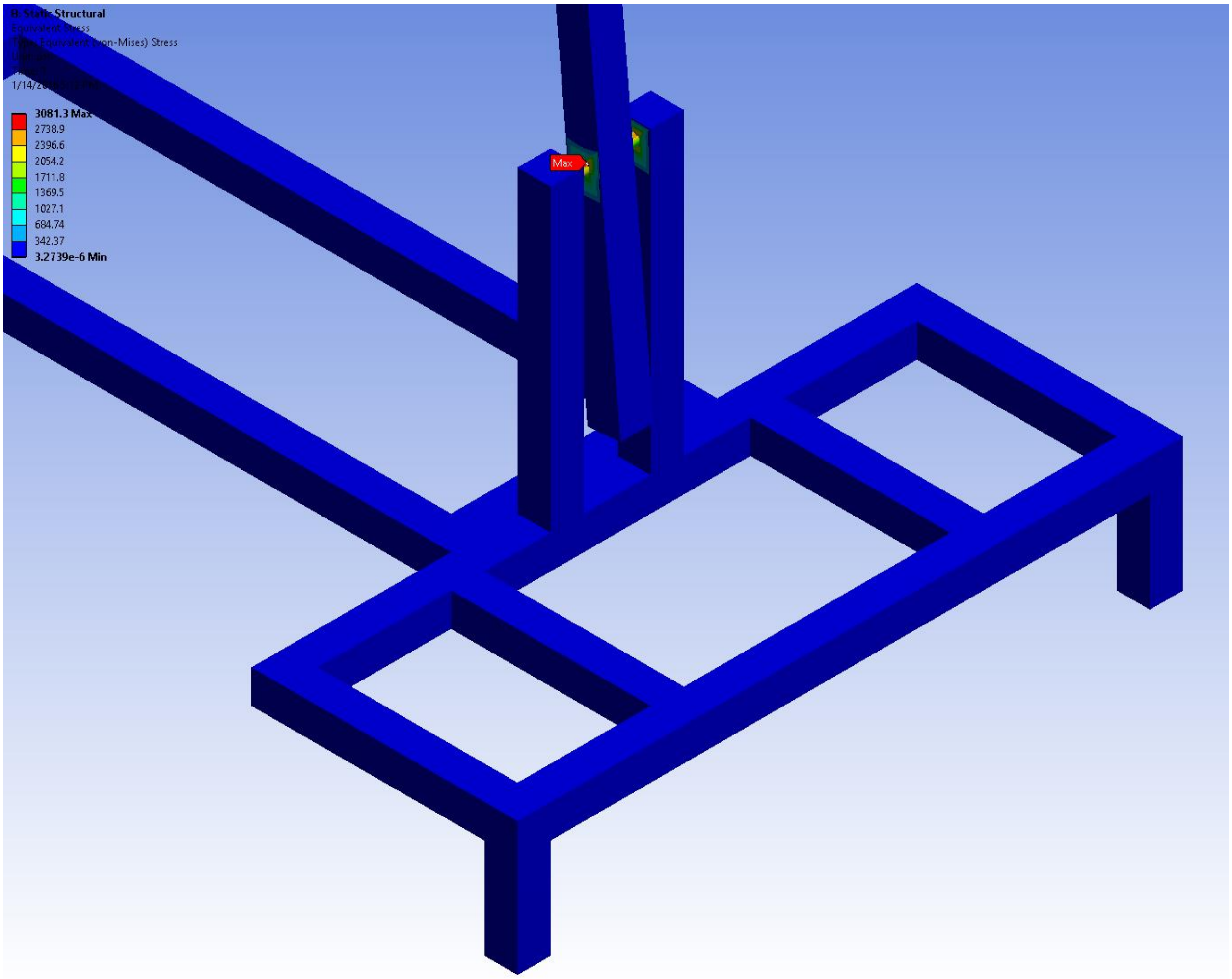



Figure 47 AGSE Model Equivalent von-Mises Stress Contour in Fully Erect Position

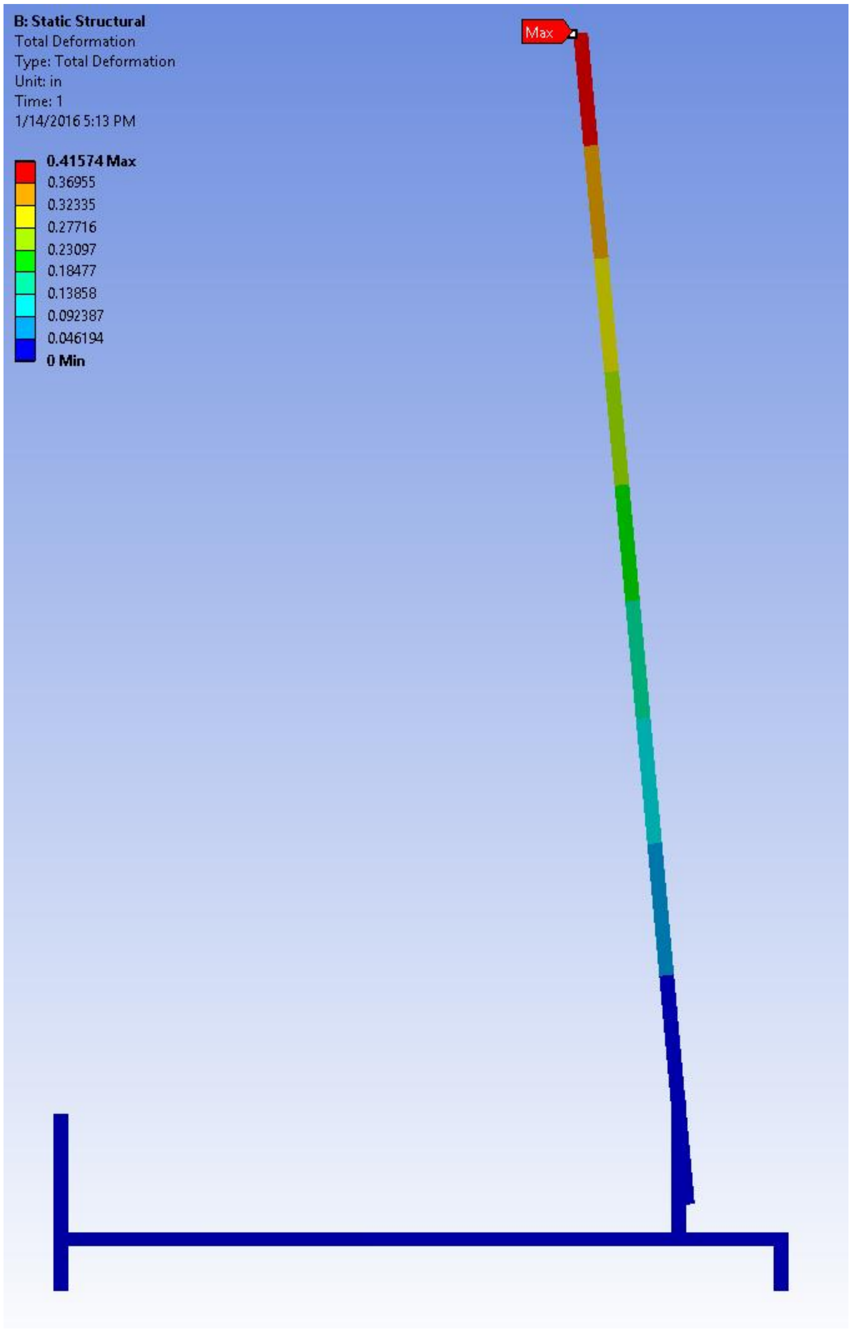



Figure 48 AGSE Model Total Deformation Contour in Fully Erect Position

**Sample Retrieval**

The sample will be retrieved using a six degree of freedom robotic arm. Four degrees of freedom are provided by the arm itself and two degrees by the mechanical gripper placed on the end of the arm to pick up the sample. The arm will be built using a RobotShop M100RAK V2 Modular Robotic Arm Kit as a base, however based on previous experience with this arm the standard HS-785HB Winch Servo Motors are being replaced with HS-7950TH Servos to provide better control and speed. The mechanical gripper will be made from a Lynxmotion Little Grip Kit. The kit includes two HS-422 servos that can act to rotate and close the grip. A depiction of the arm and gripper is shown in *Figure 49*. As per the manufacturer's specifications each joint on the arm has 180 degrees of possible rotation and the gripper can rotate 180 degrees about its axis. The gripper can open to 1.3 inches which is large enough to fit around the diameter of the sample. The arm has a gear ratio of 2:1 and has a maximum reach of 24 inches not including the gripper. Each servo on the arm has a stall torque of 486 ounce-inches, which should be more than sufficient to raise the arm and payload.

Figure 49 Robotic Arm and Gripper

The sample will be placed at a set location at least 12 inches from the AGSE. The arm will be programmed such that it will reach the sample and position the gripper around the sample before closing the gripper head to secure the sample in the gripper. The arm will then place the sample into the "Pick 'n Pluck" polyurethane foam cradle in the payload bay. After the sample is in the bay, the arm will retract and push the payload door closed until the magnets connect to seal the rocket.

**Rocket Erection**

The rocket and the launch rail will be erected using a gear-driven system. This system will consist of a sector-shaped gear with an angle of 120 degrees fixed to rotate with the launch rail, a smaller driving gear, and a planetary gearbox stepper motor as depicted in *Figure 50*. The sector-shaped driven gear will have a radius of 8 inches while the intermeshed driving gear will have a radius of 1 inch giving a gear ratio of 8:1. Both of the gears will be made of 3/8 inch thick steel to prevent gear slipping or warping. Specifications for the planetary stepper motor are included in *Table 9* below. The stepper motor was chosen over a regular electric motor for its ability to rotate discrete angular steps. For a pre-determined number of pulses, the stepper motor can be commanded to rotate the driven gear and the launch rail to the desired 85 degree angle.

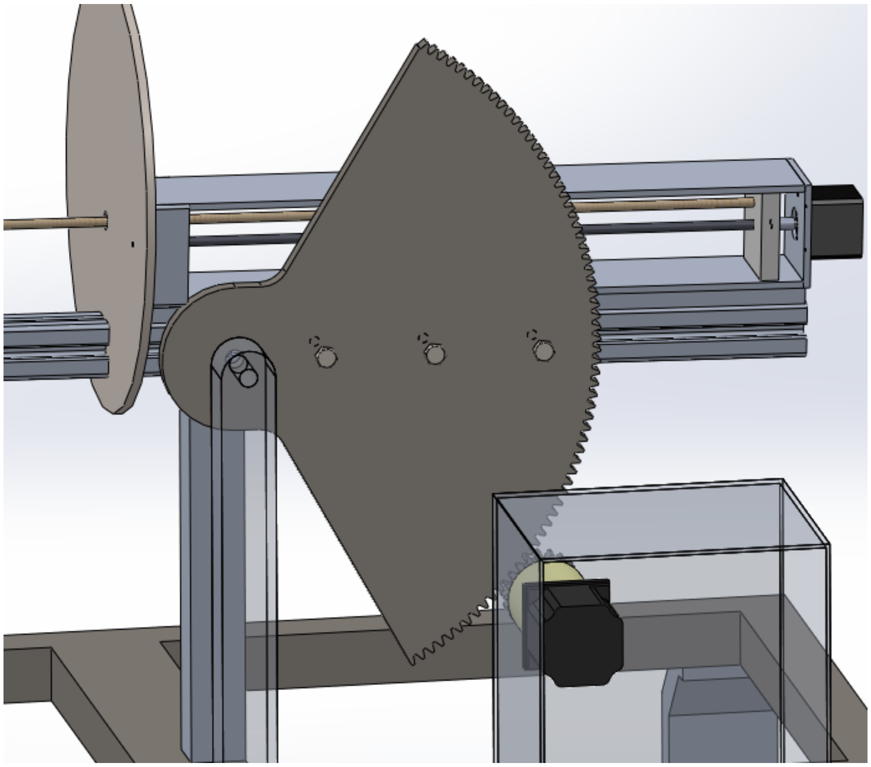


Figure 50 Gear Driven Rocket Erection System

To calculate the required holding torque of the stepper motor, the moments from the weight of the rocket, the launch rail, and the large driven gear were summed about the pivot point of the launch rail. The weight of the rocket was overestimated to be 35 pounds to account for any possible increases in vehicle weight; the weight of the launch rail was taken to be about 9 pounds; the weight of the driven gear was calculated with the steel density of 490.06 pounds per cubic foot to be about 7.13 pounds. Dividing the resulting moment by the gear ratio or 8:1 yielded a required holding torque of 19.5. The maximum holding torque of the planetary gearbox stepper motor is 29.5 ft-lb, giving the system a factor of safety over 1.5. For the required 85 degree angular rotation of the launch rail and the given gear ratios, it was determined that the stepper motor would need to undergo about 110 rotations (~22,000 steps). The stepper motor will be commanded by the BeagleBone Black through the stepper motor driver.

There will be a ratchet bolted to each of the pillar blocks that support the launch rail at the pivot point. These ratchets will be mounted axially with the pivot point and prevent the launch rail from falling in the event of motor failure or loss of power. Current mass distribution indicates that 160 foot-pounds of torque will be necessary to accomplish this. Tests will be conducted to verify that the ratchets can hold that much torque without breaking. The switches on the ratchets can reverse the direction of the ratchets to allow the rail to be raised and lowered back into the horizontal position. There will be a support pillar at the forward end of the AGSE on which the launch rail will rest when in the horizontal position to avoid unnecessary strain on the motor and ratchets.

Table 9 Launch Rail Raising System Stepper Motor Specs

| **Manufacturer Part Number** | 23HS22-2804S-PG47 |
|---|---|
| **Motor Type** | Bipolar Stepper |
| **Gearbox Output Step Angle** | 0.0386 deg. |
| **Gearbox Output Holding Torque** | 29.5 ft-lb |
| **Gear Ratio** | 46.656:1 |
| **Gearbox Mech. Efficiency** | 73% |
| **Rated Current/phase** | 2.8 A |
| **Recommended Voltage** | 24-48 V |

Figure 51 23HS22-2804S-PG47 Used to Erect the Launch Vehicle

**Igniter Insertion**

To insert the igniter, the linear actuator system in Figure 52 will be used. The 17HS15-0404S stepper motor, shown in Figure 53, will be attached to a threaded rod via a small coupler. The rod will thread through a plate that is prevented from rotating by the two parallel guides. Attached to the nut will be a dowel holding the igniter. As the stepper motor turns, the plate/dowel assembly moves upwards, inserting the igniter into the base of the rocket.

Table 10 Igniter Insertion System Stepper Motor Specs

| | |
|---|---|
| **Manufacturer Part Number** | 17HS15-0404S |
| **Motor Type** | Bipolar Stepper |
| **Rated Current/phase** | 0.4 A |
| **Recommended Voltage** | 12-24 V |

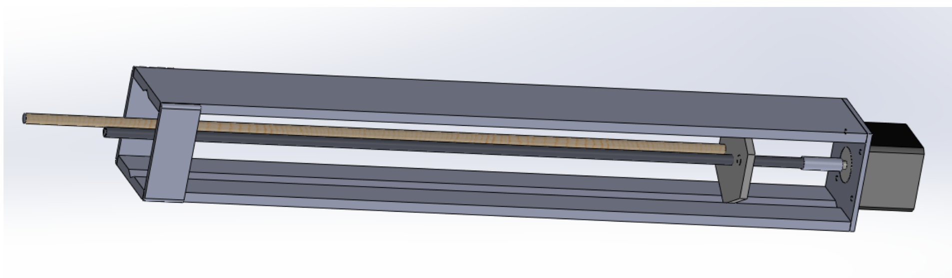


Figure 52 Igniter Insertion System

Figure 53 17HS15-040S Motor Used to Insert the Igniter

The preliminary weights of the various components are broken down in the following tables. Table 11 lists the weights of all the strictly structural portions of the AGSE: the 8020 Rail and the hardware that holds it together. Table 12 lists the individual weights of different components on the AGSE.

Table 11 Weights of 8020 Rail and Accessory Components

| **Extrusions** | | | |
|---|---|---|---|
| **Part** | **Length (in.)** | **Quantity** | **Total Weight (lbs.)** |
| 1515-UL-Black-FB | 4.5 | 4 | 1.39 |
| 1515-UL-Black-FB | 9 | 7 | 4.85 |
| 1515-UL-Black-FB | 6 | 2 | 0.92 |
| 1515-UL-Black-FB | 30 | 2 | 4.62 |
| 1515-UL-Black-FB | 12 | 3 | 2.77 |
| 1515-UL-Black-FB | 63 | 2 | 9.70 |
| 1515-UL-Black-FB | 120 | 1 | 9.24 |
| 1010 | 6 | 4 | 1.02 |
| 1010 | 10 | 4 | 1.70 |
| 1010 | 8 | 4 | 1.36 |
| | | | 37.57 |
| **Hardware** | | | |
| **Part** | | **Quantity** | **Total Weight (lbs.)** |
| 4481-Black | | 8 | 2.06 |
| 4480-Black | | 4 | 0.99 |
| 4302-Black | | 26 | 2.11 |
| 4366-Black | | 2 | 0.62 |
| 4336-Black | | 2 | 0.49 |
| 4306-Black | | 8 | 1.24 |
| 4332-Black | | 8 | 0.89 |
| 3527 | | 172 | 6.71 |
| 4108 | | 16 | 0.34 |
| 3520 | | 32 | 0.48 |
| | | | 15.91 |

Table 12 Weights of Individual AGSE Components

| Item | Individual Weight (lbs) | Total Weight (lbs) |
|---|---|---|
| 1 x Beaglebone Black | 0.09 | 0.09 |
| 1 x Large Stepper Motor Controller (M542) | 0.62 | 0.62 |
| 1 x Small Stepper Motor Controller (ST-6128) | 0.66 | 0.66 |
| 1 x Large Stepper Motor (23HS22-2804S-PG47) | 3.75 | 3.75 |
| 1 x Small Stepper Motor (17HS15-040S) | 0.64 | 0.64 |
| 1 x SSC-32U Servo Controller | 0.08 | 0.08 |
| 1 x 37 V Thunder Power DC Battery (10-Cell LiPo) | 2.54 | 2.54 |
| 1 x 11.1 V Thunder Power DC Battery | 0.80 | 0.80 |
| 3 x HS7950TH Servo Motor | 0.15 | 0.45 |
| 1 x HS-785HB Servo Motor | 0.24 | 0.24 |
| 2 x HS-422 Servo Motor | 0.10 | 0.20 |
| 2 x LTC1799 Crystal Oscillator | 0.02 | 0.03 |
| 435 inch x 1515 8020 Rail | 0.08 | 33.50 |
| 96 inch x 1010 8020 Rail | 0.04 | 4.07 |
| 8020 Connectors and Hardware | --- | 15.91 |
| 1 x 8 inch Sector Gear | 7.13 | 7.13 |
| 1 x 1 inch Driver Gear | 4.88 | 4.88 |
| 2 x Ratchets | 0.75 | 1.50 |
| 3 x AGSE Ground Stakes | 0.25 | 0.75 |
| 1 x Blast Plate | 1.00 | 1.00 |
| 1 x Insertion Track | 5.80 | 5.80 |

### 4.1.2. Demonstrate Satisfaction of Functional Requirements

***Launch Rail Raising Experiment***

The goal of the launch rail raising experiment was to determine if the launch rail stepper motor would be able to meet the required torque and speed values. Using a vehicle weight of 35 pounds, a 120 inch launch rail, and launch rail sector gear and drive gear radii of 8 inches and 1 inch respectively, the required stepper motor holding torque was 19.5 foot-pounds. In addition, a launch rail rise time of 45 seconds or less was desired to allow sufficient time for other AGSE processes. Lacking a completed AGSE for the experiment, the torque load was simulated with three weights totaling 19.5 pounds hanging vertically from a rope attached to the perimeter of a 24 inch diameter plywood pulley. The resulting torque of 19.5 foot-pounds is well below the stepper motor’s 30 volt maximum holding torque. The pulley attached to the 23HS22-2804-PG47 planetary gear stepper motor and weights can be seen below in Figure 54.

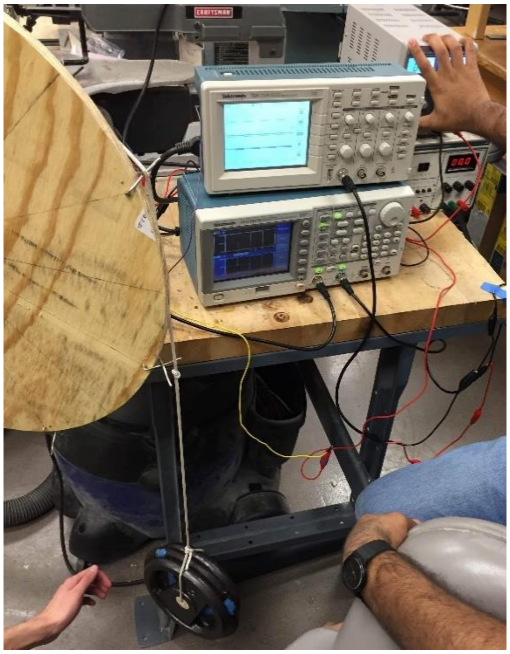


Figure 54 Launch Rail Stepper Motor and Pulley Apparatus

The system used to power and control the stepper motor can be seen below in Figure 55. Attached to a Leadshine M542 stepper motor driver is a Mastech HY5003D DC power supply (in the upper right corner) set at 37 Volts and 3.0 amps to approximate the 37 Volts 5000 milliamp-hour Thunderpower battery. The power supply powered both the driver and stepper motor. Beside the power supply is a Textronix AFG 3022B function generator. This acted as the stepper motor controller, generating a 5 volt amplitude square wave. In the future, this square wave will be generated using the Beaglebone Black. For each square wave cycle, the stepper motor was set to rotate by one step. The rotation rate of the stepper motor was adjusted by varying the square wave frequency. Above the function generator is the Tektronix TDS210 oscilloscope. In the bottom left of the picture is a power supply supplying 5 volts to the stepper motor driver used to control the stepper motor's rotation direction. Completing the battery circuit yielded counterclockwise stepper rotation and disconnecting it yielded clockwise rotation when viewed from the front of the pulley.

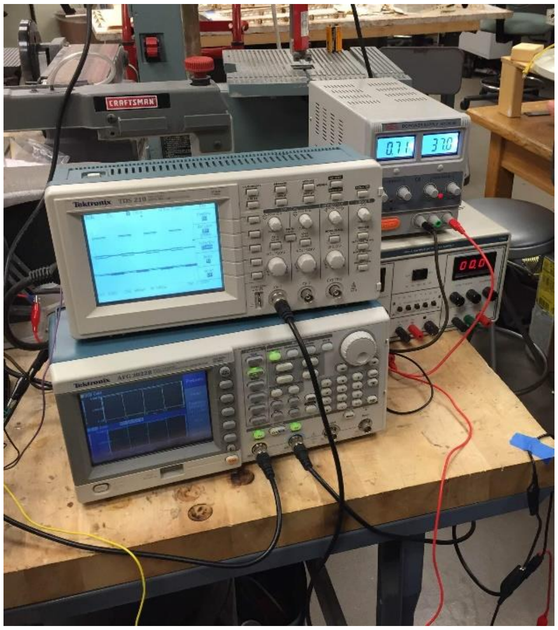



Figure 55 Tektronix Function Generator and Oscilloscope

To conduct the test, the time required for the pulley to rotate 90 degrees under the 19.5 foot-pound load was recorded for different square wave frequencies. A 90 degree rotational angle was chosen to keep the hanging weights from touching the ground during the test. The 90 degree rotation time could then be easily converted to the total launch rail rise time knowing the required rotations of the stepper motor output shaft (1.889 rotations for an 85 degree launch rail angle). The results are shown in Table 13 below. This table illustrates that launch rail rise times as low as 15.49 seconds were achieved, well below the desired value of 45 seconds. The surprising ease and speed at which the stepper motor rotated under the 19.5 foot-pound load at all tested frequencies clearly demonstrated its ability to accomplish the required task.

The other requirements and the means by which they were verified are outlined in Appendix E.

Table 13 Square Wave Frequencies and Resulting Launch Rail Rise Times

| Function Generator Square Wave Frequency (Hz) | 90 Degree Rotation Time (s) | Calculated Launch Rail Rise Time (s) |
|---|---|---|
| 400 | 13.24 | 100.04 |
| 500 | 9.54 | 72.08 |
| 600 | 7.74 | 58.48 |
| 700 | 6.67 | 50.39 |
| 800 | 5.58 | 42.16 |
| 900 | 4.87 | 36.80 |
| 1000 | 4.31 | 32.56 |
| 1250 | 3.13 | 23.65 |
| 1500 | 2.82 | 21.31 |
| 1750 | 2.41 | 18.21 |
| 1900 | 2.05 | 15.49 |
| 2000 | N/A | N/A |

***Igniter Insertion Experiment***

The goal of the igniter insertion experiment was similar to that for launch rail stepper motor. Verification that the igniter insertion stepper motor could translate the threaded igniter plate vertically in 45 seconds or less was desired. Before insertion, the igniter will sit just behind the vehicle's base. Therefore, the translation distance required for the linear stepper actuator is the internal length of the rocket motor, approximately 21 inches for the AeroTech L1150R. So this experiment was designed to time a 6 inch vertical translation along the threaded rod at different stepper motor frequencies and then the times were scaled up for the needed 21 inches. The experiment setup can be seen below in Figure 56. The setup consisted of the 17HS15- 0404S stepper motor attached to an 8 turn per inch ACME threaded rod via a coupler, the igniter plate, and two parallel rods to prevent igniter plate rotation. Because the wooden dowel and igniter wire are quite light, their weights were neglected for this experiment. The igniter plate was made out of two quarter inch white Delrin plates bolted together with an ACME nut mounted in the lower plate. Delrin was chosen for its low friction coefficient. The power and control system was the same as for the launch rail raising experiment except that the smaller StepperOnline ST-6128 driver was used instead of the Leadshine M542.


Figure 56 Igniter Insertion Stepper Motor Experiment Setup

In Table 14 through 17 below can be seen the testing for different voltages from the power supply applied to the igniter insertion stepper motor. The tests were done at multiple increasing frequencies at 12, 15, 18, and 21 volts. In all of the tables is a point where the frequency was too great for the motor to move the Delrin block. The motor would just grind and not move the block at all. As the voltage increased in each test, the motor was able to increase its pulse frequency which peaked at 1800 Hz at 21 volts. Because there was still a small amount of grinding at 1800 Hz, the team has decided to operate the motor at 1700 Hz at 21 volts to achieve the best insertion time. At 39.45 seconds, this is still under our desired igniter insertion time of 45 seconds and will allow the team to stay in the allotted time.

Table 14 12V Test of Igniter Insertion Stepper Motor

| Function Generator Square Wave Frequency (Hz) | 6 inch Rise Time (s) | 21 inch Rise Time (s) |
|---|---|---|
| 300 | 63.70 | 222.95 |
| 450 | 42.13 | 147.46 |
| 600 | 31.95 | 111.83 |
| 750 | 24.97 | 87.395 |
| 900 | 21.37 | 74.80 |

| | | |
|---|---|---|
| 1050 | 17.95 | 62.83 |
| 1200 | 15.95 | 55.83 |
| 1350 | 14.12 | 49.42 |
| 1400 | 13.79 | 48.27 |
| 1500 | N/A | N/A |

Table 15 15V Test of Igniter Insertion Stepper Motor

| Function Generator Square Wave Frequency (Hz) | 6 inch Rise Time (s) | 21 inch Rise Time (s) |
|---|---|---|
| 500 | 38.07 | 133.25 |
| 750 | 25.53 | 89.36 |
| 1000 | 19.08 | 66.78 |
| 1250 | 15.55 | 54.43 |
| 1500 | 12.69 | 44.42 |
| 1600 | N/A | N/A |

Table 16 18V Test of Igniter Insertion Stepper Motor

| Function Generator Square Wave Frequency (Hz) | 6 inch Rise Time (s) | 21 inch Rise Time (s) |
|---|---|---|
| 1000 | 19.06 | 66.71 |
| 1250 | 15.45 | 54.08 |
| 1500 | 12.84 | 44.94 |
| 1600 | 12.13 | 42.46 |
| 1700 | 11.61 | 40.635 |
| 1800 | N/A | N/A |

Table 17 21V Test of Igniter Insertion Stepper Motor

| Function Generator Square Wave Frequency (Hz) | 6 inch Rise Time (s) | 21 inch Rise Time (s) |
|---|---|---|
| 1500 | 12.82 | 44.87 |
| 1600 | 11.86 | 41.51 |
| 1700 | 11.27 | 39.45 |
| 1800 | 10.87 | 38.05 |
| 1900 | N/A | N/A |

### 4.1.3. Approach to Workmanship

Improper construction of the AGSE may lead to failure of the mission. Therefore, it is imperative that care is taken to uphold quality workmanship when the AGSE is being manufactured. The team believes that the quality of the workmanship is the foundation for success of the mission. To accomplish this mission, all senior members with experience in construction and design will be the primary contributors to manufacturing with guidance given to younger members whenever possible.

### 4.1.4. Status and Plans of Remaining Manufacturing and Assembly

The parts have been ordered for the AGSE and once all of the aluminum railing arrives, assembly will begin. The plan is finalized and, unless unforeseen problems are found during assembly, there will be no changes made. When STORM is complete, the rocket will be mounted and tested.

### 4.1.5. Integration Plan

*Figure 57* provides some details into the flow of the AGSE system. A BeagleBone Black (BBB) will be central to the monitoring, scheduling, and control of the system. To monitor the progress of the system, the BBB will interface with a system of software flags that monitor and relay task completeness. The key tasks to be verified by these flags will be grabbing the sample, placing the sample in the rocket clamp, closing the door of the rocket, verifying the rocket was erected to the correct position, and verifying the igniter is in the correct position. The BBB can schedule and control procedures for the next task. The completion of each task will also be electronically stored on the BBB so the system knows where to resume in case of a power failure.

| Main Task |
|---|
| Beagle Control |
| Power on a System |
| Power off a System |

**Start System**

- Verify all sensors are connected
- Reset all controllers to default values
- Reset all threads and clear previously cached items

**Grab the sample**

- Power on arm
- Arm startup program
- Find sample

**Insert sample in clamps**

- Move sample to compartment on rocket with arm
- Push sample into foam of rocket.
- Release hand.
- Close rocket door with arm.
- Move arm to preset location out of rocket path.
- Power off arm

**Raise the rocket**

- Power on step motor
- Run step motor
- Power off step motor

Insert the igniter

Power on igniter stepper motor

Operate igniter motor until igniter is inside rocket motor

Power off igniter motor

System ready to launch

Figure 57 AGSE Task Progression

#### 4.1.6. AGSE Electronics

The AGSE will be controlled by one central computer which will use a series of controllers to manage all the subsystems. The team will be using a Beaglebone Black (BBB) as the central computer. It has 512 MB of RAM, 1.2 GHz Processor, and 36 GB of flash memory which should be sufficient for any computations needed to achieve the desired tasks. The team will be using an SSC- 32U servo controller to control all the servos on the robotic arm. The arm will be used to pick up the sample and load it into the rocket. Stepper motor controllers will be used to control the motors used for erecting the rocket and inserting the igniter. The schematic below shows the relationship between the BBB and all other subsystems that interact with it.

Legend:

- Black Wire: Ground
- Red Wire: Power
- Pink Wire: Digital Association
- Green Wire: USB Association

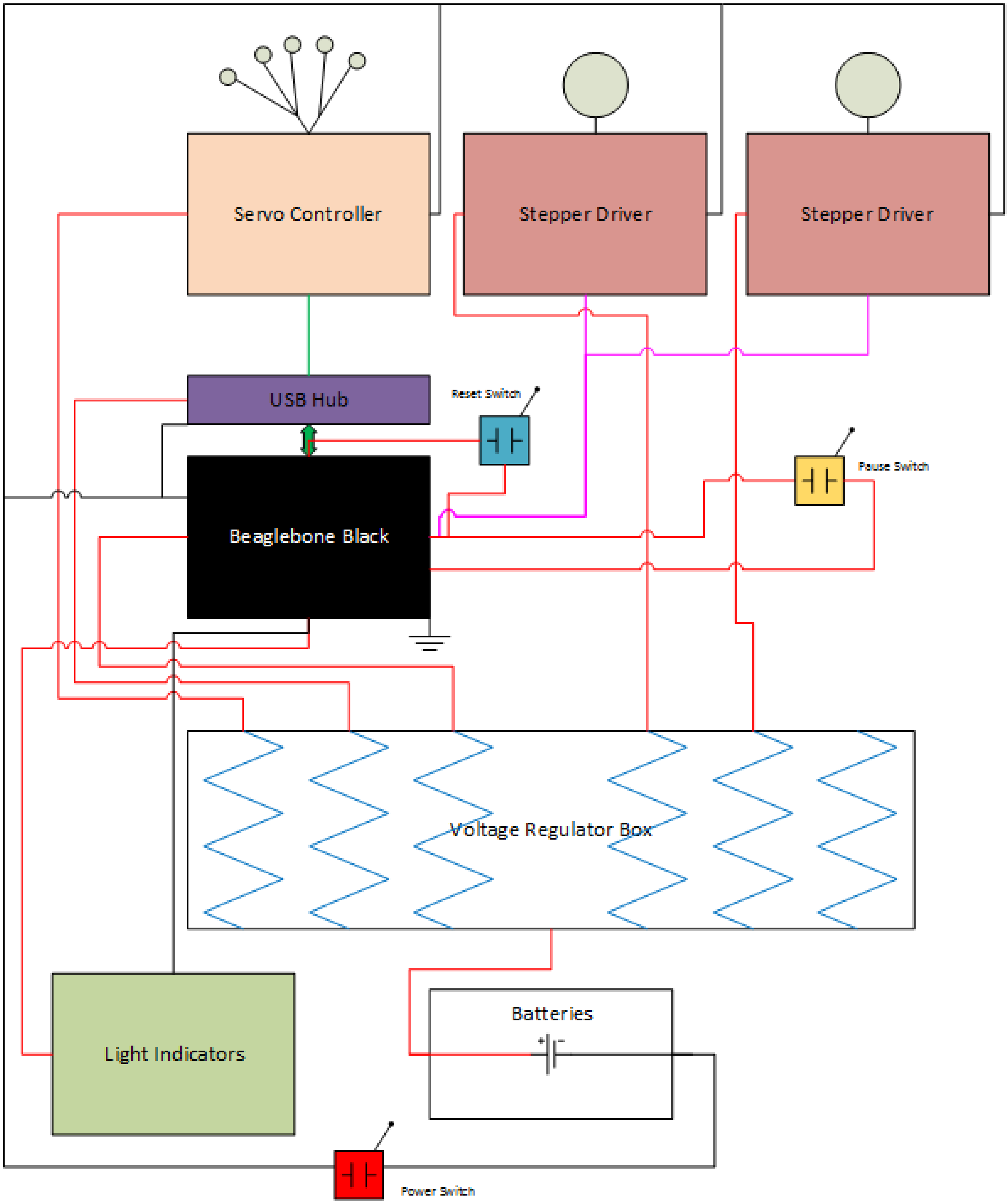



Figure 58 AGSE Electrical Diagram

The system will include both a master power switch (to supply and take away power for all systems of the AGSE), and a pause switch to pause all AGSE routines during system execution. A series of voltage regulators (Voltage Regulator Box) will be used to supply the correct voltages to all the subsystems. The power will be supplied by 37 V and 11.1 V lithium polymer batteries. The team will be using C and the

POSIX API to program the AGSE system. Light indicators will be used to indicate when the system is paused or un-paused.

### 4.1.7. Batteries/Power

As described above, the AGSE uses a 37 volt and an 11 volt battery to control all of the components. In order to provide the necessary voltage to the components, step down regulators of various sizes will also be used. These batteries will also be used to power the indicator lights that display when the system is paused and when all systems are go. For safety, the pause and master switches will control the power being delivered to the system.

### 4.1.8. Switch and Indicator Wattage and Location

As per the requirements, the AGSE will utilize a master switch and a pause switch that will be hardwired to the AGSE and easily accessible. The wattages will be clearly visible from the voltage regulator box.

### 4.1.9. Test Plans

Once the circuits are created, the continuity will be tested throughout the circuit to make sure that everything is connected correctly. The master and pause switches will also be tested to ensure that they perform their expected tasks. The indicator lights will also be connected for testing in order to confirm they operate as expected. Verifying their functionality prior to the experiment will help prevent a malfunction on the day of the competition that would potentially put the team or other personnel at risk.

### 4.1.10. Safety and Failure and Analysis

Any implications of failure in the electronic systems are adequately outlined in the FMECA diagrams in Appendix A. If the indicator lights fail, then the operators may be misinformed about the current state of the AGSE and may be put into danger when they approach the equipment. Furthermore, if the switches malfunction, then the AGSE will not be able to be paused if something were to go wrong. These situations must be avoided; therefore, care will be taken to adequately test the AGSE's electronic systems to make sure that the system can be operated safely.

## 4.2. AGSE Concept Features and Definition

### 4.2.1. Creativity and Originality

Although all of the individual subsystems have been done before in other projects, they are all put together in a way that makes the design unique. For example, the rocket will be raised for launch using a large gear system and the igniter will be inserted with a threaded rod system. These two systems provide an effective mechanical means of preparing the vehicle for launch without increasing the number of potential modes of failure inherent to a complex electrical system of motors and actuators.

### 4.2.2. Uniqueness or Significance

This AGSE design differs from others the team has seen in several aspects. First is the shape of the AGSE frame. In order to decrease the volume and weight while maintaining ease of assembly, the shape of the AGSE is that of a T. The AGSE is also utilizing a tripod leg design which will greatly reduce the possibility of tipping as three points always form a plane. The feet of the AGSE also have terrain-gripping spikes protruding from the bottoms to further improve stability and decrease the chance of tipping in high winds or shifting as the thrust of the rocket taking off acts on it.

### 4.2.3. Suitable Level of Challenge

The level of difficulty is high, as the team is attempting to retrieve the payload with an arm with five degrees of freedom. Because of how much the reach varies on the arm, programming and testing will be more difficult than it would if a simpler design were used, such as a crane.

The team is also attempting to cut the weight of the AGSE as much as possible while maintaining stability, which can lead to many problems on its own. While the team is reusing igniter insertion device and rocket raising system, it is still devising a new AGSE with new devices and ideas that increase the level of difficulty of the challenge.

## 4.3. Science Value

### 4.3.1. AGSE Objectives

The goal of the AGSE is to retrieve a sample and insert it into the rocket. On Mars, or any other distant body, a similar process will need to be done so that the soil sample can be processed on Earth. Therefore, the processes investigated in the AGSE portion of the project have a direct correlation to actual systems that can be used. Having a robotic arm obtain and secure the sample in the rocket is a feasible system. The AGSE must also erect the rocket into launch position 85 degrees from vertical and insert an igniter into the motor.

### 4.3.2. AGSE Success Criteria

The AGSE will be successful if it can identify, capture, and retain the sample. After these tasks have been completed, the vehicle will then be erected for launch. Success for the AGSE will only be obtained if these tasks are completed. Success with the AGSE will prove the viability of the system as a whole to be implemented in other tasks, such as missions to Mars.

### 4.3.3. Experimental Logic, Approach, and Method of Investigation

All of the experiments described above are physical tasks that will need to be completed by the team. By testing each of the crucial subsystems, overall success of the project can be ensured. It is important that all modes of failure are analyzed to account for any means of failure. Therefore, each test will be performed several times in order to collect sufficient data and prove the repeatability of the processes. It is important that viable data be obtained from each test so that the real system will work correctly. As such, each test will be approached as if performed for the actual competition. Improper testing would lead to inaccurate data and failure of the mission, detracting from the scientific value of the project.

### 4.3.4. Describe Test and Measurement

The data will be collected using accurate measurements, such as with digital calipers and a gram scale. As described above, the variables to be tested are the amounts of black powder needed, the accuracy of the robotic arm, and the force load of the motors erecting the rocket. Due to the fact that all of the tests are experimental in nature and are rated on a success/failure scale, control tests cannot be used to establish the baseline for the experiments.

### 4.3.5. Relevance of Expected Data

The data collected during the experiments will show if the current plan will work. The data is critical to the success of the project, and is thus relevant to the tasks at hand.

### 4.3.6. Experiment Process Procedures

As described above in Section 4.1.2, the experiments were carefully conducted so that accurate results could be obtained. Careful experimentation preserves the scientific value of the experiments and keeps the results indicative of the project. Each experiment followed the general guidelines of any scientific study; a problem was present that needed to be investigated or solved. Next, an experiment was formed that tested possible solutions to the problem or provide more insight into the issue. The experiments were designed to account for any issues that might arise and to test the capabilities of the design. The experiments were then carefully conducted so as to not corrupt the results and to preserve their legitimacy. The results were then analyzed to make sure that the initial requirements were met and that the data received was accurate. This process of experimentation is valid for any scientific study, and thus the experimental process procedures have scientific value.

# 5. Project Plan

## 5.1. Budget Plan

Table 18 Budget Plan

| Category | Supplier | Item | Amount | Total Price |
|---|---|---|---|---|
| **AGSE** | Digi-Key | BeagleBone Black | 1 | $45 |
| | Stepperonline | Leadshine M542 Stepper Motor Driver | 1 | $40 |
| | Stepperonline | Nema 17 Bipolar Stepper | 1 | $10 |
| | Stepperonline | Nema 23 Geared Stepper Motor | 1 | $60 |
| | RadioShack | 5mm-5mm Couplers | 1 | $5 |
| | RadioShack | USB Extension Cable | 1 | $2 |
| | RadioShack | USB Hub | 1 | $7 |
| | Thunder Power | Thunder Power 37 V Battery | 1 | $268 |
| | RadioShack | 12 V Step Down to 5V Power Module | 1 | $10 |
| | RadioShack | 2.1 mm Coax Power Plug | 1 | $5 |
| | RadioShack | 48V Step Down to 24V Power Module | 1 | $24 |
| | RadioShack | 12V Step Down to 6V Power Module | 1 | $10 |
| | Thunder Power | Thunder Power 12V Battery | 1 | $100 |
| | Digi-Key | Xtend Radio Units | 2 | $600 |
| | Metals Depot | 3/8" A573 Steel Plate | 2 sq ft | $48 |
| | Bertelkamp | 1515 Aluminum Railing | 36.25 ft | $248 |
| | Bertelkamp | 1010 Aluminum Railing | 8 ft | $18 |
| | Bertelkamp | 5/16-18 T-nut | 200 | $342 |
| | Bertelkamp | 1/4-20 T-nut | 50 | $92 |
| | Bertelkamp | 8020 Connectors | 58 | $288 |
| | Lynxmotion | Lynxmotion Servo Controller | 1 | $45 |
| | Lynxmotion | HS-7950TH Servo | 3 | $416 |
| | RobotShop | M100RAK V2 Modular Robotic Arm | 1 | $600 |
| | RobotShop | Gripper for Robotic Arm | 1 | $40 |
| | RadioShack | 22 Gage Servo Connector Wire | 100 ft | $32 |
| | Digi-Key | Molex lockable connectors and pins | 50 | $40 |
| | -- | Misc. Hardware | -- | $100 |
| | Lowes | 1/8" Balsa Wood Dowel | 1 | $1 |
| | Electronics-Salon | Crystal Oscillator | 2 | $25 |
| | Lowes | Threaded Rods | 3 ft | $21 |
| | OnlineMetals | Delrin Sheet 12"x12"x1/4" | 1 | $25 |
| | Sears | Ratchet Wrench | 2 | $40 |
| | | **AGSE Subtotal** | | **$3,607** |
| | | | | |

| | | | | |
|---|---|---|---|---|
| **Vehicle** | Apogee | 1010 Rail Buttons | 1 | $3 |
| | Apogee | 4" Diameter Nosecone | 1 | $65 |
| | Rocketry Warehouse | 4" Fiberglass Tubing | 7 ft | $158 |
| | Rocketry Warehouse | 4" Fiberglass Coupler | 2 | $62 |
| | Rocketry Warehouse | 38mm Fiberglass Tubing | 12 in | $14 |
| | Madcow Rocketry | 5.5" Diameter Nosecone | 1 | $115 |
| | Madcow Rocketry | 5.5" Fiberglass Coupler | 1 | $64 |
| | Madcow Rocketry | 5.5" Fiberglass Tubing | 8 ft | $330 |
| | Madcow Rocketry | 75mm Retainer | 1 | $44 |
| | West Marine | Epoxy and Hardener | 1 | $50 |
| | Askew Taylor | Aircraft Birch Plywood (1/8"x1'x2') | 10 | $63 |
| | Apogee | 1515 Rail Buttons | 1 | $5 |
| | Apogee | Entacore AIM 3.0 Altimeters | 2 | $200 |
| | Apogee | StratoLogger Altimeters | 2 | $160 |
| | Home Depot | Paint | -- | $30 |
| | BigRedBee | GPS Bee | 3 | $95 |
| | RadioShack | Wires | -- | $30 |
| | Fruity Chutes | Kevlar Shock Cord | 60 ft | $125 |
| | Fruity Chutes | 18" Elliptic Parachute | 1 | $58 |
| | Fruity Chutes | 48" Elliptic Parachute | 1 | $119 |
| | Fruity Chutes | 60" Irish Ultra Parachute | 1 | $180 |
| | Bass Pro Shop | Black Powder | 1 lb | $20 |
| | Performance Hobbies | RATTworks ARRD | 1 | $95 |
| | mentor | Igniters | 5 | $10 |
| | mentor | E-matches | 20 | $25 |
| | Rocketry Warehouse | 3" Fiberglass Tubing | 24 in | $40 |
| | mentor | 75mm Motor Casing | 1 | $100 |
| | mentor | 38mm Motor Casing | 1 | $65 |
| | ULINE | “Pick ‘n Pluck” Foam | 2 | $40 |
| | BuyRocketMotors | L1150R Motor | 2 | $320 |
| | Firgelli | Firgelli P16-50-22-12-P Linear Actuator | 1 | $45 |
| | Firgelli | Linear Actuator Control Board | 1 | $20 |
| | | **Vehicle Subtotal** | | **$2,750** |
| | | | | |
| **Other** | | Travel Expenses (hotel, rental car, gas) | 12 people | $3,000 |
| | | Incidentals (replacement tools, hardware, safety equipment | -- | $1,000 |
| | | Shipping Costs | | $750 |
| | | **Other Subtotal** | | **$4,750** |

| | | | | |
|---|---|---|---|---|
| | | | | |
| **Total** | | | | **$11,107** |
| | | | | |
| **Total of Final Product (Full-scale, AGSE)** | | | | **$5,699** |

## 5.2. Funding Plan

The original budget for the 2015-2016 year was largely based off of the NASA SL requirements from the previous year and previous awards from various sources. The current budget is a more refined version of the budget in the PDR, with more specific information on what funds the team will receive from our student organizations as well as more specific line items. The total budget is currently $10,506 which includes the full-scale competition rocket, AGSE, sub scale rocket and estimated travel expenses. The total amount that can be spent on the full-scale competition rocket and AGSE is $7,500.

Funding requests from the Engineering Council at NC State and the Student Government at NC State have been processed. The Engineering Council has granted the club $2,500 of the $4,500 that was requested. The Student Government denied the request for funding from the club. Funding from the Engineering Technology Fee Fund from the Mechanical and Aerospace Engineering Department and from Space Grant have also now been processed. The Engineering Technology Fee Fund provided the entire $2,000 that was expected and the NC Space Grant provide the entire $7,000 that was expected. This brings the total amount of funding the club has received to $11,500.

Table 19 Summary of Project Funding

| Funding Source | Amount Requested | Amount Received |
|---|---|---|
| NC State Engineering Council<br><br>Fall 2015<br><br>Spring 2016 | <br><br>$4500<br><br>$4500 | <br><br>$2500<br><br>$0 |
| Engineering Technology Fee Fund | $2000 | $2000 |
| North Carolina Space Grant | $7000 | $7000 |
| | | |
| Total | $20,000 | $11500 |

## 5.3. Timeline

Table 20 Timeline

| Event/Task | Start Date | Finish Date |
|---|---|---|
| **Completed CDR Submission** | 1/15/2016 | 1/15/2016 |
| **CDR Team Teleconference (Tentative)** | 1/19/2016 | 1/29/2016 |
| **Flight Readiness Review (FRR) Writing** | 1/16/2016 | 3/14/2016 |
| **Order Full-scale Rocket Parts** | 1/7/2016 | 1/14/2016 |
| **Construct Full-scale Rocket** | 1/21/2016 | 2/5/2016 |
| **Full-scale Ground Testing** | 2/11/2016 | 2/11/2016 |
| **Order AGSE Parts** | 11/16/2015 | 1/15/2016 |
| **Full-scale Launch (Tentative)** | 2/27/2016 | 2/27/2016 |
| **Completed FRR Submission** | 3/14/2016 | 3/14/2016 |
| **FRR Team Teleconference (Tentative)** | 3/17/2016 | 3/30/2016 |
| **Team Travel to Huntsville, Alabama** | 4/13/2016 | 4/13/2016 |
| **Launch Readiness Review (LRR)** | 4/13/2016 | 4/14/2016 |
| **NASA Safety Briefing** | 4/14/2016 | 4/14/2016 |
| **Rocket Fair and Tours of MSFC** | 4/15/2016 | 4/15/2016 |
| **Launch Day** | 4/16/2016 | 4/16/2016 |
| **Backup Launch Day** | 4/17/2016 | 4/17/2016 |
| **Post-Launch Assessment Review** | 4/29/2016 | 4/29/2016 |
| **Winning Team Announced by NASA** | 5/11/2016 | 5/11/2016 |

## 5.4. Educational Engagement Plan and Status

**Event: STEM Career Fair for Students with Disabilities**

Location: North Carolina Museum of Natural Sciences, Raleigh, NC 27601

When: Friday, October 9th from 11am to 2pm

Andrew M. and John I. represented the High-Powered Rocketry Club at a special career fair designed to aid students with physical and learning disabilities find support from local organizations and individuals who are successful in their field. Andrew and John spoke with many of these students about the opportunities available to them in various fields of engineering as well as courses offered at NC State University. The members brought several static displays of previous competition rockets to better explain how the rockets worked and to talk about the NASA Student Launch competition.

**Presentation to NC-MSEN PCP Middle School Students**

Location: Centennial Campus Magnet Middle School, Raleigh, NC 27607

When: Wednesday, December 16th from 2:30pm to 5pm

Several members from the High-Powered Rocketry Club travelled to the Centennial Campus Magnet Middle School (CCMMS) to visit an afterschool program as part of the North Carolina Mathematics and Science Education Network Pre-College Program (NC-MSEN PCP). This program is designed to prepare "underserved students at the middle and high school levels for careers in STEM." The team gave a prepared a presentation with information regarding engineering at NC State University, NASA SL & Centennial Challenges, basic rocket physics, rocket design considerations, and comparing the physics of water bottle rockets to high-powered rockets. Following the presentation, the students were able to ask the team an extensive amount of questions regarding rocketry before building their own water bottle rockets. Members from the club were able to help students design their water bottle rockets for a future launch. The afterschool teacher was very impressed with the team's presentation and we have been discussing another future visit during the Spring semester.

**Event: Lacy Elementary School STEM Night**

Location: Lacy Elementary School, Raleigh, NC 27607

When: Thursday, January 14th, 5pm to 7:30pm

Members of the High-Powered Rocketry Club will attend the Lacy Elementary School STEM night to give a presentation on high-powered rocketry, NASA SL & Centennial Challenges, and engineering at NC State University. The team will also have a booth set up during the event featuring static displays of previous competition rockets along with posters describing high-powered rocketry design and flight. Team members will also bring club promotional materials (stickers, pens, etc.) for the students who visit the booth to help advertise the club amongst younger students.

**Event: Astronomy Days**

Location: North Carolina Museum of Natural Sciences, Raleigh NC 27601

When: January 30th and 31st, 2016

The High-Powered Rocketry Club will have a booth at the NC Museum of Natural Sciences' Astronomy Days event to inform visitors about the club, high-powered rocketry, NASA SL & Centennial Challenges, and engineering at NC State University. The booth will feature static displays of previous competition rockets along with posters describing high-powered rocketry design and flight.

**Event: Thales Academy Rocket Unit Kick-Off**

Locations: Thales Academy 1201 Granite Falls Blvd, Rolesville, NC 2757 &

Thales Academy 1177 Ambergate Station, Apex, NC 27502

When: TBD

Some members of the High-Powered Rocketry Club will travel to both Thales Academy high schools in the Rolesville and Apex areas to discuss high-powered rocketry and aerospace engineering concepts with the students. Some topics that will be discussed include thrust, drag, stability, and recovery systems on both high-powered rockets and water bottle rockets. Team members will then lead the students in the design and construction of water bottle rockets for launch during the same day. Communication with the Thales Academy Director of Development is ongoing to determine a time and date for each visit.

**Event: YMCA Kite and Rocket Day**

Location: Carter Finley Stadium, 4600 Trinity Rd., Raleigh, NC 27607

When: March 8th, 2016

The High-Powered Rocketry Club intends to continue its tradition of being an integral part of the local YMCA Kite and Rocket Day event which will occur sometime during the Spring semester. Team members will set up an informational booth at Carter-Finley Stadium to assist young rocketeers with assembling and launching their model rockets. Last year's event had over 200 student attendees with even more predicted to attend this year's event. Communication with YMCA representatives is ongoing to determine a time and date for the event.

**Event: Sigma Gamma Tau Boy Scout Merit Badge Event**

Location: NC State Centennial Campus, Raleigh, NC 27695

When: TBD March

The High-Powered Rocketry Club is planning to partner with NC State's chapter of Sigma Gamma Tau in hosting the annual Boy Scout Merit Badge Event during the Spring semester of 2016. The event will begin with a model rocket launch and recovery for the enjoyment of the Scouts and their families. The Scouts are then shown a presentation by members of Sigma Gamma Tau before receiving their Space Exploration badges. This event will take place on NC State's Centennial Campus and usually involves 30-40 Boy Scouts and their families. The details of this event will be finalized in the coming weeks.

# 6. Conclusion

With the conclusion of the CDR, the NC State Rocketry Team, Tacho Lycos, will move ahead with the fabrication of the full-scale launch vehicle and STORM.

## Appendix A Milestone Review Flysheet

# Milestone Review Flysheet

| Institution | North Carolina State University | Milestone | CDR |
|---|---|---|---|

| Vehicle Properties | |
|---|---|
| Total Length (in) | 102 |
| Diameter (in) | 5.5 |
| Gross Lift Off Weigh (lb) | 29.3 |
| Airframe Material | Fiberglass |
| Fin Material | Birch Aircraft Plywood |
| Drag Coeffficient | 0.385 |

| Motor Properties | |
|---|---|
| Motor Manufacturer | AeroTech |
| Motor Designation | L1150R |
| Max/Average Thrust (lb) | 302.6 / 258.3 |
| Total Impulse (lbf-s) | 790.6 |
| Mass Before/After Burn (lb) | 8.10 / 3.91 |
| Liftoff Thrust (lb) | 218.3 |

| Stability Analysis | |
|---|---|
| Center of Pressure (in from nose) | 76.3 |
| Center of Gravity (in from nose) | 64.3 |
| Static Stability Margin | 2.18 |
| Static Stability Margin (off launch rail) | 2.25 |
| Thrust-to-Weight Ratio | 8.816 : 1 |
| Rail Size and Length (in) | 1.5 x 1.5 x 101 |
| Rail Exit Velocity | 63 |

| Ascent Analysis | |
|---|---|
| Maximum Veloxity (ft/s) | 745 |
| Maximum Mach Number | 0.662 |
| Maximum Acceleration (ft/s^2) | 300 |
| Target Apogee (From Simulations) | 5569 |
| Stable Velocity (ft/s) | 63 |
| Distance to Stable Velocity (ft) | 3.71 |

| Recovery System Properties | | | | |
|---|---|---|---|---|
| Dogue Parachute | | | | |
| Manufacturer/Model | FruityChutes | | | |
| Size | 18 | | | |
| Altitude at Deployment (ft) | 5280 | | | |
| Velocity at Deployment (ft/s) | 1.9 | | | |
| Terminal Velocity (ft/s) | 85.4 | | | |
| Recovery Harness Material | Kevlar | | | |
| Harness Size/Thickness (in) | 0.5 | | | |
| Recovery Harness Length (ft) | 25 | | | |
| Harness/Airframe Interfaces | ARRD and U-bolt with quick link | | | |
| Kinetic Energy of Each Section (Ft-lbs) | Section 1 | Section 2 | Section 3 | Section 4 |
| | 2,666 | | | |

| Recovery System Properties | | | | |
|---|---|---|---|---|
| Main Parachute | | | | |
| Manufacturer/Model | FruityChutes | | | |
| Size | 48 | 60 | | |
| Altitude at Deployment (ft) | 1000 | 700 | | |
| Velocity at Deployment (ft/s) | 88.2 | 65.9 | | |
| Terminal Velocity (ft/s) | 27 | 16.6 | | |
| Recovery Harness Material | Kevlar | | | |
| Harness Size/Thickness (in) | 0.5 | | | |
| Recovery Harness Length (ft) | 16 | | | |
| Harness/Airframe Interfaces | U-bolt with quick link | | | |
| Kinetic Energy of Each Section (Ft-lbs) | Section 1 | Section 2 | Section 3 | Section 4 |
| | 60.2 | 60.7 | | |

| Recovery Electonics | |
|---|---|
| Altimeter(s)/Timer(s) (Make/Model) | Perfectflite Stratologger SL100 |
| Redundancy Plan | Apogee charges will have a 1 s delay. Main redundant charge will be programmed for 600 ft AGL at 125% primary charge size. |
| Pad Stay Time (Launch Configuration) | 1 hour |

| Recovery Electonics | |
|---|---|
| Rocket Locators (Make/Model) | Big Red Bee GPS Locator (2) |
| Transmitting Frequencies | 900 MHz on Channel 128 |
| Black Powder Mass Drogue Chute (grams) | 1.8 |
| Black Powder Mass Main Chute (grams) | 2.3 (top) / 2.1 (bottom) |

## Milestone Review Flysheet

| Institution | North Carolina State University | Milestone | CDR |
|---|---|---|---|

| Autonomous Ground Support Equipment (MAV Teams Only) | |
|---|---|
| | Overview |
| Capture Mechanism | A crafted robotic arm based on a previously purchased robotic arm kit with different servos and gears will move the gripper to a predetermined point above the sample and then the gripper will engage to capture the sample. |
| | Overview |
| Container Mechanism | The robotic arm will carefully insert the sample into the pick and pluck foam padded payload bay, attached to the avionics sled bay in the payload compartment. This will secure the sample on three sides. The arm will then close the door to seal the payload bay and a section of foam on the inside wall of the door will fully secure the sample. |
| | Overview |
| Launch Rail Mechanism | The launch rail will be raised by a planetary geared steppermotor. While being raised, the rail will be supported by a double ratchet system in case of a loss of power. The gearing ratio between the sector gear and the driver gear will be 8:1. |
| | Overview |
| Igniter Installation Mechanism | A stepper motor powered linear actuator will raise the electric match igniter into the rocket on a wooden dowel by rotating a threaded rod which drivese a delrin plate that the dowel rests on. |

| Payload | |
|---|---|
| | Overview |
| Payload 1 | The MAV challenge sample. The payload will be made of .75 x 3 inch PVC tubing filled with sand and weigh approximately 4 oz. The payload will be a cylindrical shape with a .75 inch diameter and a 4.75 in length. Ends of the tubing will be secured with domed PVC caps. |
| Payload 2 | Overview |

| | |
|---|---|
| | |

| Test Plans, Status, and Results | |
|---|---|
| Ejection Charge Tests | Ejection charges will be sized for each of the compartments to be separated. Charges will be constructed with black powder in a PVC cap with an E-match secured in the cap using paper wadding and tape. Charge ignition for main and drogue charges are capable of being separately fired at the user's input. Both charges are attached to the wire leads of a switch that fires the charges when activated. If the test is a failure, analysis will be conducted to find the cause of the failure with new tests to follow. |
| Sub-scale Test Flights | The subscale flight test took place on November 28, 2015. The subscale rocket was overly stable which led to weather cocking and an apogee that was signifcantly lower than expected. Despite that, the drogue successfully deployed at apogee and the main deployed at 700 feet as planned. |
| Full-scale Test Flights | The full scale flight test is planned to take place on February 27th at the TRA launch site in Bayboro, NC. Parts have been ordered and construction will commence after completion of the CDR. |

## Milestone Review Flysheet

| Institution | North Carolina State University | Milestone | CDR |
|---|---|---|---|

| Additional Comments |
|---|
| |

Appendix B Failure Mode Effects and Criticality Analysis

| Function / Component | Failure Mode | Causal Factors | Failure Effects | | Hazard | Recommendations | Verification |
|---|---|---|---|---|---|---|---|
| | | | Subsystem | System | | | |
| Robotic Arm Electrical System | Wires Twisted | Careless/messy wiring. Tangled wires because of poor or no planning | This could cause the robotic arm to cease functionality which means that the payload is not retrieved | The payload would not be stored in the rocket, but the rocket would still be able to launch | 2 | Make sure that wires are laid out cleanly in a manner that allows for easy identification and replacement | Look to ensure that wires are properly organized |
| | Bad Servo Motor(s) | Manufacture Defect, Motor burns out due to power or programming issues | | | 2 | Make sure that servos are tested thoroughly to ensure that it is free of any manufacturer defects. Also take care to not supply too much voltage/amperage to the servos | Servos thoroughly tested prior to use as part of the AGSE |
| | Loss of Power | Poor connection or bad battery | | | 2 | Make sure that all batteries are fully charged and that wires are securely attached | The LiPo batteries used will be charged the day before |
| | Bad Programming | Careless programming of the subsystem, or no testing is done | | | 2 | Ensure that all code is tested thoroughly to minimize the risk of programmer error | Code will be locked down once the mission goals are met, to prevent any corruption. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Rocket Erector | Wires Twisted | Careless/messy wiring. Tangled wires because of poor or no planning | This could cause the erection system to fall or not get the rocket up to the proper launching angle | The rocket may not be able to launch, and it could cause damage to the entire AGSE and Rocket system | 2 | Make sure that wires are laid out cleanly in a manner that allows for easy identification and replacement | Look to ensure that wires are properly organized |
| | Stepper Motor Failure | Manufacture Defect, Motor burns out due to power or programming issues | | | 1 | Make sure that the stepper motor is tested thoroughly to ensure that it is free of any manufacturer defects. Also take care to not supply too much voltage/amperage to the motor | Testing of the stepper motor prior to integration with the AGSE. |
| | Loss of Power | Poor connection or bad battery | | | 1 | Make sure that all batteries are fully charged and that wires are securely attached | Look to ensure that wires are properly organized |
| | Bad Programming | Careless programming of the subsystem, or no testing is done | | | 2 | Ensure that all code is tested thoroughly to minimize the risk of programmer error | Code will be locked down once the mission goals are met, to prevent any corruption. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Igniter Inserter | Wires Twisted | Careless/messy wiring. Tangled wires because of poor or no planning | This would prevent the igniter from being inserted into the rocket | The rocket may not be able to launch, because the motor will not be able to launch without a functioning igniter | 2 | Make sure that wires are laid out cleanly in a manner that allows for easy identification and replacement | Look to ensure that wires are properly organized |
| | Stepper Motor Failure | Manufacture Defect, Motor burns out due to power or programming issues | | | 1 | Make sure that the stepper motor is tested thoroughly to ensure that it is free of any manufacturer defects. Also take care to not supply too much voltage/amperage to the motor | The stepper motor will be tested the day before competition to ensure that it works properly |
| | Loss of Power | Power is disconnected from subsystem because of bad connections or faulty batteries | | | 1 | Make sure that all batteries are fully charged and that wires are securely attached | Look to ensure that wires are properly organized and use of fresh, unopened batteries for launch day. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Bad Programmin g | Careless programming of the subsystem, or no testing is done | | | 2 | Ensure that all code is tested thoroughly to minimize the risk of programmer error | Code will be locked down once the mission goals are met, to prevent any corruption. |
| Beaglebo ne (System Computer ) | Loss of power | Poor connection or bad battery | This would halt all AGSE subsystems | The AGSE would not be able to perform its mission and the rocket would not be able to launch | 2 | Make sure that all batteries are fully charged and that wires are securely attached | Look to ensure that wires are properly organized and use of fresh, unopened batteries for launch day. |
| | Shorting out | Incorrect amount of power is supplied to the computer | | | 1 | Ensure that the correct voltage regulators are always between the power source and the computer | The voltage regulators in place between the power source and computer will be checked prior to powering the system on |
| | Program Malfunction | Careless programming of the subsystem, or no testing is done | | | 1 or 2 | Ensure that all code is tested thoroughly to minimize the risk of programmer error | Code will be locked down once the mission goals are met, to prevent any corruption. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Bad Wiring | Inputs and outputs are connected to the incorrect ports on the computer | | | 2 | Make sure that all wiring is connected properly and follows the diagram that was computed prior to wiring | Look to ensure that wires are properly organized |
| Crystal Oscillator | Incorrect Oscillation Rate | Oscillation output is not measured with an oscilloscope | This would cause improper functionality of the Erector and Igniter subsystems | The AGSE would may not be able to erect the rocket to the correct launching angle, and/or it may not be able to insert the igniter | 2 | Use an oscilloscope to make sure we are getting the desired oscillation outputs for the designated stepper motor | Before wiring the oscillator into the stepper motor it will be adjusted using an oscilloscope to the desired frequency |
| | Shorting out | Incorrect amount of power is supplied to the device | | | 1 | Ensure that the correct voltage regulators are always between the power source and the computer | The voltage regulators in place between the power source and computer will be checked prior to powering the system on |
| Robotic Arm Structure | Gripper misses target payload | Arm gears aren't aligned on AGSE base | Payload will not be retrieved nor stored within the rocket | The payload will not be stored in the rocket, but the rocket will still be able to launch | 3 | Calibrate the system on a regular basis and ensure that the gears are mounted squarely | The arm will be inspected prior to operation to ensure that the gears are properly aligned |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Gear Damage | Debris in gears due to incomplete inspection | Arm will not move to the correct position and payload will not be retrieved nor stored within the rocket | | 2 | Check gears before and after each use to ensure that teeth are not blocked by debris or dull from previous use | The gears will be inspected prior to each operation of the arm to check the gears for wear or a buildup of debris. If the gears have become so worn that they are no longer fit for operation they will be replaced |
| | | Dull gears after continued use | | | 2 | | |
| | Support tubes break | Improper handling of equipment | The robotic arm will be rendered useless and the payload will not be retrieved nor stored within the rocket | | 1 | Teach members proper handling procedure for robotic arm and other associated equipment | Support tubes will be inspected before arm operation to check for bending or cracking. If damage is found the tubes will be replaced |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Servos burn out | Improper use. (i.e. Hyper-extension, or excess voltage) | | | 1 | Check the limits for the servos before applying any loads | Proper testing of the servos and inspection of servos before use |
| | Faulty Equipment | Dull Gears | | | 3 | Check equipment after shipping to ensure correct dimensions and no visible damage | The gears, servos, support tubes and gripper will be inspected after each operation to check for signs of wear. |
| | | Faulty wiring | | | 2 | | |
| | | Manufacturing Defects | | | 2 | | |
| | Damage occurred during transit | Improper handling | | | 3 | Teach member proper handling and storage procedures for transporting the robotic arm | A senior member will oversee the handling and packaging of the robot arm on its way to competition and ensure that sufficient measures are taken to prevent damage |
| | | Insufficient packing | | | 3 | | |
| Erection System | Gearing | Gear damage | Motor will be unable to raise the rocket | Rocket will not be able to launch if not erected to 5 degrees from vertical | 1 | Fabricate both gears with the same thickness and same teeth depth | Proper testing of gears before being integrated with the AGSE |
| | | Gear slipping | | | 1 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Debris in gears due to incomplete inspection | | | 1 | Ensure that gear teeth are clear before operation | The teeth of the gear will be inspected before each erection to remove any debris that may have accumulated |
| | Ratchet | Ratchet jams due to improper alignment | Erection system will stop moving | | 1 | Ensure proper alignment of erection system on AGSE base | The ratchet will be inspected before erection to make sure that it is properly aligned |
| | | Ratchet weld fails | Rocket and rail will fall with no support | | 1 | Check for cracks in welding before each run | The ratchet welds will be inspected before each erection |
| | | Incorrect direction of ratcheting | Erection system does not move | | 1 | Check the direction of ratcheting before each run | The correct direction of ratcheting will be set prior to operation of the erection system |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Motor | Over torqued | Motor will be unable to raise the rocket and permanent damage may occur | | 1 | Ensure that motor selection includes a factor of safety for applied torque greater than 1.0 | Care will be taken so that no accidental overloading occurs and that the motor is only used in the intended manner |
| Leg Failure | Legs fall or break off | Screws come loose | Legs fall off of the AGSE | The AGSE topples and can't launch the rocket | 2 | Check that screws are tight before use | The AGSE will be agitated prior to loading the rocket to check for any loose screws |
| | | Manufacturing defect | Structural instability in the legs | | 2 | Check the parts before assembling | All parts will be fully inspected after they are received and any defective parts will not be used |
| | | Damage occurred during transit due to improper packaging or handling | | | 2 | Check equipment after shipping to ensure no visible damage | All parts will be fully inspected after transit |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Blast Plate | Rocket emissions are reflected back at the rocket | Plate is angled incorrectly | Reflected emissions could ignite the motor unevenly before it leaves the launch rail | Structural damage can occur which may result in a catastrophic failure | 1 | Check the angle of the plate before use | A visual inspection of the blast plate will be made when the system is fully erected without the rocket in place and any angular changes that need to be made will be noted and the plate will be adjusted |
| Igniter Insertion System | Dowel rod fails | Dowel breaks | Motor fails to ignite | System requires human intervention to launch | 2 | Test dowels prior to implementation | The dowel will be tested to make sure it can take the loading. Prior to insertion the dowel will be checked for damages |
| | | Dowel improper size | | | 2 | Ensure dimensions are correct on equipment and test igniter action before launch | The dowel will be measured and mounted such that will not scrape the propellant on the inside of the rocket motor and will properly insert the igniter |
| | | Dowel scrapes propellant | | | 2 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | No ignition | Igniter is not fully inserted into motor | | | 2 | Make sure igniter is secure on the rail | The igniter will be agitated prior to insertion to ensure it is secured on the rail. |
| | | Bad igniter | | | 3 | Ensure that igniters have been stored properly and are visually undamaged | The igniter will be checked for damage prior to insertion |
| | | Electrical short in wiring | | | 2 | Ensure that no damage to the wiring has occurred via visual inspection | The wiring will be inspected for fraying or other damage prior to insertion |
| Batteries | Insufficient Power | System loses power during operation because of uncharged or insufficiently charged batteries | Loss of system power will halt all launch operations | Loss of system power supply will halt all launch operations | 2 | Check charge of battery at least 12 hours prior to operation | The batteries will be charged prior to competition and tested at least 12 hours prior to operation |
| | Leaking | Battery will be rendered useless | | | 1 | Teach members safe handling and storage techniques for the batteries | Batteries will be visually inspected for cracks and leaking before the batteries are attached to the system |
| | | Permanent damage to environment or equipment | | | 1 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Damage occurred during transit | Insufficient packing | Battery will be rendered useless | | 3 | Use a padded envelope to store batteries during transit | Batteries will be carefully packaged and transported to competition in padded pouches |
| AGSE Stability | Instability during rocket erection or launch | Imbalanced AGSE | AGSE topples before or during erection | Launch platform instability could result in damage to the rocket or AGSE during rocket erection and launch | 2 | Using hand levels to orient the AGSE with no tilt | The AGSE will be adjusted for tilt before operation of any of its systems. |
| | | Strong winds | | | 3 | Monitoring weather conditions prior to launch to ensure that the wind is within limits | The AGSE has cleated legs that allow for additional lateral support for launches in high winds |
| | | Set up on an inclined surface | | | 4 | Cleated legs for extra grip on surface | The ground will be visually inspected and the AGSE will be set up on a flat surface |
| Black Powder Charges | Failure to Ignite | E-Match doesn't light | First ejection charge does not ignite | Rocket fails to separate and deploy parachute(s) | 4 | Conduct ground tests to ensure that enough black powder will be used for proper separation. Thoroughly check redundant systems prior to launch | Ground testing will be done with the fully assembled full scale rocket to check the wiring and design of the ejection charge system. |
| | | Altimeter Malfunction | | | 4 | | |
| | | Improper Programming | | | 4 | | |
| | Redundant black powder fails to ignite | E-Match doesn't light | Failure of both ejection charges | | 1 | | |
| | | Altimeter Malfunction | | | 1 | | |
| | | Improper Programming | | | 1 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Violent ejection causes accidental separation | Charge is too big | Causes violent separation and/or damage to surrounding area | Could cause damage to bulkheads or shock-cord, resulting in a possible failure of parachute deployment | 1 | Verify that charges are sealed properly and the correct amount of black powder using pre-flight checklists | Test black powder charges using static tests to ensure that the black powder is the proper amount |
| Avionics (altimeters) | No power to avionics or charges | Uncharged or insufficiently charged batteries | Loss of real-time altitude data | Failure of parachute deployment | 1 | Begin charging batteries at least 12 hours prior to launch, and ensure all batteries have the correct voltage before flight | Step 32 of section 3.6.1 |
| | Faulty Altimeter | Manufacturer defect | No ejection or premature/late ejection | | 1 | | Testing to ensure the altimeters are in working condition |
| BigRedBee (GPS) | Ground System Failure | Loss of power to ground receiver or the laptop | In ability receive data from the GPS | Inability to track and recover the rocket (in a reasonable amount of time) | 3 | Make sure that the receiver and laptop are fully charged at least 6 hours prior to flight | Charge the receiver and the laptop the night before any launch. |
| | Loss of signal | Environment or rocket materials blocking signal | | | 3 | Perform range tests to ensure reliability of the system at simulated altitudes and ground distances | Test the GPS prior to integrating with launch vehicle and ensure its reliability. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Radio Interference | Multiple radio devices on the same local frequency and channel | | | 3 | Make sure that all transmitting devices are on separate channels and confirm with other teams and launch officials that no frequency conflict exists | Coordinate with NASA to ensure selected frequency is free of conflicted transmissions |
| | Loss of power | Flight forces cause GPS to disconnect from power supply | | | 3 | Make sure all GPS units are fully charged and use simulated load tests to determine the necessary procedures to secure the units | GPS units will be test loaded similarly to how they will be during the launch. |
| Airbrakes and Telemetry | Arduino Failure | Loss of power, damage during flight, severed data connection, bad altitude readings | Failed deployment of one or both airbrake flap s | Failure of airbrakes may cause the rocket to break the altitude goal | 4 | Take steps to ensure that all system components are properly seated to prevent any shifting during flight. Ensure that all wires are connected properly and that batteries are fully charged prior to launch | The electronics that operate the airbrakes will be test loaded to similar loads as they will experience during flight. All wired connections will be tested and all electronics will be properly secured to the airframe. |
| | Altimeter Connection Failure | | | | 4 | | |
| | Datalogger Failure | | | | 4 | | |
| | GPS Failure | | | | 4 | | |
| | Radio Failure | | | | 4 | | |
| | Linear Actuator Failure | | | | 4 | | |

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| Fiberglass Airframe | Cracks or Breaks | Manufacturing Defect | Structural integrity of fiberglass sections at risk | Possible premature separation of rocket segments or rapid unscheduled disassembly during flight | 1 | Visual inspection after shipping before any structural implementation | Ensure the fiberglass doesn't have any cracks before constructing the launch vehicle |
| | | Experienced loads beyond design specifications | | | 1 | Implement a safety factor greater than 1.0 to ensure that flight conditions do not exceed design specifications | Thoroughly test the limits that the airframe will face in flight and ensure a safety factor greater than 1.0 |
| | | Damaged during handling | | | 1 | Team members will be taught proper handling procedures for body tubing and the assembled rockets | Only team members who have been trained will handle the fiberglass airframe |
| | | Improper maintenance | | | 1 | Thorough pre- and post-launch inspections of body tubing | Airframe will be checked before each launch and after recovery of the rocket. |

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|---|---|---|---|---|---|---|---|
| Bulkheads | Separation of bulkhead from airframe during flight | Manufacturing Defect | Structural integrity of rocket segments at risk | Possible premature separation of rocket segments, rapid disassembly of rocket, or recovery system failure during descent | 1 | Visual inspection after completing construction before any implementation | Bulkheads will be inspected for damage before construction starts |
| | | Loads beyond design specifications | | | 1 | Implement a safety factor to ensure that flight conditions do not exceed design specifications | Bulkheads will be designed such that their critical load is greater than their expected load. |
| | | Damaged during handling due to improper handling techniques | | | 1 | Team members will be taught proper handling and installation procedures for bulkheads | Care will be taken such that the bulkheads are not damaged due to negligence or carelessness |
| | | Improper maintenance | | | 1 | Thorough pre- and post-launch inspections of bulkheads | Bulkheads will be inspected for damage before and after each assembly of the rocket |

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| | Parachute and bulkhead separation during flight | Loads beyond design specifications | Without an attached parachute, a rocket segment could be free to free fall | Loss of recovery system will result in mission failure and can cause harm to ground crew | 1 | Implement a safety factor to ensure that flight conditions do not exceed design specifications | Bulkheads will be designed such that their critical load is greater than their expected load. |
| | | Improper maintenance | | | 1 | Thorough pre- and post-launch inspections of bulkheads | Bulkheads will be inspected for damage before and after each assembly of the rocket |
| | Non-compromising cracks | Loads beyond design specifications | Present potential for further damage to bulkhead | If left unnoticed, a small crack can expand during flight which may result in bulkhead failure | 3 | Implement a safety factor to ensure that flight conditions do not exceed design specifications | Bulkheads will be designed such that their critical load is greater than their expected load. |
| | | Damaged during handling due to improper handling techniques | | | 3 | Adhere to proper handling procedure | Care will be taken such that the bulkheads are not damaged due to negligence or carelessness |

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| | | Improper maintenance | | | 3 | Thorough pre- and post-launch inspections of bulkheads | Bulkheads will be inspected for damage before and after each assembly of the rocket. If the crack is seen to increase in width or propagate the bulkhead will be replaced |
| Fins | Surface damage | Loads beyond design specifications | Damage to fin will necessitate its replacement before any future launches | Fin failure during flight will decrease stability of rocket and will likely cause a catastrophic failure | 1 | Implement a safety factor to ensure that flight conditions do not exceed design specifications | The fins have been designed such that they will not experience delamination or flutter under the expected load conditions |
| | | Damaged during handling due to improper handling techniques | | | 1 | Team members will be taught proper handling procedures for fins and fin section | Care will be taken such that the fins are not damaged due to negligence or carelessness |

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| | | Improper maintenance | | | 1 | Pre- and post-launch thorough inspections of the fins | The fins will be inspected after the fin section is handled to check for damage |
| | | Ground impact | | | 2 | Implement a recovery system design that ensures a low speed surface impact | Proper calculations and testing of the recovery systems |
| | Fin flutter | Loads beyond design specifications | Loss of fin subsystem effectivenes s | Decreased flight stability, and possible damage to other components | 4 | Maintain operations within design specification s | Proper modelling of stresses in flight and ensure the fin's strength allows for a safety factor greater than 1.0 |
| | | Damaged during handling due to improper handling techniques | | | 4 | Adhere to proper handling procedure | All team members who handle the fins shall be properly trained |
| | | Improper maintenance | | | 4 | Pre- and post-launch thorough inspections of the fins | Ensure the fins are not damaged in any way as a result of launches or transit. |

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| Shear Pins | Pins break before charge detonation | Manufacturing Defect | Loose assembly of compartment | Separation of vehicle compartments | 2 | Visual inspection after shipping before any implementation | Step 54 of section 3.6.1 |
| | | Loads beyond design specifications | | | 2 | Maintain vehicle within design specifications | Proper selection of shear pins based on weight and size of vehicle |
| | | Improper maintenance | | | 2 | Use of new pins after each launch | Step 54 of section 3.6.1 |
| | Pins don't break at charge detonation | Manufacturing Defect | Failure to separate | Loss of safe and effective recovery system | 1 | Pre-launch visual inspection of shear pins | Step 54 of section 3.6.1 |
| | | Poor Design | | | 1 | Proper calculation of the force exerted on the pins during detonation | Testing of shear pins during static testing of separation of sections |
| Avionics Sled | Detaches from secured position | Loads beyond design specifications | Damage to/loose wiring of avionics components | Loss of recovery system initiation | 1 | Use simulations to test max load before failure | Run proper simulations to ensure the tests are accurate to conditions on launch of the vehicle |

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| | | Damaged during handling due to improper handling techniques | | | 1 | Team members will be taught proper handling and installation procedures for the avionics sled | Only team members who have been trained will be handling the avionics sled |
| | | Improper maintenance | | | 1 | Pre- and post-launch thorough inspections of the avionics sled | Prior to any launch and following each launch, an inspection of the avionics bay will be done |
| Nosecone | Non-compromising cracks | Loads beyond design specifications | Potential for future damage | If left unattended this could lead to catastrophic failure of the entire system | 3 | Use simulations to test max load before failure | The nosecone has been certified to be able to withstand the expected loading case of the launch and recovery. |

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| | | Damaged during handling due to improper handling techniques | | | 3 | Team members will be taught proper handling and installation procedures for nosecone | Care will be taken such that the nosecone will not be subjected to unnecessary loading due to improper use |
| | | Improper maintenance | | | 3 | Pre- and post-launch thorough inspections of the nosecone | The nosecone will be inspected before and after each launch to check for cracks |
| | Damage from impact | Loads beyond design specifications | Loss of future nosecone use | If left unattended this could lead to catastrophic failure of the entire system | 2 | Visual inspection of nosecone after shipping before any implementation | The nosecone will be inspected before and after each launch to check for cracks |
| | | Damaged during handling due to improper handling techniques | | | 2 | Team members will be taught proper handling and installation procedures for the nosecone | |
| | | Improper maintenance | | | 2 | Pre- and post-launch thorough inspections of nosecone | |

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| | Premature separation from other structural members | Damaged during handling due to improper handling techniques | Potential for structural damage | Loss of controlled and stabilized flight | 2 | Team members will be taught proper handling and installation procedures for the nosecone | The nosecone will be handled in a manner such that it will not be dented or otherwise damaged in between launches |
| | | Improper maintenance | | | 2 | Pre- and post-launch thorough inspections of the nosecone | |
| Airbrakes | Asymmetric Engagement | Rod fails | One airbrake eng ages, the other remains stowed | Unstable flight that could lead to catastrophic failure | 1 | Test the rods to find max load capacity | The push rod will be tested to find its deflection under the expected loading of the system. If found to be sufficient for the system it will be inspected for damage prior to each flight |

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| | | Flap breaks | | | 1 | Implement a safety factor greater than 1.0 to ensure that flight conditions do not exceed design specifications | Properly calculate loads and conditions for when the airbrake system will be deployed |
| | Non-compromising cracks | Loads beyond design specifications | Potential for future damage | If left unattended could lead to catastrophic subsystem and system failure | 3 | Implement a safety factor greater than 1.0 to ensure that flight conditions do not exceed design specifications | The airbrakes have been modeled in ANSYS to find the loading case during a normal launch. The system has been designed such that the supports can withstand the normal load case. |
| | | Damaged during handling due to improper handling techniques | | | 3 | Team members will be taught proper handling and installation procedures for airbrakes | Only team members that receive training will handle the airbrakes |

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| | | Improper maintenance | | | 3 | Pre- and post-launch thorough inspections of airbrakes | The airbrake system will be inspected before and after each operation to check for cracks |
| | Damage from impact | Loads beyond design specifications | Loss of future use of airbrakes system | Permanent damage of airbrakes will render them useless | 2 | After each launch, airbrake systems will be thoroughly inspected for any minor defects | The airbrake system will be inspected before and after each launch to check for cracks and defects |
| | | Improper maintenance | | | 2 | Pre- and post-launch thorough inspections of airbrakes | All parts of the airbrake system will be properly secured to the airframe prior to launch |
| | No Engagement | Rod fails because maximum load is exceeded | Both airbrakes fail to engage | The rocket will overshoot its target altitude | 3 | Run tests to acquire the maximum load that the rods can support and make sure that the loads on the rods stay well within the limits using a safety factor | Ensure tests are an accurate recreation of launch conditions |
| | | Rod bends because of improper testing | | | 3 | | |

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| | | | | | | greater than 1.0 | |
| | | Flap breaks because maximum load is exceeded | | | 3 | Use simulations to test max load before failure and implement a safety factor greater than 1.0 | In depth testing using computer modelling to create a safety factor greater than 1.0 |
| | | Debris in the hinges due to incomplete inspection | | | 3 | Pre- and post-launch thorough inspections of airbrakes | Ensure that the airbrakes are clear of any debris |
| | | Linear actuator fails to activate | | | 3 | Pre- and post-launch thorough inspections of linear actuators, and proper installation of linear actuators | Check the linear actuators for proper wiring organization and any potential wear and tear |
| | Failure for the airbrakes to stow on descent | Linear actuator fails to activate | Damage to airbrakes subsystem on landing | Permanent damage to airbrakes will render them useless | 2 | Pre- and post-launch thorough inspections of linear actuators, and proper installation of linear actuators | Check the airbrakes for debris in the system, wear and tear in the system, and any damage caused from landing. |

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| | | Debris in the hinges due to incomplete inspection | | | 2 | Pre- and post-launch thorough inspections of airbrakes | Inspect the airbrakes for debris in the system |

## Appendix C Material Safety Data Sheets

List of links for relevant MSDS documents

GOEX Black Powder: http://www.goexpowder.com/images/LoadCharts/SDS%20Sheets-GOEX%20Black%20Powder.pdf

Klean-Strip Acetone: http://www.kleanstrip.com/uploads/documents/GAC18_SDS-LL34.pdf

West System 105 Epoxy Resin: http://www.westsystem.com/ss/assets/MSDS/MSDS105.pdf

West System 206 Slow Hardener: http://www.westsystem.com/ss/assets/MSDS/MSDS206.pdf

Fiberglass Fabric: http://www.toolchemical.com/TOOLCHEMICAL/Tubing-Room%20Temp.pdf

Batteries: http://www1.mscdirect.com/MSDS/MSDS00024/00338228-20151101.PDF

Electronic Matches: http://www.pyropak.com/docs/sds/electric-match-(all)-sds.pdf

Cotton Floc: http://www.toolchemical.com/TOOLCHEMICAL/cotton%20flock%20msds.pdf

Baby Wipes: http://westhurleylibrary.org/CircBlog/MSDS/Pampers_Wipes.pdf

Igniter: http://www.aerotech-rocketry.com/customersite/resource_library/RegulatoryDocuments/OSHA(MSDS)/aerotech_igniter_msds_11-12-08.pdf

Liquid Nails: http://www.liquidnails.com/LNDatasheets/MSDS/LN-901_LNP-901

Glass Microspheres: http://cdn.fibreglast.com/downloads/PDCT-MSDS-00003.pdf

Turtle Wax: https://www.turtlewax.com/docs/default-source/msds-english/msds-consumer/turtle-wax-zip-wax-car-wash-concentrate

WD-40: http://wd40.com/files/pdf/msds-wd482671453.pdf

## Appendix D Vehicle Verification Matrix

| Number | Requirement | Verification | Status |
|---|---|---|---|
| **1.1.** | The vehicle shall deliver the payload to an apogee altitude of 5,280 feet above ground level (AGL). | The vehicle is projected to reach an apogee of 5,569 feet not accounting for the effect of the airbrakes. With the application of the airbrakes which will be deployed based on altitude and velocity, the vehicle will meet the 5,280 foot requirement. | In Progress. Implemented in design but not built. |
| **1.2.** | The vehicle shall carry one commercially available, barometric altimeter for recording the official altitude used in the competition scoring. | The vehicle shall carry four commercially available, barometric altimeters. One of these will be designated at the field on launch day as the officially-scored altimeter. An additional fifth altimeter will be used in conjunction with the airbrakes system. | In Progress. Implemented in design but not built. |
| **1.2.1.** | The official scoring altimeter shall report the official competition altitude via a series of beeps to be checked after the competition flight. | The designated altimeter will have the ability to report its recorded altitude via a series of beeps. | Completed at competition. |
| **1.2.2.** | Teams may have additional altimeters to control vehicle electronics and payload experiment(s). | All four altimeters installed in the launch vehicle will have specific purposes relating to the recovery system. The Arduino-controlled airbrake system will also have its own barometric altimeter. | In Progress. Implemented in design but not built. |

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| **1.2.2.1.** | At the Launch Readiness Review, a NASA official will mark the altimeter that will be used for the official scoring. | The specific altimeter which will be the designated competition altimeter will be presented to the NASA official at LRR to be marked. | Completed at competition. |
| **1.2.2.2.** | At the launch field, a NASA official will obtain the altitude by listening to the audible beeps reported by the official competition, marked altimeter. | The designated competition altimeter will indicate the launch vehicle's apogee. | Completed at competition. |
| **1.2.2.3.** | At the launch field, to aid in determination of the vehicle's apogee, all audible electronics, except for the official altitude-determining altimeter shall be capable of being turned off. | Each electronic device on the launch vehicle will be independently powered, allowing for each to be easily deactivated when the officially scored altimeter is indicating the altitude. | In Progress. Implemented in design but not built. |
| **1.2.3.1.** | The official, marked altimeter is damaged and/or does not report an altitude via a series of beeps after the team's competition flight. | The avionics bays in which the altimeters are located will be robust enough to prevent external damage, and the altimeters will be secured within the bays in such a way as to prevent damage due to excessive movement. | In Progress. Implemented in design but not built. |
| **1.2.3.2.** | The team does not report to the NASA official designated to record the altitude with their official, marked altimeter on the day of the launch. | The team will report to the designated NASA official with the altitude from the official, marked altimeter on the launch day. | Completed at competition. |

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| **1.2.3.3.** | The altimeter reports an apogee altitude over 5,600 feet AGL. | The current projected apogee is less than 5,600 feet AGL and the operation of the airbrakes will reduce the apogee to 5,280 feet AGL. | In Progress. Implemented in design but not built. |
| **1.2.3.4.** | The rocket is not flown at the competition launch site. | The rocket will be flown at the competition launch site. | Completed at competition. |
| **1.3.** | The launch vehicle shall be designed to be recoverable and reusable. | The vehicle is designed to be robust enough to withstand the forces of launch and to ensure recovery of the vehicle. If the full-scale rocket is damaged during the test flight, the design will be altered to ensure the reusability of the vehicle launched at the competition. | In Progress. Implemented in design but not built. |
| **1.4.** | The launch vehicle shall have a maximum of four (4) independent sections. | The rocket has four sections: the nose cone section, forward airframe, aft airframe, and fin section. | In Progress. Implemented in design but not built. |
| **1.5.** | The launch vehicle shall be limited to a single stage. | The AeroTech L1150R rocket motor is a single stage motor. | In Progress. Implemented in design but not built. |

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| **1.6.** | The launch vehicle shall be capable of being prepared for flight at the launch site within 2 hours, from the time the Federal Aviation Administration flight waiver opens. | The vehicle is designed with hatches on the electronics bays so that it can be prepared for launch quickly and efficiently. Additionally, the checklist for launch has been written so that it is efficient and logical. | In Progress. Implemented in design but not built. |
| **1.7.** | The launch vehicle shall be capable of remaining in launch-ready configuration at the pad for aminimum of 1 hour without losing the functionality of any critical on-board component. | New 9 Volt batteries that have sufficient power for at least a 1-hour waiting period will be used on launch day for the electronics and avionics. | In Progress. Implemented in design but not built. |
| **1.8.** | The launch vehicle shall be capable of being launched by a standard 12 volt direct current firing system. | The launch vehicle is designed to be launched using the standard 12 Volt direct current firing system provided by NASA. | In Progress. Implemented in design but not built. |
| **1.9.** | The launch vehicle shall use a commercially available solid motor propulsion system using ammoniumperchlorate composite propellant (APCP) which is approved and certified by the National Association ofRocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR). | The AeroTech L1150R rocket motor that will be used for the full-scale rocket is approved and verified by the NAR and TRA. | Completed. |
| **1.9.1.** | Final motor choices must be made by the Critical Design Review (CDR). | The final motor choice has been made and the full-scale rocket will use an AeroTech L1150R rocket motor. | Completed. |

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| **1.9.2.** | Any motor changes after CDR must be approved by the NASA Range Safety Officer (RSO), and will only be approved if the change is for the sole purpose of increasing the safety margin. | If the motor choice changed after CDR, the NASA Range Safety Officer will be notified and changes will only be made for safety-related reasons. | N/A at the time of CDR completion. |
| **1.10.** | The total impulse provided by a launch vehicle shall not exceed 5,120 Newton-seconds (L-class). | The selected motor is an AeroTech L1150R motor, which does not exceed the L-class limitations. | Completed. |
| **1.11.1.** | The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) shall be 4:1 with supporting design documentation included in all milestone reviews. | No pressure tanks will be used in the full-scale rocket. | N/A. |
| **1.11.2.** | Each pressure vessel shall include a pressure relief valve that sees the full pressure of the tank. | No pressure tanks will be used in the full-scale rocket. | N/A. |
| **1.11.3.** | Full pedigree of the tank shall be described, including the application for which the tank was designed, and the history of the tank, including the number of pressure cycles put on the tank, by whom, and when. | No pressure tanks will be used in the full-scale rocket. | N/A. |

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| **1.12.** | All teams shall successfully launch and recover a subscale model of their full-scale rocket prior to CDR. | The team has successfully launched a subscale rocket that has the same number of sections, same design, and same avionics as the full-scale rocket. The subscale was launched and recovered without any damage. | Completed. |
| **1.13.** | All teams shall successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. | The team will launch the full-scale rocket prior to the FRR in its final flight configuration. | In Progress. Implemented in design but not built. |
| **1.13.1.** | The vehicle and recovery system shall have functioned as designed. | The vehicle and recovery system will have functioned as designed. | In Progress. Implemented in design but not built. |
| **1.13.2.** | The payload does not have to be flown during the full-scale test flight. | The payload will be flown during the full-scale test flight | In Progress. Implemented in design but not built. |
| **1.13.3.** | The full-scale motor does not have to be flown during the full-scale test flight. | The full-scale motor will be flown during the full-scale test flight. | In Progress. Implemented in design but not built. |
| **1.13.4.** | The vehicle shall be flown in its fully ballasted configuration during the full-scale test flight. | The vehicle will be flown in its fully ballasted configuration during the full-scale test flight. | The vehicle shall be flown in its fully ballasted configuration during the full-scale test flight. |
| **1.13.5.** | After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components shall not be modified without the concurrence of the NASA Range Safety Officer (RSO). | If the launch vehicle or any of the components are modified, the NASA Range Safety Officer will be notified and changes will only be made for safety-related reasons. | N/A at the time of CDR completion. |

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| **1.14.** | Each team will have a maximum budget of $7,500 they may spend on the rocket and its payload(s). | The budget for the rocket and payload does not exceed $7500. The budget includes items that were donated to or already owned by the team. | In Progress. Implemented in design but not built. |
| **1.15.1.** | The launch vehicle shall not utilize forward canards. | The vehicle does not include forward canards, forward firing motors, motors that expel titanium sponges, hybrid motors, or a cluster of motors. | N/A. |
| **1.15.2.** | The launch vehicle shall not utilize forward firing motors. | The vehicle does not include forward canards, forward firing motors, motors that expel titanium sponges, hybrid motors, or a cluster of motors. | N/A. |
| **1.15.3.** | The launch vehicle shall not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.). | The vehicle does not include forward canards, forward firing motors, motors that expel titanium sponges, hybrid motors, or a cluster of motors. | N/A. |
| **1.15.4.** | The launch vehicle shall not utilize hybrid motors. | The vehicle does not include forward canards, forward firing motors, motors that expel titanium sponges, hybrid motors, or a cluster of motors. | N/A. |
| **1.15.5.** | The launch vehicle shall not utilize a cluster of motors. | The vehicle does not include forward canards, forward firing motors, motors that expel titanium sponges, hybrid motors, or a cluster of motors. | N/A. |

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| **2.1.** | The launch vehicle shall stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee and a main parachute is deployed at a much lower altitude. | The drogue parachute will come out at apogee, and two main parachutes will come out at 1000 feet and 700 feet for the forward and aft sections respectively. | In Progress. Implemented in design but not built. |
| **2.2.** | Teams must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full scale launches. | The team performed a ground ejection test for the subscale launch and will be done for the full scale launch. | Completed for subscale launch. In Progress. Implemented in full-scale design but not built. |
| **2.3.** | At landing, each independent section of the launch vehicle shall have a maximum kinetic energy of 75 ft-lbf. | Given the current projections, the nosecone section will have a kinetic energy of 20 feet per second, and the fin section will have a maximum kinetic energy of 17 feet per second. | In Progress. Implemented in design but not built. |
| **2.4.** | The recovery system electrical circuits shall be completely independent of any payload electrical circuits. | The design does not use payload electrical circuits. | N/A. |

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| **2.5.** | The recovery system shall contain redundant, commercially available altimeters. | The desing uses four altimieters- two as primary altimeters and two as redundant altimeters. The primary altimeters will be the Entacore AIM 3.0 for the forward parachute and the Stratologger CF for the aft parachute. The redundant altimeters will be of he same brand with the Stratologger SL 100 for the aft parachute. | In Progress. Implemented in design but not built. |
| **2.6.** | Motor ejection is not a permissible form of primary or secondary deployment. An electronic form of deployment must be used for deployment purposes. | At apogee and the preprogrammed altitudes of 1000 and 700 feet, the altimeters will send a signal to the e-matches to deploy the parachutes. | In Progress. Implemented in design but not built. |
| **2.7.** | A dedicated arming switch shall arm each altimeter, which is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad. | There will be 4 switches with each switch dedicated to a single altimeter. | In Progress. Implemented in design but not built. |
| **2.8.** | Each altimeter shall have a dedicated power supply. | Each altimeter will have its own new, Duracell 9 volt battery. | In Progress. Implemented in design but not built. |
| **2.9.** | Each arming switch shall be capable of being locked in the ON position for launch. | Each altimeter will use a lockable 110/220 volt Rotary Selecting switch. | In Progress. Implemented in design but not built. |

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| **2.10.** | Removable shear pins shall be used for both the main parachute compartment and the drogue parachute compartment. | 4 removable shear pins will be used for both compartments to provide adequate connection until deployment. | In Progress. Implemented in design but not built. |
| **2.11.** | An electronic tracking device shall be installed in the launch vehicle and shall transmit the position of the tethered vehicle or any independent section to a ground receiver. | Each section will use a Big Red Bee 900 MHz GPS to transmit the location of the independent sections. | In Progress. Implemented in design but not built. |
| **2.11.1.** | Any rocket section, or payload component, which lands untethered to the launch vehicle shall also carry an active electronic tracking device. | Both of the sections of the rocket will have their own electronic tracking devices. | In Progress. Implemented in design but not built. |
| **2.11.2.** | The electronic tracking device shall be fully functional during the official flight at the competition launch site. | Both Big Red Bee tracking devices will be fully functional during the official flight. | Completed at competition. |
| **2.12.** | The recovery system electronics shall not be adversely affected by any other on-board electronic devices during flight (from launch until landing). | The recovery system electronics will be shielded from any on-board electronic devices using the 3/4 inch bulkheads. | In Progress. Implemented in design but not built. |

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| **2.12.1.** | The recovery system altimeters shall be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device. | The altimeters will not be placed inside the same compartment as the GPS for both sections of the rocket. | In Progress. Implemented in design but not built. |
| **2.12.2.** | The recovery system electronics shall be shielded from all onboard transmitting devices, to avoid inadvertent excitation of the recovery system electronics. | As mentioned above, the altimeters will be shielded from any transmitting devices by being put in separate compartments. | In Progress. Implemented in design but not built. |
| **2.12.3.** | The recovery system electronics shall 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. | There are no magnetic wave generators on board the vehicle. | N/A. |
| **2.12.4.** | The recovery system electronics shall be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics. | Proper care will be taken to ensure that the altimeters will not malfunction because of other components on the vehicle. | In Progress. Implemented in design but not built. |

## Appendix E AGSE Verification Matrix

| Number | Requirement | Verification | Status |
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| **3.3.2.1.1** | Teams will position their launch vehicle horizontally on the AGSE. | The launch vehicle will be positioned horizontally on the AGSE. This position can be seen in *Figure 41*. | Completed at competition. Verified by design and setup at competition. |
| **3.3.2.1.2** | A master switch will be activated to power on all autonomous procedures and subroutines. | The master switch will be hardwired into the system separate from the kill switch. A diagram for this subsystem can be seen in Figure 58. | In Progress. Implemented in design but not built. |
| **3.3.2.1.3** | All AGSEs will be equipped with a pause switch in the event that a judge needs the AGSE to be temporarily halted for any reason. The pause switch halts all AGSE procedures and subroutines. Once the pause switch is deactivated the AGSE resumes operation. | The pause switch will halt the progression of the AGSE and can be implemented at any time. The handbook states it must activated after the master switch is turned on. A diagram can be seen in Figure 58. | In Progress. Implemented in design but not built. |

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| **3.3.2.1.4** | Once the judge signals "START", the AGSE will begin its autonomous functions in the following order: 1) capture and containment of the payload; 2) erection of the launch platform from horizontal to 5.0 degrees off vertical (85.0 degrees), 3) insertion of the motor igniter. The judge may re-enable the pause switch at any time at his/her discretion. If the pause switch is re-enabled all systems and actions shall cease immediately. The judge will only do this if there is a question about safe operation of the AGSE. The judge and team leader will discuss and decide if the team will be allowed to continue their attempt. No modifications to the hardware or software will be allowed prior to a rerun. | A diagram of the AGSE task progression can be seen in Figure 57. | In Progress. Implemented in design but not built. |
| **3.3.3.1** | For the purpose of this challenge, the ASGE is defined as all mechanical and electrical components not part of the launch vehicle, and is provided by the teams. This includes, but is not limited to, the payload containment and igniter installation devices, computers, electric motors, batteries, etc. | The team has ensured that all necessary components for the AGSE are implemented | In Progress. Implemented in design but not built. |
| **3.3.3.2** | All AGSE systems shall be fully autonomous. The only human interaction will be if the judge pauses the AGSE. | The entirety of the AGSE's subsystems will function autonomously except for upon the activation of the pause switch. | In Progress. Implemented in design but not built. |

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| **3.3.3.3** | The AGSE shall be limited to a weight of 150 pounds or less and volume of 12 feet in height x 12 feet in length x 10 feet in width. | The current design of the AGSE has a weight of 81.9 pounds and the dimensions are 120 inches long x 30 inches wide x 19 inches tall. | In Progress. Implemented in design but not built. |
| **3.3.4.1.2** | Sensors that rely on Earth's magnetic field | The AGSE design does not include any sensory equipment that relies on the Earth's magnetic field | N/A. |
| **3.3.4.1.3** | Ultrasonic or other sound-based sensors | The AGSE design does not include any ultrasonic sensors | N/A. |
| **3.3.4.1.4** | Earth-based or Earth orbit-based radio aids (e.g. GPS, VOR, cell phone). | The AGSE does not include any navigational equipment reliant on Earth-based or Earth orbit-based radio aids | N/A. |
| **3.3.4.1.5** | Open circuit pneumatics | The AGSE design does not include any open circuit pneumatic systems | N/A. |
| **3.3.4.1.6** | Air breathing systems | The AGSE does not utilize any air breathing systems | N/A. |
| **3.3.5.4** | Gravity-assist shall not be used to place the payload within the rocket. If this method is used no points shall be given for payload insertion. | The payload compartment and door will be oriented in such a way that gravity will not assist in payload insertion. | In Progress. Implemented in design but not built. |
| **3.3.5.6** | Each team will be given 10 minutes to autonomously capture, place, and seal the within their rocket, and erect the rocket to a vertical launch position five degrees off vertical. | The AGSE will autonomously capture, place, and seal the sample within the rocket and then raise the rocket to a launch position five degrees off of vertical. The complete AGSE task progression is shown in Figure 57. | In Progress. Implemented in design but not built. |

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| **3.3.6.1.1** | A master switch to power all parts of the AGSE. The switch must be easily accessible and hardwired to the AGSE. | The AGSE features a master power switch that controls all the power to the functions of the AGSE. This can be seen in section 4.1.6 AGSE Electronics. | In Progress. Implemented in design but not built. |
| **3.3.6.1.2** | A pause switch to temporarily terminate all actions performed by AGSE. The switch must be easily accessible and hardwired to the AGSE. | The AGSE features a pause switch that once activated, terminates all actions currently being performed by the AGSE. This can be seen in section 4.1.6 AGSE Electronics. | In Progress. Implemented in design but not built. |
| **3.3.6.1.3** | A safety light that indicates that the AGSE power is turned on. The light must be amber/orange in color. It will flash at a frequency of 1 Hz when the AGSE is powered on, and will be solid in color when the AGSE is paused while power is still supplied. | The AGSE has a light connected in the circuits that will either be amber or orange in color. This can be seen in section 4.1.6 AGSE Electronics | In Progress. Implemented in design but not built. |
| **3.3.6.1.4** | An all systems go light to verify all systems have passed safety verifications and the rocket system is ready to launch. | The AGSE features an all systems go light once all systems have passed all safety verifications and the rocket is ready for launch. This can be seen in section 4.1.6 AGSE Electronics | In Progress. Implemented in design but not built. |
| **3.3.7.1** | Any team who fails to complete any of the procedures in requirement 3.3 will be ineligible of obtaining Centennial Challenges prizes. | The above verification matrix shows that the team has accounted for all items in Section 3.3 | Completed at competition. |
| **3.3.7.2** | The head judge and the MAV Project Manager will have the final decision authority to determine if the procedures in requirement 3.3 have been met. | All final decisions will be handled by the head judge and the MAV Project Manager. | Completed at competition. |

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| **3.3.8.1** | Any academic team or non-academic team may participate in the MAV Project, however, to be eligible for prize money, less than 50% of the team make-up may be foreign nationals and the team entity must be a United States entity. | There are no foreign nationals on the team and the team is the High-Powered Rocketry Club at North Carolina State University. | Completed. |
| **3.3.8.2** | Name of person or business or entity who will be receiving the award check in the event the team places in the competition and address. If a business or other entity is to receive the check then also provide a tax identification number. | High-Powered Rocketry Team 911 Oval Drive Raleigh, NC 27695 | Completed. |
| **3.3.8.3** | In addition to SL requirements, for the CDR presentation and report, teams shall include estimated mass properties for the AGSE. | The estimated mass properties of the AGSE and all its components is seen in Table 8. | Completed. |
| **3.3.8.4** | In addition to SL requirements, for the FRR presentation, teams shall include a video presented during presentation of an end-to-end functional test of the AGSE. The video shall be posted on the team's website with the other FRR documents. Teams shall also include the actual mass properties for the AGSE. | A video of the complete AGSE task progression will be created prior to the FRR and the actual mass properties will be complied in a table in the FRR. | In Progress. Completed in the FRR. |