The Pennsylvania State University

LionTech Rocket Labs

2017-2018 USLI Project Nimbus

Critical Design Review

046 Hammond Building, University Park, PA 16802
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List of Acronyms

A&R	Avionics and Recovery
CFD	Computational Fluid Dynamics
EIT	Electronic and Information Technology
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
EHS	Environmental Health and Safety
GPS	Global Positioning System
HPCL	High Pressure Combustion Lab
LTRL	LionTech Rocket Labs
MDRA	Maryland Delaware Rocketry Association
MSDS	Material Safety Data Sheet
NAR	National Association of Rocketry
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
PPE	Personal Protective Equipment
PSC	Pittsburgh Space Command
PSU	The Pennsylvania State University
RSO	Range Safety Officer
SDS	Safety Datasheet
STEM	Science Technology Engineering and Mathematics
STTR	Small Business Technology Transfer
TRA	Tripoli Rocket Association
UPAC	University Park Allocation Committee
USLI	University Student Launch Initiative

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1. Summary of Report

1.1 Team Summary

Team Name and Address

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1.2 Launch Vehicle Summary

Size and Mass

The launch vehicle was designed to incorporate a rover payload while minimizing weight and providing sufficient strength. A diameter of 5.5 inches was chosen to give sufficient space for the payload. The length of the launch vehicle was determined to be 112 inches to provide enough space for payload and recovery systems. The dry weight of the final flight vehicle will be 31.25 pounds, while the wet mass, which includes the motor and casing, will be 38.5 pounds. An OpenRocket rendering of the final flight vehicle is shown in Figure 1.

Figure 1. OpenRocket Rendering of Fullscale

Motor Choice

The motor selection process is based on the mission performance criteria outlined in the NASA USLI 2017-18 Handbook and preliminarily uses OpenRocket to simulate flight characteristics. Through this motor selection process the Aerotech L1390 was selected.

Recovery System

The avionics bay will be fully redundant, consisting of two independent Stratologger CF altimeters with corresponding independent power sources switches, and charges. The redundant altimeter will be at a one-second delay so that the body of the rocket is not overwhelmed when the ejection charges detonate. The rocket will have a dual-deployment parachute recovery where the drogue parachute will deploy at apogee and the main parachute will deploy at 750 ft above ground level (AGL). The drogue parachute will be a 12” Fruity Chutes Classical Elliptical and the main parachute will be an 84” Fruity Chutes Iris Ultra Compact. These parachutes guarantee that the rocket will land within the NASA kinetic energy requirement of 75 ft-lbs.

1.3 Payload Summary

The payload challenge chosen this year is build a remotely deployable autonomous rover. The rover will be deployed from the launch vehicle and then autonomously move at least 5 feet away from all parts of the rocket. After the rover has reached its destination, it will deploy a set of foldable solar panels.

2. Changes made since PDR

2.1 Changes made to Vehicle Criteria

Since PDR, very few design changes have been made regarding the airframe of the launch vehicle. The camera cover and recording device has be moved to a section directly above the motor to ease the initiation of the camera. The motor selection has also changed since PDR due to the carbon fiber wrapping being 5 lbm heavier than expected. The new motor will be an L1390 Aerotech 3 grain.

Since PDR, the avionics bay design has been redesigned to include access through an external door. This door will allow the avionics and recovery team to assemble the avionics bay more easily and readily access the altimeters. Last year, the avionics bay was complicated to assemble so it took a lot of time to access the altimeters if there were incomplete continuity beeps. This discontinuity was a problem for the team because one of the wires came loose on the launch pad at the USLI competition. With the new design, the avionics and recovery team can access the altimeters immediately and connect any loose wires. More detailed information about the new avionics bay is provided later in the report.

The estimated weight of the rocket increased slightly. The weight increase does not change the size of parachutes chosen because the initial parachute choice was too large for the initial mass. With the new mass, the 84" main parachute will allow the rocket to descend within the kinetic energy limit.

2.2 Changes made to Payload Criteria

The rover will no longer include treads. The justification for this change is that the estimated mass of the rover is low enough such that treads would add unnecessary weight. Additionally, instead of using infrared sensors, the rover will utilize ultrasonic sensors. The justification for this change is that ultrasonic sensors are easier to work with and will have a higher level of accuracy since heat signatures are not consistent. The mechanism for measuring distance has been switched from using an accelerometer to generate a displacement vector to using a GPS to identify a location that is 15 feet away from the rocket for the rover to travel to. An Arduino mega will now be used instead of an Arduino Nano due to the need for more pins. The mass and size of the mega are larger than the Nano, but the increased size will allow for a more organized design.

2.3 Changes made to Project Plan

Since PDR, the club has managed to make changes to the outcome to ensure being financially successful. The club has changed its hotel plans to save $1,015.30. LTRL is also cutting back one car rental which will save the club an estimated amount of $648.79. This change will help the remain in budget since travel is the most expensive sector. Additionally, now that the club is farther into the fullscale project, a more realistic budget has been set. The improved budget saves the club $300.57 compared to the budget from PDR. Unfortunately, the club's expected income has lessened since PDR LTRL was expecting more financial support from the Aerospace Engineering Department. Also, the club is unsure of financial support from the Engineering Undergraduate Council.

3. Vehicle Criteria

3.1 Design and Verification of Launch Vehicle

Mission Statement

For the 2018 NASA Student Launch, LTRL aims to design, fabricate, and launch a vehicle to an apogee at 5,280 feet and effectively deploy a rover capable of unfolding solar panels. To classify mission success, the launch vehicle must descend under drogue and main parachute at safe kinetic energies and land without sufficient damage to the externals of the vehicle, payload, or recovery system. The launch vehicle must be capable of being reassembled post recovery within a 2-hour time frame and meet criteria for re-flight. Throughout the academic year, LTRL plans to educate and inspire youth in the community on science and engineering.

Mission Success Criteria

- The launch vehicle shall exit the launch rail at a minimum velocity of 65 ft/s.
- The launch vehicle shall maintain a minimal stability margin of 2.5 calibers at rail exit and a static margin of 2.2 calibers until apogee
- The launch vehicle shall reach apogee at the altitude of 5,280 ft with a tolerance of 100 ft in either direction.
- The launch vehicle shall deploy parachutes at each predetermined altitude and each shall open completely.
- All vehicle sections shall descend in a stable fashion and land under kinetic energy requirements.
- Rover shall deploy successfully, drive a sufficient distance away from the vehicle, and deploy solar panels.
- All vehicle sections shall be in reusable condition upon retrieval.
- The Avionics Bay must be accessible on the launch pad to securely switch the altimeters to the on position.
- The drogue parachute must deploy within two seconds of reaching apogee.
- The main parachute must deploy within two seconds of reaching 700 feet altitude.
- The descent under main and drogues parachutes must be slow enough that the energy of each section of the rocket is not greater than 75 foot-pounds upon landing.
- The descent under drogue and main parachutes must be fast enough that drift does not exceed 2500 feet from the launch pad.

3.2 Launch Vehicle Selections

Airframe Design

Blue tube wrapped in carbon fiber was selected as the material for the airframe for this year's launch vehicle. This decision was made based on the scores given in a weighted design matrix.

Seven factors were considered when selecting the material for the airframe. A score of 1-5 (one being the worst and five being the best) was assigned for each factor based on its performance in that specific criteria. The seven criteria considered for airframe selection were strength, cost, workability, weight, appearance, legacy, and hazardousness. Strength was rated based on each material's ability to withstand forces throughout flight. Material that can withstand higher forces received a higher score. The cost criteria score was determined based on each material's price per foot. The cheaper the material, the higher the score. The easier it is to cut, sand, and modify a material, the higher its workability score. Weight was given a score dependent on each material's impact on the total mass of the rocket. The lighter the material, the higher the score. Appearance was graded based on each material's overall look and ability to be painted over. This category was included to account for the rocket's overall presentation value during the rocket fair in Alabama. The better the material looks, the higher the score. Legacy was graded based on club members' previous experience working with the selected material. Thorough experience and knowledge of the material receives a higher grade. Hazardousness was graded based on safety concerns that were associated with working each material. A safer material received a higher score.

Each factor was assigned weight in importance on a scale from 0-1 where all the weights of all the factors sum to one. Strength was given a rating of 0.25 due its significant effect on the durability of the flight vehicle. The rocket must sufficiently withstand potential zippering, impact forces, thrust forces, buckling, and denting to ensure success in its launch, deployment, and landing. Cost was given a rating of 0.15 to account for its importance on staying on the yearly budget. The cost of the airframe is especially important when considering potential failures where body tube would need to be replaced. Workability was given a weight of 0.1 to reflect the ease of handling the material while considering factors such as types of tools needed. The weight (mass) category was given a large weight of 0.25, to reflect its importance on the flight of the rocket. Weight directly affects the altitude and the stability of the rocket which are critical to mission success. Weight of the material is especially important when considering potential mass creep occurring from discrepancies between manufacturer and actual parts and the variable mass added from epoxy when rolling carbon fiber. The appearance of the rocket is given a relatively low weight of 0.05 due to its lack of impact on the actual flight of the vehicle. However, this category should be accounted for due to the appearance category of the competition. Legacy was given a weight of 0.1 due to importance when constructing the rocket. Knowledge and experience with the material yields better results but is not essential. Hazardousness was assigned a weight of 0.1 due to its importance in providing a safe work environment for members. However, for most materials careful planning and use of proper safety precautions can limit the overall hazardousness of a material. The scores for each weighted category are shown in Table 1.

Table 1. Airframe material selection matrix

		Fiberglass		**Blue Tube**		**Carbon Fiber**		**Carbon Fiber Wrapped Blue Tube**	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Strength	0.25	4	1	1	0.25	5	1.25	5	1.25
Cost	0.15	2.5	0.375	5	0.75	1	0.15	2.5	0.375
Workability	0.1	2	0.2	3.5	0.35	1	0.1	3	0.3
Weight	0.25	1	0.25	4	1	5	1.25	4	1
Appearance	0.05	5	0.25	3	0.15	5	0.25	5	0.25

Legacy	0.1	5	0.5	5	0.5	1	0.1	2	0.2
Hazardousness	0.1	1	0.1	5	0.5	1	0.1	2	0.2
Total			**2.675**		**3.5**		**3.2**		**3.575**

The scores for each category are justified below.

Strength

Yield strength is determined to be the primary factor when discussing strength. The ratings for yield strength for each material are show below in Table 2. The launch vehicle will undergo several types of stresses during flight. Examples of those are, but not limited to, compressive loads throughout ascent, tensile loads during charge deployment and drift, and various shear forces. Carbon fiber has a clear strength advantage with its high yield strength and impact resistance over fiberglass and blue tube and received a five as a result. Fiberglass is significantly stronger than blue tube and the score of a four reflected this. Blue tube performs the worst out of all three materials and received a one as a result. It is assumed that blue tube wrapped in carbon fiber would have similar strength measurements as regular carbon fiber tubes.

Table 2. Material Strength Comparison

	Yield Strength (KSI)
Fiberglass (G70)	30
Blue Tube	5.07
Carbon Fiber	610-700

Cost

The cost for each material was measured by dollars per foot for 5.5 in. diameter and approximately ⅛ in. thickness body tube is shown in Table 3. To properly quantify the scores for each material, a scale was created to determine at what price each score should be awarded. A total cost of less than 20 dollars per foot was awarded the best score of 5, with the remaining scores decreased by 1 for every increase of 10 dollars per foot. Therefore, a 4 would be awarded for a cost per foot between $20-$30, a 3 for cost between $30-$40, etc. Finally, anything over 50 dollars per foot would result in a score 1.

Table 3. Material Cost Comparison

	Cost ($ / ft)
Fiberglass	43.75
Blue Tube	14.25
Carbon Fiber Tube (5.26 Diameter)	165.40
Carbon Fiber Wrapped Blue Tube	14.25 (blue tube) + 18.42 (carbon fiber weave) + 9.9 (epoxy)= 42.58

Workability

Fiberglass and carbon fiber were given relatively low ratings of two and one respectfully due to the difficulty of cutting and sanding these materials to desired dimensions. A major impact in this score is the difficulty to find machine shops that allow the cutting of these materials due to Penn State safety restrictions. In contrast, blue tube can be cut in any machine shop on campus. For carbon fiber wrapped blue tube, the body can cut before the carbon fiber is put on the body tube to avoid these restrictions. An ongoing goal of the club is to attempt to find workshops that will allow cutting of carbon fiber wrapping or fiberglass to ensure more precise cuts at key separation points. Since blue tube is easier to cut and sand without major health concerns such as those of fiberglass and carbon fiber and received a higher score as a result.

Weight

The estimated density of blue tube wrapped in carbon fiber was calculated to be .878 oz/in^3 using subscale's measured weight and thickness. The main parachute section for the upcoming full-scale rocket was rolled in carbon fiber and weighed recently to more accurately estimate the mass contribution of the body tube and fiber of 5.5 in. diameter for the final product. There are discrepancies between the density given by the manufacturer's website and the density given by OpenRocket for many of the materials that have been used by LTRL. Those discrepancies were extremely noticeable throughout assembly of the previous year's rocket and preventative measures will be made to mitigate this issue for all future competition participation. This includes extensive weighing of full scale parts upon receiving them to validate mass properties. OpenRocket was deemed acceptable for estimating mass of the rocket after those modifications to density were made. The densities used in OpenRocket are shown in Table 4.

Table 4. Density Discrepancy between manufacturer and OpenRocket

	OpenRocket Density (oz / in^3)	Website Density (oz / in^3)
Fiberglass (1)	1.07	1.03
Blue Tube (2)	0.751	0.583
Carbon Fiber (5)	1.03	0.923

Appearance

Fiberglass, carbon fiber, and blue tube wrapped in carbon fiber all received a score of five due to their sleek and finished appearance and their ability to be painted over. Blue tube only received a three due to its coarse and unfinished appearance once painted.

Legacy

Both fiberglass and blue tube received a five for legacy due to the LTRL members having multiple years of experience working with each of these materials. Members are comfortable working with these materials and understand the limitations of each material. LTRL has no prior experience with carbon fiber and the material received a one in this category as a result. Blue tube wrapped in carbon fiber received a two. This score was originally a one in proposal, but after using the material in construction of subscale, this score was increased to a two to reflect the experience gained.

Hazardousness
Blue tube received a score of five since it poses no problematic safety hazards. Both carbon fiber and fiberglass received a score of one for hazardousness due to the known safety concerns when handling these materials. Carbon fiber and fiberglass shards are known to be cancerous when inhaled and get lodged in skin. As a result, when working with both materials, safety glasses and respirator masks must be worn as well as covering any exposed skin. Blue tube wrapped in carbon fiber received a better score than regular carbon fiber since cutting and sanding the material can be done before carbon fiber is applied, but still received a relatively low score of two since all the previous risk hazards mentioned are in effect once the blue tube is wrapped in carbon fiber.

Final Selection
After the scores were weighed and summed, blue tube wrapped in carbon fiber had the highest score and was selected as a result. The team will test the strength of the body tube while it is wrapped in one layer, two layers, and three layers of carbon fiber weaving to determine how many layers are needed to ensure sufficient structural integrity.

Camera Cover
As part of the team derived requirements, a down body camera has been included to supply visual data of flight performance and monitor fin flutter. The exterior portion of the camera is cylindrical with a diameter of 0.75 in and length of 4 in. To securely seat the larger camera on the exterior of the rocket, a 3D printed cover was designed to tightly hold the camera to the body while also providing aerodynamic efficiency. This cover is to be printed in PLA material due to its lightweight characteristics. Subscale flight results has shown that the camera cover’s effect on drag did not render the vehicle unstable at any point during flight. The design has again been improved from last year’s much bulkier design. Figure 2 shows the more spatially efficient design for this year’s competition on subscale.

Figure 2. Refined camera cover design on subscale rocket (3” body tube)

Figure 3 contains dimensioned representation of the camera cover used on full scale.

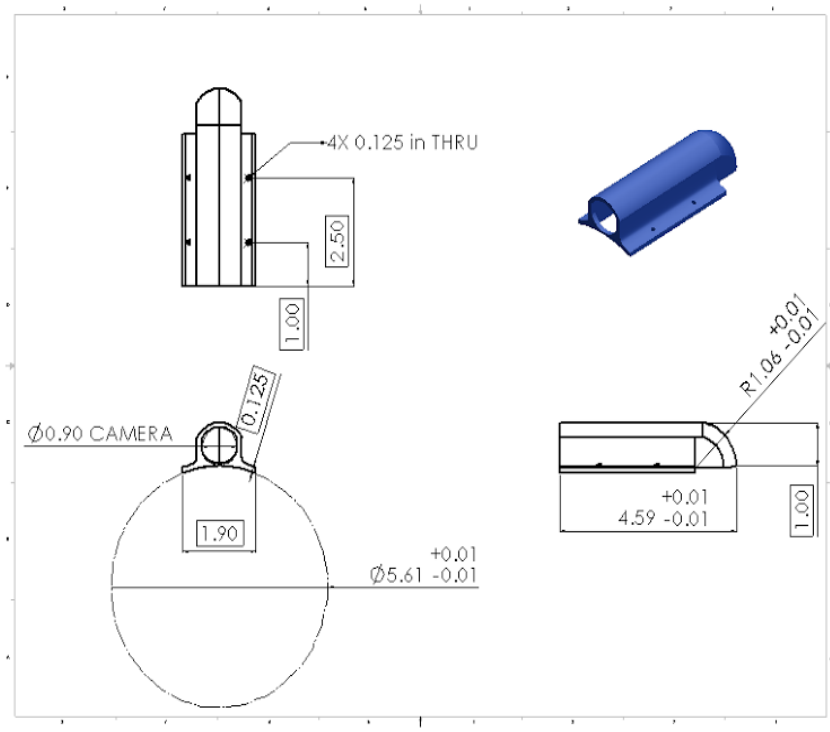


Figure 3. Camera cover specifications

The camera cover is designed to hold a cylindrical camera of 0.90 in. diameter and a length of approximately 4.25 in. including the portion of wire bending into the vehicle.

Fin Retention

One of the airframe highlights of the rocket last year was the application of 3D printed fin brackets to retain the fins during flight. The goal of that design was to easily remove and replace the fins to ease assembly on launch day. Improvements upon this design were made, including the decision to remove the use of epoxy and employ screw-only retention. The new design will lay both on the exterior and interior of the body tube to provide extra structural integrity. This removes the sole reliance upon the screws to hold the bracket to the body tube. The body tube will be cut straight from the end to allow the brackets to be inserted from the bottom of the rocket in one piece and will lay flush to the bottom of the body tube. Figure 4 contains an image of the brackets attached to that tube. Notice the segment that is slid into the rocket through the slots on the final centering ring, which will be laser cut to ensure equidistant placement of the three fins. Eight bolts will be placed equally along the length to be secured through use of nuts placed on the interior of the fin bracket. The fins will be fastened via nuts and bolts through the top section of the brackets. A conic rho fillet was chosen to decrease stress concentrations throughout the length of the bracket. This filet also allows the screws to be aligned perpendicular to the body tube to maximize contact. A secondary purpose of the bracket is to mitigate much of the fin flutter that may be encountered for larger fins.

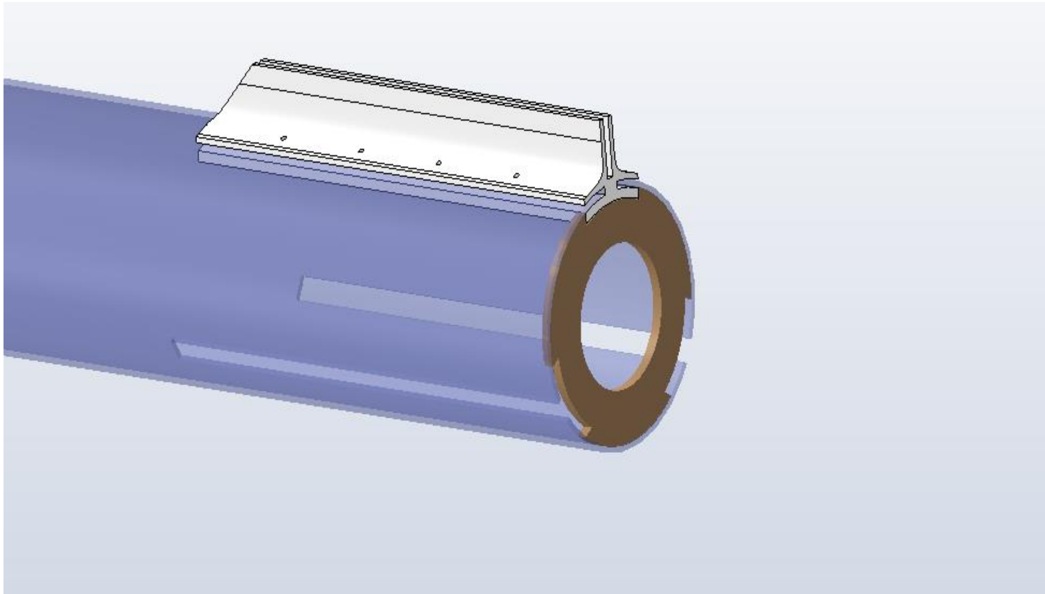


Figure 4. Fin Bracket Model

This concept was chosen by using a concept selection matrix. Three concepts were compared to each other. The first concept was to use the same fin retention system as last year, a 3D printed bracket epoxied to the body tube. The second concept was to epoxy the fins directly to the body tube. The last concept was to use the concept that was explored above. One concept was chosen arbitrarily to be the reference model, the concept where the fins would be epoxied directly to the body tube. The three concepts were then rated from 1 to 5 for several metrics. These metrics were as follows: cost, strength, simplicity of implementation, lead time, and replaceability. The reference concept was assigned a score of 3 for all metrics, then each alternative concept was rated compared to the reference concept. If the concept being scored met the criteria of the metric better than the reference a score of 4 was assigned, or if the concept was much better than the reference a score of 5 was assigned. Likewise, if the concept being scored was less effective at meeting the criteria of the metric a score of 2 was assigned, or if the concept was much less effective than the reference a score of 1 was assigned. These scores were then multiplied by a weight value and summed. The total for the weight values added up to a sum of 1. The concept with the highest score at the end was the one that was chosen.

For cost, having a lower cost meets the criteria for being more effective while having a higher cost would be less effective. Cost was given a weight of 0.15 to account for the importance to stay within the project's budget. For strength, a concept that would be able to withstand higher forces than the reference without breaking would score a 4 if slightly stronger or 5 if much stronger. Likewise, the concept would score a 2 or 1 if the concept was slightly weaker or much weaker, respectively. Strength was given a weight of .20 to reflect the importance that a concept will not fail in operation. For simplicity of implementation, being easier to install the concept would meet the criteria for being more effective, while being more difficult to install would be less effective. Simplicity of implementation was given a weight of 0.20 to ensure that a concept that is overly complicated to be weeded out unless that concept is superior the alternative options. Lead time refers to how much time the concept requires to prepare, and was given a weight of 0.15 to help ensure that the selected concept would not be overly time consuming. A fin retention concept that is easily removable and replaceable in case of damage would receive a score of 4 if the concept is slightly better than the reference, or a score of 5 if the concept is much easier to replace than the reference. If the concept is more difficult or much more difficult to replace, a score of 2 or 1 would be assigned, respectively. With replaceability being the primary design requirement for this year's fin retention system, a weight of .30 was assigned to the replaceability metric. Table 5 shows the fin retention selection matrix.

Table 5. Fin Retention Selection Matrix

		3D Printed, Epoxied		**Epoxied (reference)**		**3D Printed, Bolted**	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Cost	0.15	2	.30	3	0.45	2	0.30
Strength	0.20	3	.60	3	0.60	3	0.60
Simplicity of Implementation	0.20	4	.80	3	0.60	5	1.00
Lead Time	0.15	2	.30	3	0.45	2	0.30
Replaceability	0.30	3	.90	3	0.90	5	1.50
Total			2.90		3.00		3.70
Rank		3		2		1	

The 3D Printed-Epoxied concept scored a 2 for cost because both plastic filament and epoxy are required to implement this concept. This concept was relatively as strong as the reference, so a score of 3 was assigned. The process of epoxying a 3D printed part designed to mate with the side of the body tube is much easier than trying to epoxy a fin directly to the body tube, so a score of 4 was assigned to the 3D Printed-Epoxied concept. Since 3D printing takes quite a bit of time to complete, the concept was assigned a score of 2 for lead time. Because this concept is not easily removable, but not necessarily more difficult to remove than the reference, a score of 3 was assigned.

The 3D Printed-Bolted concept scored a 2 because the plastic filament and screws costs more than the epoxy does for the reference concept. This concept was relatively as strong as the reference, so a score of 3 was assigned. The process of sliding a custom part into a slit designed to mate with the part is much easier than the process used in the reference concept. A score of 5 was assigned to this concept for simplicity of implementation. Since 3D printing takes quite a bit of time to complete, the concept was assigned a score of 2 for lead time. Because this concept is entirely removable by simply removing a few bolts and then sliding the part out, this concept received a score of 5 for replaceability.

Using these scores, the new design that was shown in Figure 4 was chosen. These fin bracket specifications can be observed in Figure 5.

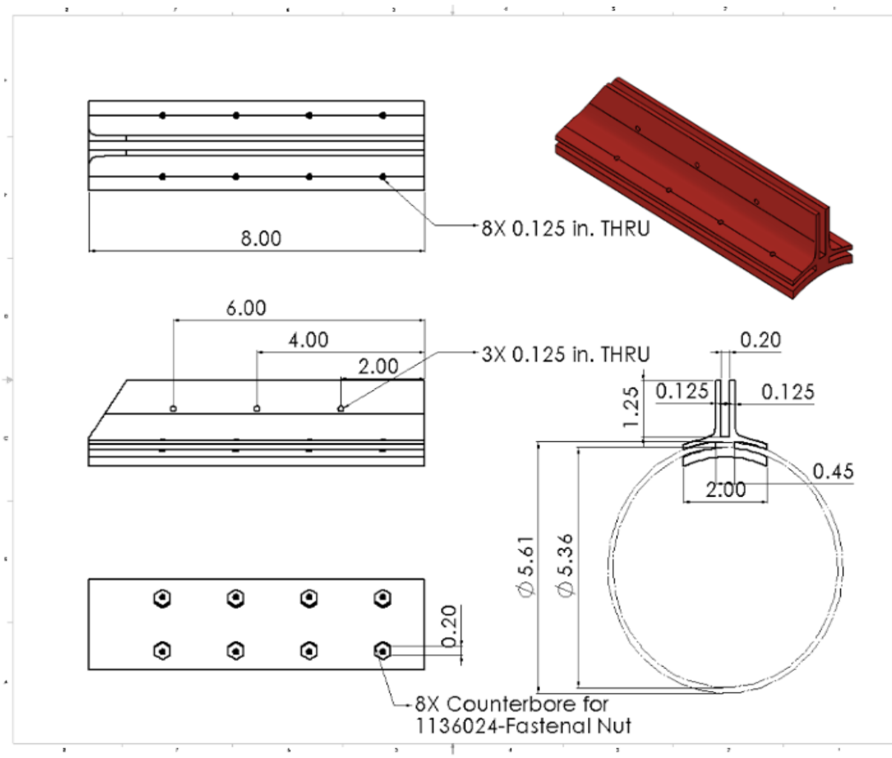


Figure 5. Fin bracket dimensional drawing

The brackets are counterbored for a Fastenal nut used with a ⅛ in. bolt. The nut will be epoxied into the counterbore prior to assembly. This will ensure sufficient compression between the bracket and airframe and provide additional integrity.

Nose Cone Design

The nose cone is the forward most part of the rocket and is the first thing to experience drag. The nose cone should be as light as possible but also be as aerodynamic as possible. Two nose cone shapes have been chosen to be selected from: 4:1 ogive and Von Karman. To decide which concept would be selected, a trade study was conducted. Each concept was rated from 1 to 5 (five being the best, one being the worst) in several categories. These categories are as follows: availability, cost, aerodynamic friction drag, and weight. Aerodynamic pressure drag was not considered because the rocket will not be exceeding Mach 1 speeds.

The easier the concept is to find for purchase, the higher the score is that is assigned for the availability metric. The less the nose cone costs, the higher the score is for the cost metric. The lower the aerodynamic drag the nose cone causes, the higher the score is for the drag metric. Lastly, the less the nose cone weighs, the higher the score is. The full comparison of the ogive vs Von Karman can be seen in Table 6.

To compare the options, the criteria should be assigned weights. With the team's budget being lower than previous years, cost effectiveness is the most important criteria. A weight of 35% has been assigned to cost. Mass and drag both heavily affect how efficient the rocket is, and have both been assigned a weight of 20%. Lastly availability has been assigned a weight of 15%.

Table 6. Nose Cone Selection Matrix

		Ogive 4:1		Von Karman	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score
Availability	0.15	5	0.75	5	0.75
Cost	0.35	4	1.40	2	0.70
Drag	0.20	3	0.60	5	1.00
Mass	0.20	4	0.80	3	0.60
Total			3.55		3.05
Rank		1		2	

With these two nose cone shapes being two of the most common shapes used in rocketry, both options are equally simple to find for purchase and therefore both are awarded a score of five. Ogive nose cones are substantially more cost effective. Von Karman nose cones cost about 1.5 times as much as an ogive nose cone. Because of this, the ogive option was awarded a score of 4 while the Von Karman was awarded a score of 2. The rocket is not expected to ever exceed Mach 1, resulting in only subsonic drag efficiencies needed to be taken into consideration. At subsonic speeds, Von Karman performs better than 4:1 ogive. Because of this, Von Karman is awarded a score of 5 while ogive is awarded a score of 3. Von Karman nose cones have roughly 30% more mass than their Ogive counter parts. Because of this, the Von Karman was awarded a score of 3 and Ogive was awarded a score of 4. After analyzing the strengths and weaknesses of both nose cone options, the ogive 4:1 nose cone has been determined to be the better choice.

Separation Points

Separation points are where the rocket will separate during flight to deploy parachutes and the rover payload. There will be three separation points: two for parachute deployment and one for rover deployment. The separation point for drogue parachute is located between the booster and avionics bay sections. The separation point for main parachute will be located between the avionics bay and payload body tube sections. These separation points were chosen so that one avionics bay would be sufficient for both drogue and main deployment. Attachment point strength was another huge factor, in which couplers were used to secure the attachment points. This allows for the force during deployment to be easily transferred to the body tube, which is preferred over relying upon the shear strength of epoxy to hold a bulkhead in place. The separation points chosen allows for the parachutes to be pushed out of the body tube to further ensure proper separation and parachute deployment. The final separation point occurs at the nose cone to open a section of the rocket for the rover to exit. The rover deployment will separate the entire nose cone from the body tube instead of separating the nose cone from the nose cone shoulder.

An added benefit to the sectioning scheme that has been chosen is that each subsystem will have a dedicated section of the rocket to work on during launch day while being independent of the other subsystems. This will increase the efficiency of each subsystem and reduce assembly time on launch day.

Fins

Three fins were designed to shift the center of pressure towards the aft end of the aircraft and increase the stability of the rocket. Fiberglass was chosen as the material the fins will be made of due to its strength and aerodynamics. The fins will have a thickness of 3/16 in. to combat fin flutter and ensure structural integrity. Doing this will improve rocket performance and allow for safer stability margins. These fins will be bolted into the fin brackets. Figure 6 details the dimensions of the fin design.

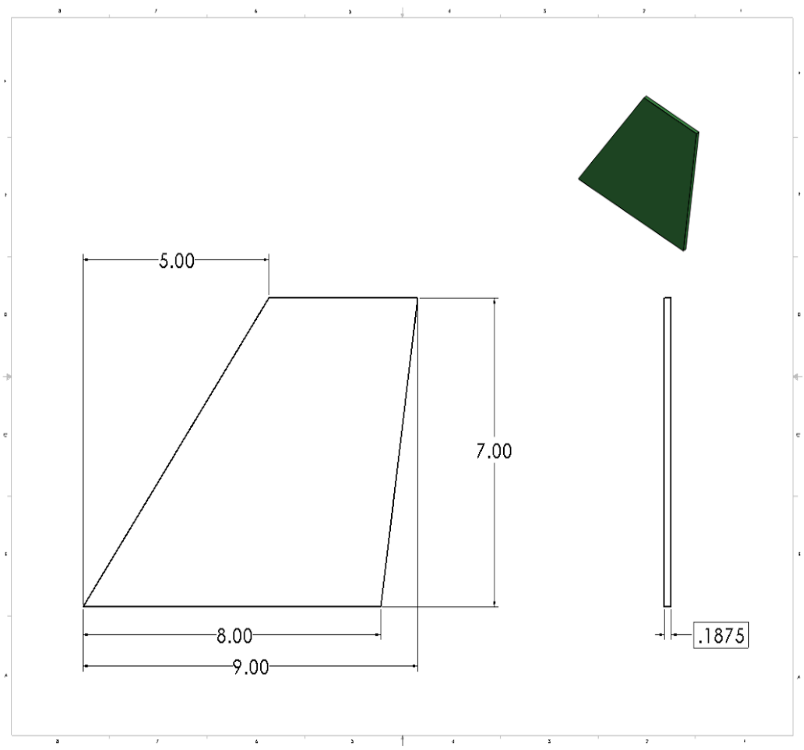


Figure 6. Proposed fin shape

The fins will be composed of G10 Fiberglass. The size and thickness of the fins will assist vehicle stability while minimizing fin flutter.

Fin Flutter Calculations

To maximize stability of the launch vehicle and prevent flight catastrophe, the vehicle fins must not flutter at any point during flight. The addition of fin brackets mitigates this issue by reducing the length of the fins that will experience bending. Using the fin flutter calculations from Apogee Components located in Appendix F: Apogee Rockets Fin Flutter, LTRL is able to evaluate the critical airspeed that would result in fluttering of the fins. So long as the launch vehicle does not exceed this airspeed, the fins will not flutter. Using the geometry of the fin and bracket assembly, along with the material properties of 3/16 in G10 Fiberglass, the minimum airspeed to cause fin fluttering is V_f = 1032.5 ft/sec. The maximum velocity of the launch vehicle will not exceed 612 ft/s, thus fin fluttering will not occur.

Bulkheads

Bulkheads will be used for attachment points of the parachutes and to contain the avionics bay within a coupler. ¼" plywood will be used for attachment point bulkheads due to their cheap cost but reliable strength. Fiberglass bulkheads were also considered because of their superior strength but the drawback of the extra cost and mass of fiberglass bulkheads outweighed the benefit of their strength.

A selection matrix was conducted in which the plywood bulkhead was set to be the reference and the other option was compared to these values. The criteria were rated from 1 to 5, five being the best and one being the worst, on the following metrics: cost, mass, and strength. Each metric was given a weight and the scores were multiplied by the weight values then summed to achieve a final score. Cost was given a weight of 0.30, to ensure that the bulkheads remain within the budget. Mass was given a weight of 0.30, to ensure that the bulkheads do not add too much weight to the overall mass of the rocket. Strength was given the highest weight of 0.40. This is because ensuring the parts do not fail is more important than any other metric. The plywood was assigned an average score of 3 for all metrics as the reference option. Table 7 lists the scores and final rankings of these two options.

Table 7. Bulkhead selection matrix (plywood reference)

		Plywood (ref)		Fiberglass	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score
Cost	0.30	3	.90	1	0.30
Mass	0.30	3	.90	1	0.30
Strength	0.40	3	1.20	5	2.00
Total			3.00		2.60
Rank		1		2	

The plywood is much less expensive than the fiberglass, therefore scoring much higher. The plywood also has much less mass as compared to the fiberglass, and the scores reflect this. The fiberglass is more durable and can withstand more stress before failing, and the scores reflect this. A summation of the scores reveals that plywood is a better bulkhead option for the project and therefore these will be used in full scale construction.

Centering Rings

The motor of the rocket must be held in place during flight to allow proper thrust of the vehicle. The motor tube is used to provide a space for the motor to be placed but must be properly secured in the rocket. Centering rings are used to attach the motor tube to the body of the vehicle to keep the motor in place during its operation. All motor retention designs that were considered use three centering rings placed equidistant from each other along the motor tube. These centering rings will act as an attachment between the motor tube and the body tube. The three materials considered for centering rings were plywood, fiberglass, and machined aluminum. The inner edge of the centering rings would be epoxied onto the motor tube using JB-Weld, and the

outer edge of the centering rings would be then be epoxied onto the body of the rocket using JB-Weld. The material of the centering rings was chosen through a weighted design matrix.
The following objectives listed in Table 8 are the criteria that will be used to compare the various centering ring designs. These criteria will be rated by the measures listed.

Table 8. Selected Criteria with appropriate weights

Objectives	Measures	Weight (1-5)
Structural Strength	Yield Strength (KSI)	3.5
Overall Weight	Density (oz/in^3)	2
Total Cost	$	2.5
Manufacturability	Time per centering ring (hrs)	3.5
Motor Retention strength	Available thicknesses of material in inches	4.5

Failure of the structural integrity of the motor rings during flight would result in multiple failure modes such as catastrophe during launch or a free-falling motor tube, motor casing, and motor during flight. As a result, the objective of structural strength of the chosen material must be met by the centering rings to ensure safe motor retention. Yield strength will measure the structural strength of the materials. This category received a moderate score of 3.5 due to the low probability of the centering ring material fully breaking during launch and flight. Most of the forces experienced from the motor will act as a shear force on the epoxy that is acting as the adhesive between the centering rings and the motor and body tube. Forces that will directly test the yield strength of the centering ring material will be experienced during landing impact. However, the airframe should absorb most of these forces. If the centering rings break during impact, the vehicle will not be able to relaunch, but there will not be failure during flight which is potentially more catastrophic.

The material of the centering rings should be lightweight to reduce the overall weight of the vehicle. This category will be measured in the density of each considered material. A lower vehicle weight will allow for a cheaper motor to be chosen. The centering rings will also be located at the bottom of the rocket. A large weight at the bottom of the rocket will lower the center of gravity and lower the stability of the rocket which should be avoided. Since the motor rings are small, their weight will be relatively small. As a result, this category received a relatively low weight of 2.

The cost of the centering rings should be low to ensure the project stays on budget. This category will be measured by price per centering ring for each material. Failure of the booster body tube or motor tube would require replacement of the centering rings since they will be permanently epoxied to both parts of the rocket. Since there are three centering rings, it should be cheap to replace them in case of failure. However, centering rings are low cost and replacement of them should not impact the budget substantially. As a result, the cost of the centering rings received a weight of 2.5 to reflect its moderate importance.

The ease of manufacturing the centering rings should be considered when selecting which material to choose for the centering rings. This category will be measured by the time it takes to manufacture a single centering ring for each material. It is important that the centering rings should take a short amount of time to manufacture. The failure of a motor tube or booster body tube would require all three centering rings to be replaced so it essential that this process is not time consuming. As a result, this category received a weight of 3.5.

The motor retention strength for each centering ring material must be considered since this is the motor rings primary function. The actual material of the motor ring will not affect this motor retention strength since the forces the vehicle will experience from the rocket will be experienced almost entirely as a shear force by the JB-Weld epoxy holding the motor and body tubes to the centering rings. The shear strength of the connection between the centering rings and the tubes will increase if more epoxy is used to establish this connection. As a result, this category will be measured in available thicknesses for each material. Higher available thicknesses will receive a higher score since more epoxy can then be applied to increase shear strength. This objective is incredibly important because failure of motor retention would result in catastrophic failure of the vehicle during launch or flight. As a result, this category received the highest weight of 4.5.

Table 9 details the scores each material received for each objective on a scale of 1-5.

Table 9. Centering Ring Selection Matrix

		Plywood			Fiberglass			Machined aluminum		
Attributes	**Weight**		Score	Weighted Score		Score	Weighted Score		Score	Weighted Score
Structural Strength	3.5	4.5-6 ksi	2	7	30 ksi	5	17.5	40 ksi	5	17.5
Weight	2	.321 oz/in^3	3.5	7	.149 oz/in^3	4.5	9	1.5607 oz/in^3	1	2
Cost	2.5	$6.78	5	12.5	$8.98	3	7.5	$10.33	2	5
Manufacturability	3.5	0	5	17.5	0	5	17.5	.67 hours	2	7
Motor Retention strength	4.5	.25”	4	18	.14”	2	9	.25”	4	18
				62			60.5			49.5

In conclusion, there will be three centering rings attached to the motor tube and to the body of the rocket with epoxy to keep the motor tube in place. The three centering rings will be located 1 inch, 9 inches, and 17 inches from the aft of the motor tube. These equidistant positions will allow the three centering rings to absorb equal amounts of force. The material used for the centering rings will be plywood based on the trade study detailed above.

3.3 Subscale Flight Results

Subscale launch went as projected with an apogee of 3733 feet, compared to the estimated 3392-foot apogee. The drift was well within reasonable margins, at roughly 1000 feet, despite somewhat windy weather. The wind driven drift was counteracted by angling the launch rail into the wind at about 20 degrees. The averaged recorded flight data from the two altimeters are shown in Figure 7.

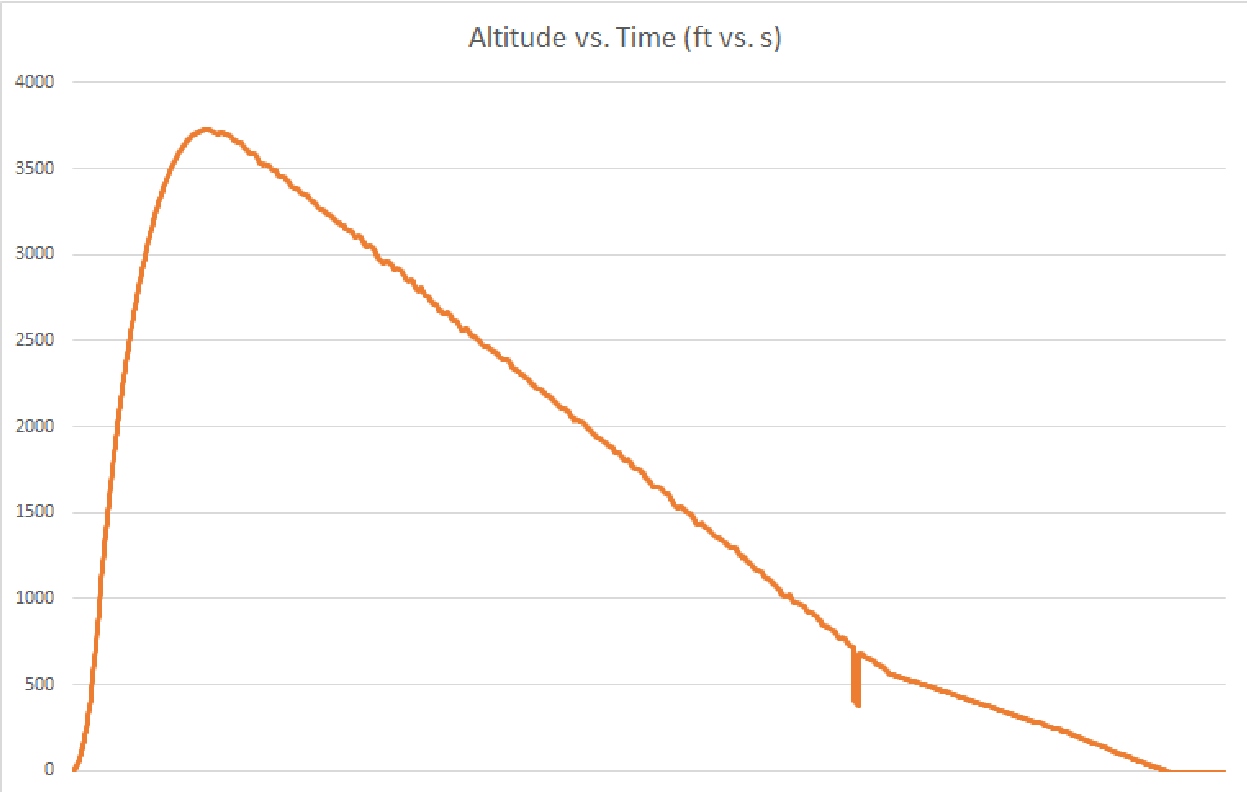


Figure 7. Graph of altimeters' averaged flight curve of the subscale rocket

Scaling Factor

The subscale launch vehicle was approximately 55% of the full-scale rocket length. Subscale was designed to imitate the full-scale launch vehicle as close as possible. The goal was to design sufficient space to pack parachutes while keeping the rocket as close to 50% of the full-scale rocket length. The subscale diameter was also 55% of the full-scale diameter due to a limited selection of body tubes available for purchase. The camera cover remained the same size on subscale as it will be on full scale since the actual camera will be the same between the two rockets. Fin brackets were shortened to accommodate the smaller fins that were needed for subscale.

The estimated drag coefficient of the fullscale rocket is approximately 0.54. This was done by taking the percentage error between subscale simulation apogee and subscale actual apogee, then modifying the fullscale simulation CD until the percent error in apogee's matched.

Structural Flight Analysis

From a structural standpoint, the subscale launch vehicle successfully fulfilled all derived and non-derived requirements. Specially designed components of the vehicle such as fin brackets and the camera cover survived flight with no issues. The airframe of the rocket experienced no buckling, abrasion, or shearing during subscale launch.

Recovery Flight Analysis

Recovery and flight data recorded during subscale launch closely reflected the predicted results. Figure 8 contains the projected flight curve of the subscale launch with the inclusion of payload mass that was absent from the subscale vehicle.

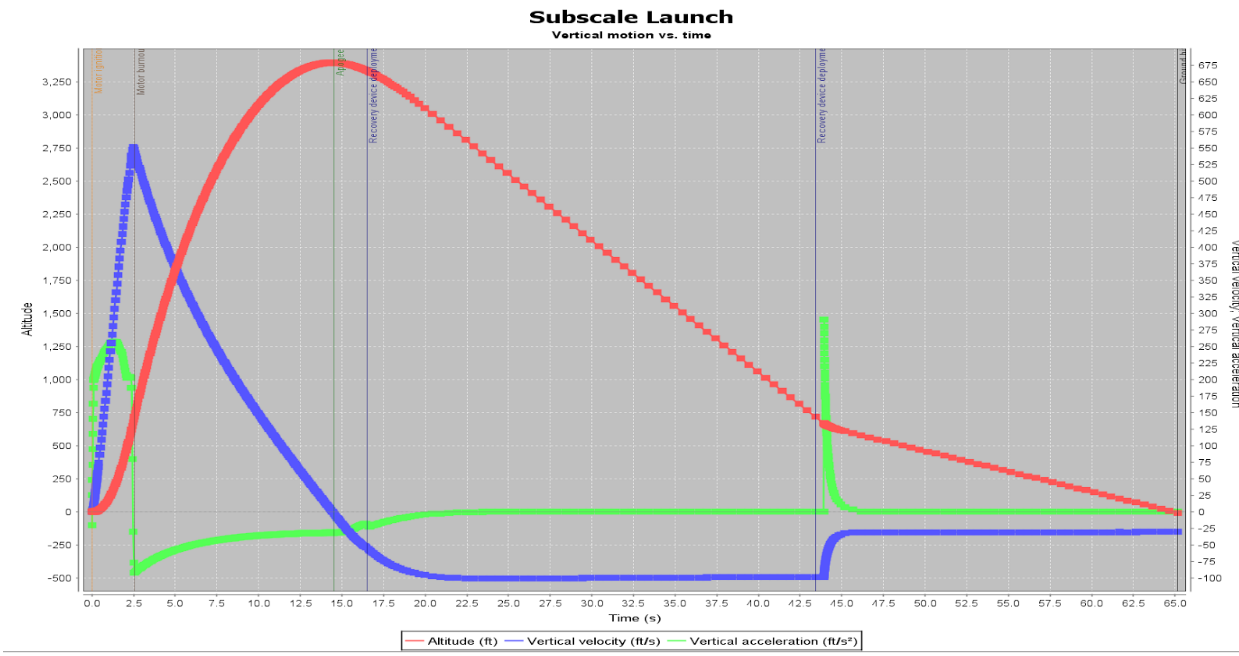


Figure 8. Projected flight curve of subscale launch including payload mass

When scaling the rocket, recovery considerations include the increased mass of the rocket, as projected by the structures subsystem, as well as an understanding that the increased surface area will create significant drag on the rocket while descending under drogue. For this reason, the descent under drogue of the fullscale rocket will appear more drastic when modeled using OpenRocket. LTRL's descent model better accounts for the drag on the airframe itself.

The discrepancy in the altitude of the rocket is due to the subscale being lighter without the weight of the payload. OpenRocket simulation of the vehicle without the payload mass, shown in Figure 9, is much more reflective of the launch with a predicted apogee of 3698 feet compared to an actual 3733 feet.

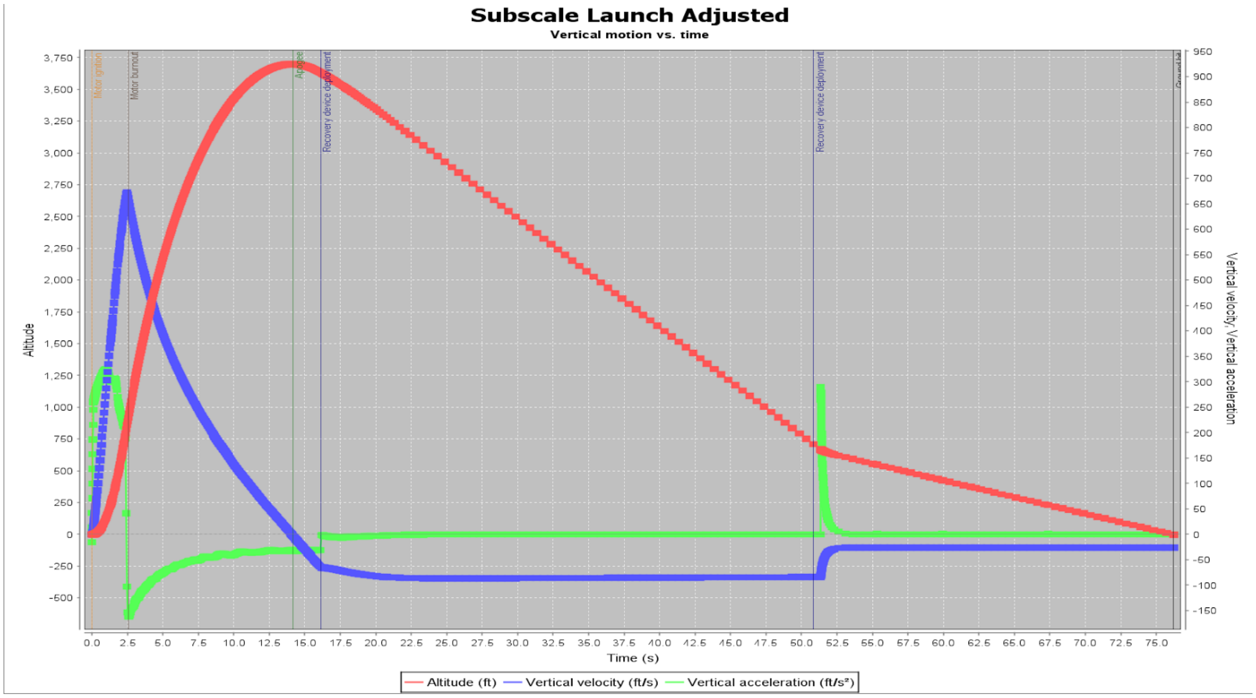


Figure 9. Projected flight performance excluding payload mass

Subscale's success has been a positive indicator that fullscale design is viable and the variance in predicted versus actual results is acceptable for mission success.

Results Summary

The subscale flight was a success and brought up no major issues in regard to the fullscale rocket design. The only change from the subscale rocket design to the fullscale rocket will be the placement of the actual camera. In the subscale rocket, the recording device for the camera was placed under a bulkhead that was screwed into the rocket. In the fullscale rocket, the recording device for the rocket will be screwed into the motor stop bulkhead. This bulkhead will be right under a coupler bulkhead that can be removed so there is easy access to the camera if needed. Other than the camera placement, LTRL's fullscale rocket design was verified through the subscale flight and there were no design changes made as a result.

3.4 Recovery Subsystem Selection

Final Component Selection

GPS Unit

In previous years, LTRL has used Garmin Astro trackers. While the Astro GPS unit worked well while it was new, it consistently suffered reliability and connectivity problems. Therefore, the A&R team determined a new tracking system was necessary. After some market research, the field was narrowed to three potential options: the Garmin Astro, the BRB9000 Tx/Rx, and the SPYTEC STI GL300. To choose between these options they were evaluated based on criteria described in Table 10.

Table 10. Scale Matrix for GPS Trade Study

	Maximum Score	Score of 1	Score of 5
Reliability	5	Not reliable for more than 10 flights	Completely reliable for over 20 flights
Range	5	1 mile, requires clear line of sight	10+ miles, does not require clear line of sight
Weight	5	Weighs more than 500g	Weighs less that 100g
Durability	5	Not able to be flown more than two or three times	Able to be used for all flights for two years
Ease of Use	5	Not easy to use and very particular to set up. Difficult or unable to access data.	Easy to setup and use on launch day. Easy to access data.

Each GPS option was assigned a score for each of the above criteria to evaluate the best option. The scores for each category, as well as their weighted scores and the total scores for each option, are shown in Table 11.

Table 11. Selection Matrix for GPS Unit

		Garmin Astro 320		**BRB9000 Tx/ Rx GPS Telemetry System**		**SPY TEC STI GL300**	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Reliability	5	4	20	3	15	3	15
Range	5	5	25	2	10	5	25
Weight	3	2	6	5	15	4	12
Durability	4	2	8	3	12	3	12
Ease of Use	4	2	8	1	4	3	12
Price	3	1	3	2	6	4	12
Total Score			70		62		88

The BRB9000 Tx/Rx requires a clear line of sight to the rocket and an amateur HAM radio certification, therefore this GPS unit is impractical for LTRL because the rocket is not always within a clear line of sight and no one in the club has a HAM radio certification. This year LTRL has selected to use the SPY TEC STI GL300 GPS unit. This unit was chosen during PDR and this will be the final GPS unit.

Avionics Board Material

Historically, LTRL has used fiberglass for the avionics board. While this material is very sturdy, it is hazardous and difficult to work with. Last year, LTRL used 3D printed avionics boards for the subscale and full-scale rocket. The 3D printed avionics boards were precise, compact, and fully customizable. Fiberglass and 3D printed boards were again the option for the fullscale avionics board. The criteria described in Table 12 were used to choose between these options.

Table 12. Scale Matrix for Avionics Board Material Trade Study

	Maximum Score	Score of 1	Score of 5
Weight	5	Weighs more than 700g	Weighs less than 500g
Durability	5	Not able to be used for more than 10 flights	Able to be used for more than 20 flights
Ease of Construction	5	Not able to be drilled or filed easily and precisely with basic tools or manufactured	Able to be built exactly to size easily and not hazardous
Price	5	More than $20 to produce	Less than $15 to produce
Specific Strength	5	Specific strength less than 100 kNm/kg	Specific strength greater than 1000 kNm/kg

The criteria laid out in Table 12 were applied to the two material options in Table 13.

Table 13. Selection Matrix for Avionics Board Material

		3D Printed		Fiberglass	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score
Weight	4	4	16	2	8
Durability	5	3	15	5	25
Ease of Construction	4	5	20	2	8
Price	2	5	10	3	6
Specific Strength	3	2	6	5	15
Total Score			67		62

This year, the avionics board will be 3D printed because, as seen in Table 12 and Table 13, the 3D printed material has the desired attributes for the avionics board.

Charges

The method used to separate the rocket and deploy the recovery system is essential for the nominal operation of the rocket and the safety of bystanders. For the purposes of this study, a CO_2 cartridge and blasting cap to open the canister is considered a "charge". After market selection for separation charges, the options were narrowed down to a CO_2 ejection system, Pyrodex charges, and Black Powder charges. The CO_2 system utilizes a CO_2 cartridge with a blasting cap that drives a pin that opens the charge. The Pyrodex and Black Powder are both explosives that have similar properties, but the Pyrodex only ignites when it is compacted, unlike the Black Powder. The metrics used to select the ejection charge are described in Table 14.

Table 14. Scale Matrix for Charges Trade Study

	Maximum Score	Score of 1	Score of 5
Adjustability	5	Only one fixed charge size.	No fixed charge size, completely variable charge size.
Ease of Use	5	Not easy to assemble or measure	Easy to assemble and use on launch day and for testing
Reliability	5	Does not deploy as expected on every flight or test	Detonates as expected every time used
Price	5	More than $200 for 15 uses	Less than $100 for 15 uses
Safety	5	Not safe to use or store in the lab, hazardous	Safe to handle and does not require special storing

Each design option was then assigned a score for each metric based on the thought process described in Table 14. These scores were then multiplied by the weights for that category and summed to evaluate the best option. This process is described in Table 15.

Table 15. Selection Matrix for Charges

		CO_2		Pyrodex		Black Powder	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Adjustability	5	2	10	5	25	5	25
Ease of Use	5	2	10	3	15	5	25
Reliability	5	3	15	4	20	5	25
Price	4	2	8	4	16	5	20
Safety	5	4	20	3	15	2	10
Total Score			68		91		105

Based on the results from Table 15, the charges used this year for the parachute deployment system will be black powder charges. This is predominantly due to the affordability, strength adjustability, and ignition reliability of black powder. The CO_2 charges have not been used often and there are only two options for the charge sizes, 12g and 8g. The lack of adjustability is a significant disadvantage. Pyrodex, while comparable to black powder, often experiences incomplete combustion due to having to be packed so tightly and is, therefore, less reliable. The final choice is currently black powder but that is subject to change if there are any safety concerns.

Bulkhead Material

LTRL has used fiberglass and layered plywood bulkheads in past years and they have both been sturdy and successful. This year, Penn State has access to a laser cutter that can cut solid/ hardwoods, which makes red oak a viable option to consider. These options were evaluated based on the criteria described in Table 16.

Table 16. Scale Matrix for Bulkhead Material Trade Study

	Maximum Score	Score of 1	Score of 5
Ease of Use	5	Difficult to manufacture, drill, and adjust	Easy to manufacture, drill, and adjust
Price	5	More than $10 for two bulkheads	Less than $5 for two bulkheads
Specific strength	5	Specific strength less than 100 kNm/kg	Specific strength greater than 1000 kNm/kg
Safety	5	Hazardous to drill and file in the lab	Not hazardous to drill and file in the lab

Each option was then assigned a score for each metric based on Table 16. These scores were then used to choose the best option, as shown in the study performed in Table 17.

Table 17. Selection Matrix for Bulkhead Material

		Layered Plywood		Fiberglass		Red Oak	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Ease of Use	5	3	15	2	10	5	25
Price	2	3	6	1	2	4	8
Specific strength	5	3	15	5	25	1	5
Safety	5	3	15	1	5	5	25
Total Score			51		42		63

Table 17 shows that the red oak, with the advantage of using the laser cutter, is the best option. This newly available technology will allow LTRL to make exceptionally accurate and precise cuts, increasing the design options for a custom bulkhead. The red oak is going to be extremely easy to modify and will simplify the assembly of the avionics bay by allowing the holes for all-thread rods to align more accurately. Red oak is currently the final choice for the bulkheads, however, it remains to be experimentally proven that red oak will be strong enough. If red oak is not strong enough, then plywood will be used. Plywood has been used for many rockets, including the USLI rocket for last year so LTRL is certain that it would work for the rocket this year.

Avionics Bay Design

Compared to last year's AV bay design, this years provides certain distinct advantages. It is far more accessible than last year's, which needed to be totally disassembled to do anything within the AV bay. Without sacrificing thermal resistance or strength, this year's design is more precise and easier to assemble. This year's design is also heavier, but the ease of assembly and access is worth the weight cost as seen in Figure 10.

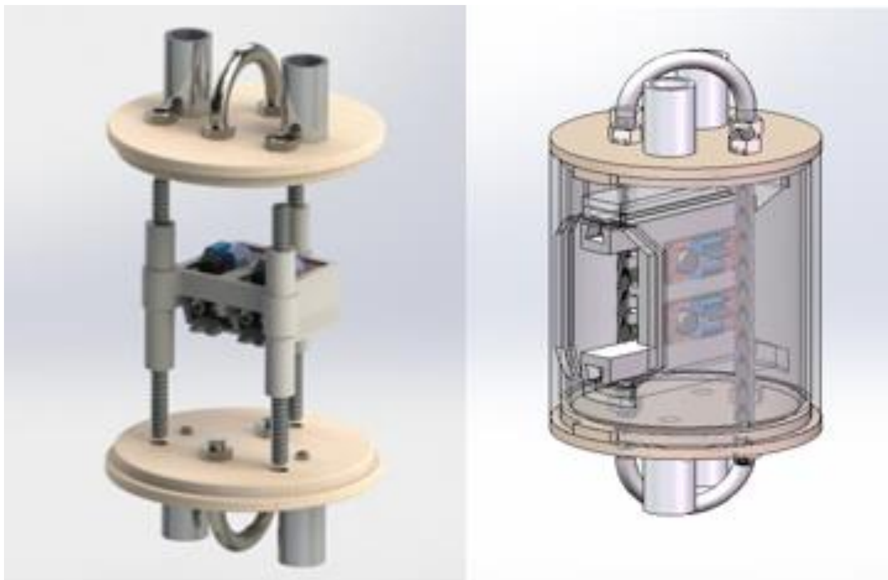


Figure 10. (Left) 2016-17 Av Bay Design, (Right) 2017-18 Av Bay Design

These two options were then evaluated based on the criteria described in Table 18. Each option was then assigned a score for each metric. These scores were used to choose the best option, as shown in the study performed in Table 19.

Table 18. Scale Matrix for Avionics Board Trade Study

	Maximum Score	Score of 1	Score of 5
Accessibility	5	Rocket must be completely disassembled to access the AV bay	AV bay is accessible without having to disassemble any part of the rocket
Mass	5	Weighs more than 500g	Weighs less than 100g
Ease of Assembly	5	Assembly takes more than 35 minutes	Assemble takes less than 10 minutes
Precision	5	Each part is not guaranteed to fit initially and requires sanding	Each part is manufactured to be the the exact dimensions required

Table 19. Selection Matrix for Avionics Bay

		Triangular Bay		AV Bay with door	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score
Accessibility	4	1	4	4	16
Mass	3	3	9	2	6
Ease of Assembly	4	2	8	3	12
Precision	2	3	6	4	8
Total			27		42

Based on the selection matrix above, LTRL will be making the 3D printed avionics bay with the door. A prototype of this avionics bay has already printed successfully so LTRL is confident that the avionics bay can be produced for the fullscale rocket.

3.5 Recovery Components

The components of the recovery system are the avionics board, the avionics bay structure, the parachutes and their corresponding harnesses, the altimeters, the faraday cage, and the method of parachute deployment.

Avionics Board

The avionics board will be a 3D printed sled that will slide into the avionics bay structure. It will contain the altimeters and their independent corresponding power supplies. The avionics board will be secured to the avionics bay structure when the door to access the avionics board is closed. This door will ensure that the avionics board will not slide out of place. The avionics board and avionics bay structure will be made of PLA. This material is one the strongest and most resilient 3D printing filaments. The club has successfully used this material for avionics boards and avionics bay structures for many flights.

Of the avionics bay options shown below in Figure 11, the design with the door feature was chosen due to the selection matrix. This will be the first time that A&R will use an avionics bay that is accessible without having to completely disassemble the rocket. This will allow A&R to access the avionics bay easily to secure any loose wires or check any connections.

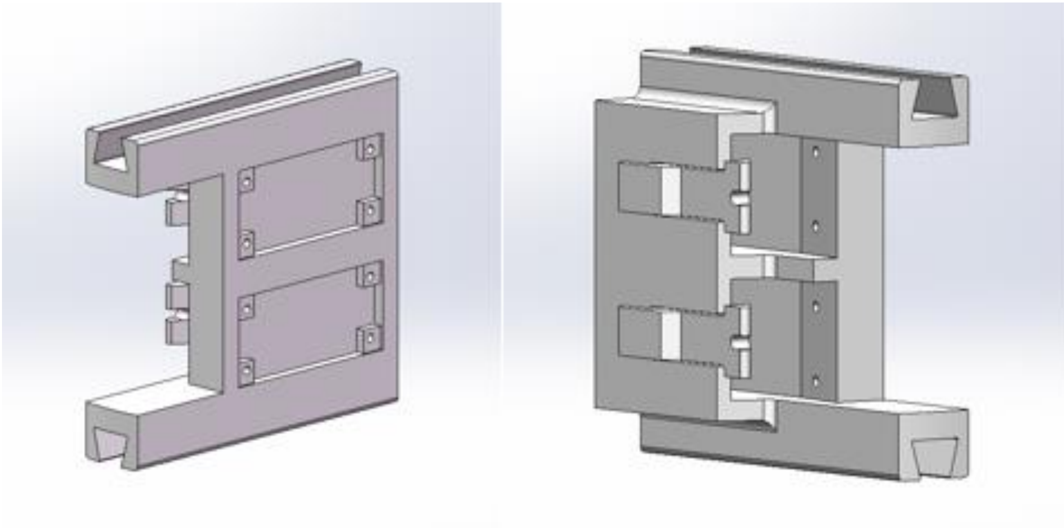


Figure 11. (Left) Altimeter Placement Area, (Right) Battery Placement Area

Avionics Bay Structure

The avionics bay is situated within the coupler below the main parachute and above the drogue parachute. As shown in Figure 12, the avionics bay is the combination of the avionics board and the avionics bay structure. The AV bay will be entirely 3D printed, using PLA filament. The AV bay is 6 inches tall, and the outer diameter of the AV bay will be the same as the inner diameter of the coupler. The AV bay will be epoxied and screwed into the coupler. The AV bay has a door that makes the interior accessible from outside the rocket without disassembling the AV bay. The door will be cut from the outside body of the rocket, and will be screwed into the coupler, so that it is flush with the body of the rocket. The switches to turn on the altimeters will be accessible interiorly. The door will allow easy access to the avionics board.

The AV bay is also designed to hold a faraday cage, which will be continuous around the sides, on the bulkheads, and in the door. The faraday cage will slide between the anterior and interior walls of the AV bay. It will also be secured to the door and bulkheads so when they are screwed in, the parts of the cage on them will contact the part of the cage within the AV bay.

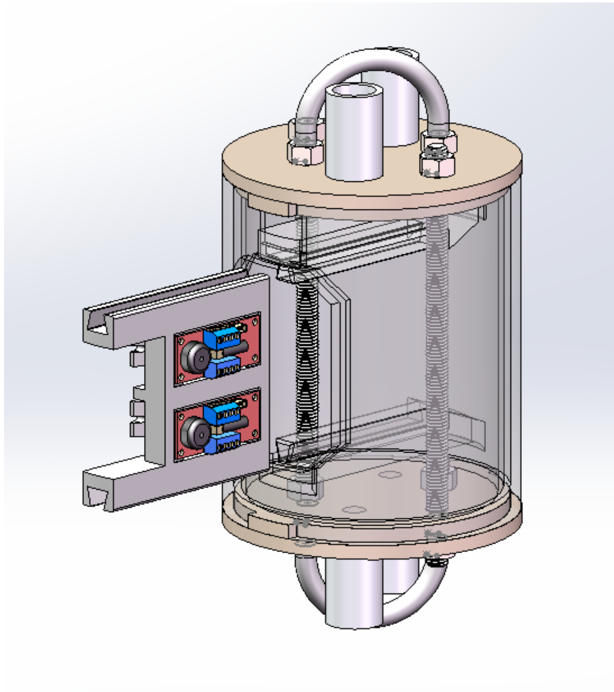


Figure 12. Avionics Bay

The bulkheads will be laser cut and made of red oak. There is still testing to be done to verify that the red oak will be strong enough to withstand the forces endured during descent. The ability to laser cut the bulkheads will allow the avionics bay to be assembled more quickly since the holes will be perfectly aligned.

Avionics Bay Electronics and Charges

The avionics bay will feature two fully independent Stratologger CF altimeters. These altimeters have been successfully used for several flights and are commercially available. Each altimeter will be connected to an internally accessible switch.

The current plan is to use black powder for the ejection charges. From the selection matrix, it should be used but due to safety concerns, A&R is going to do further testing on the other two ejection charge choices. It would be safer to use pyrodex or CO2 as ejection charges, but those options have not been verified to as reliable as black powder. With further testing, A&R could gain familiarity with the materials and be able to guarantee successful ejection charges using pyrodex or CO2. Black powder has been used for every rocket flight for two years now and it has detonated every time. The reliability of black powder is what makes it so appealing to A&R.

Parachutes and Recovery Harnesses

The drogue parachute will be a 12” Fruity Chutes Classical Elliptical and the main parachute will be an 84” Fruity Chutes Iris Ultra Compact. These parachutes were chosen using LTRL’s MATLAB code and verified using OpenRocket. The drogue parachute will deploy at apogee and the main parachute will deploy at 700ft ABG.

The parachutes will be attached to the rocket using 0.5” kevlar cord. This cord is heat and fire resistant and more than sufficiently strong enough to withstand the forces of the parachutes and rocket during descent. The kevlar cord will be attached to the rocket and parachutes using ⅜” quicklinks. Both the kevlar cord and the quicklinks were used in the USLI competition last year and were successful.

The main parachute will have a recovery harness of 40ft and the drogue parachute will have a recovery harness of 30ft. There will be at least one fireball for each parachute that will prevent zippering. The lengths of the recovery harnesses should be sufficient to prevent zippering but the addition of fireballs with further guarantee it. A diagram of the planned recovery system is shown in Figure 13.

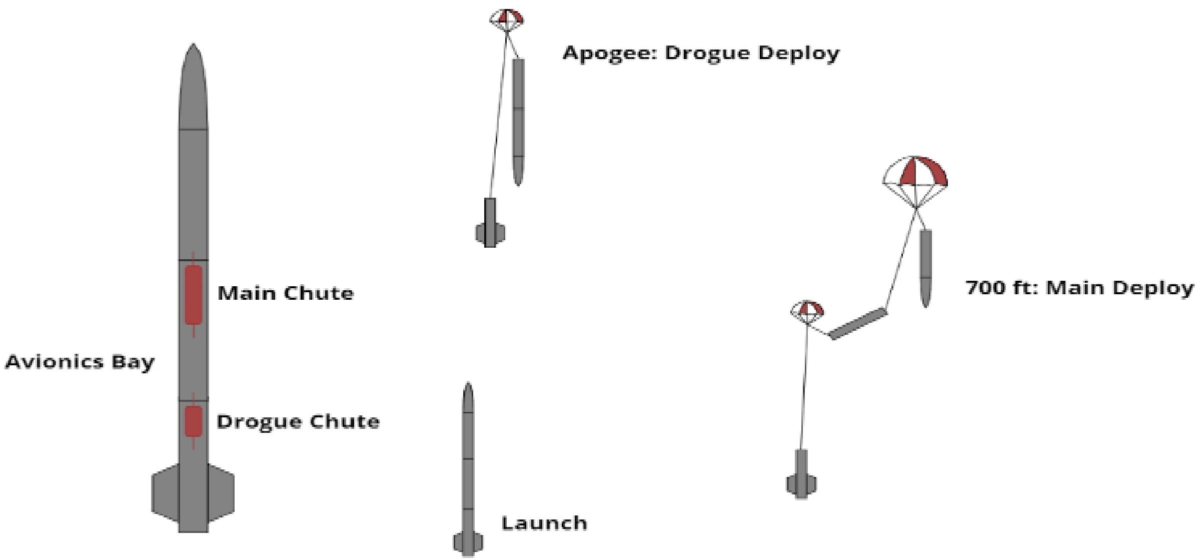


Figure 13. Parachute and Recovery Harness Diagram

Proof of Redundancy

The avionics system design includes multiple layers of redundancy. First and foremost, there are two altimeters. Each altimeter is linked to its own separate main and drogue charge. Each altimeter is also powered by its own battery. Therefore, even with the failure of a battery, altimeter, initiator, or charge ignition in one of the systems, the other system is completely independent and should still operate correctly. The deployment charges are also staggered by one second so that they do not go of simultaneously, a precaution taken to avoid overpressure events. The redundancy allows LTRL to ensure that the parachutes will deploy and that the rocket will not have ballistic descent.

3.6 Mission Performance Predictions

Final Flight Vehicle

An OpenRocket model was created to simulate flight and vehicle characteristics. This model was used to calculate the static stability margin, the center of pressure (CP), and the center of gravity (CG). The CP is located 89.98 in. aft of the tip of the nose cone, and the CG is located 70.34 in. aft of the tip of the nose cone. The final flight vehicle has a diameter of 5.5 in., with a static stability margin of 3.5 calibers. The OpenRocket model is shown in Figure 14, with a breakdown of the component weights used within the model shown in Table 20. The target apogee of exactly 1 mile will be achieved through altering the rocket's mass very slightly via incorporated ballast, along with improving the model of drag calculation and thrust curve for more accurate apogee calculation. Improvements to modeling the rocket's flight will be made via static motor testing at Penn State’s High Pressure Combustion Lab and experimental data from wind tunnel testing using a closed-circuit wind tunnel.

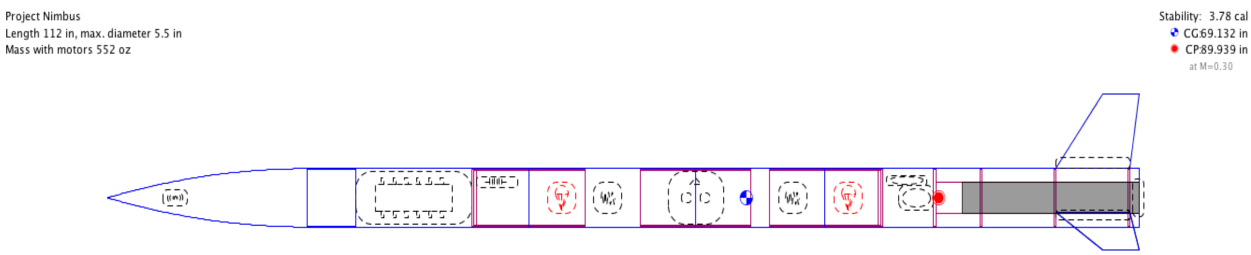


Figure 14. Fullscale OpenRocket Model

Table 20. Component weights

Component	Weight (oz)
Nose Cone	50.7
Payload Section	83.6
Payload-Main Coupler	11.4
Main Parachute Section	59.1
Main-Drogue Coupler	82.9
Drogue Parachute Section	37.4
Drogue-Booster Coupler	6.9
Booster Section	212.3
Fins (all three)	25.3
Fin Brackets (all three)	11.4

The simulated flight profile, detailing altitude, and vertical velocity versus time, are shown in Figure 15.

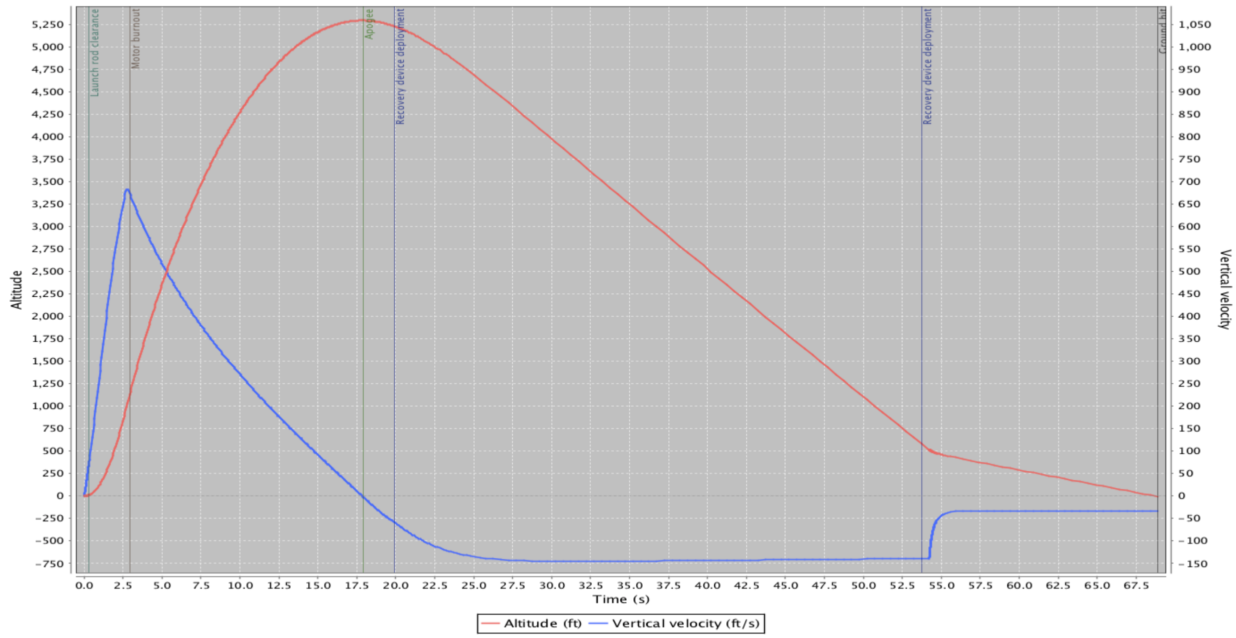


Figure 15. Flight characteristics with the L1390

It is shown in Figure 15 that a maximum velocity of 683 ft/s is reached just before motor burnout at 2.9 seconds and an altitude of approximately 1000 ft. This maximum velocity is well within the imposed limit of Mach 1 and occurs a safe distance from the launch pad. The rocket's velocity off a 10 ft rail is 71.6 ft/s, which is well above the imposed minimum of 55 ft/s and above the team's mission success criteria of 65 ft/s.

As in indicated in Figure 16, the stability off the launch rail is 2.49 calibers. This is above the team's mission success criteria and is indicative of a very stable flight, even in the low-velocity/low-altitude regime. As propellant mass decreases, the stability increases to approximately 4.25 calibers before leveling off around 4.0 calibers during the coast to apogee.

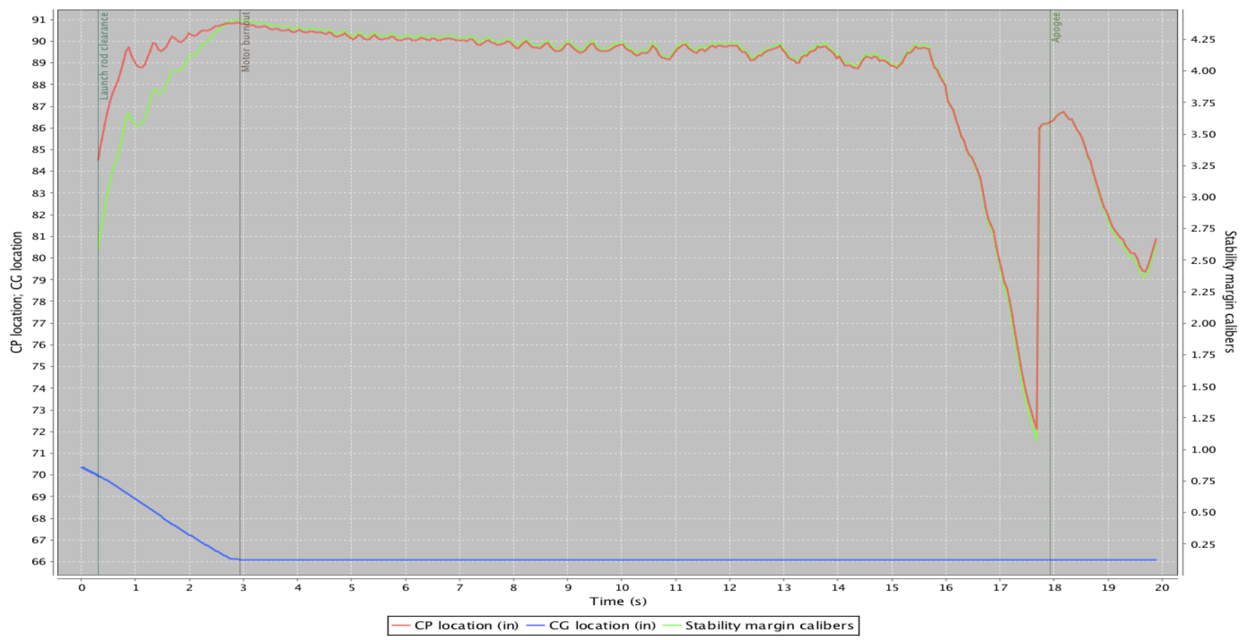


Figure 16. Stability Caliber for final flight vehicle

It is apparent that the thrust curve for the Aerotech L1390 motor has the necessary characteristics to achieve the minimum rail velocity for stable flight as the rocket leaves the pad. To more accurately characterize the thrust of the motor, static testing will be performed at Penn State's High Pressure Combustion Lab.

Verification of OpenRocket

To verify the OpenRocket simulation results, the center of pressure, center of gravity, and flight apogee were calculated using MATLAB.

To calculate the center of pressure, the following calculations were conducted. First, the center of pressure of the nosecone, X_n, was calculated using Equation 1.

$$X_n = 0.466 * L_n \tag{1}$$

X_n is the location of the center of pressure for the fins as measured from the tip, and L_n is the length of the nose cone. The center of pressure of the fins was then calculated using Equation 2.

$$X_f = X_b + \frac{X_r * (C_r + 2 * C_t)}{3 * (C_r + C_t)} + \frac{1}{6} * \left(C_r + C_t - \frac{C_r * C_t}{C_r + C_t}\right) \tag{2}$$

X_f is the location of the center of pressure of the fins as measured from the tip, X_b is the length from the tip to the fin root chord, X_r is the length from the fin root leading edge to the fin tip leading edge, C_r is the fin root chord length, and C_t is the fin tip chord length. The coefficient for the center of pressure of the fins, C_{nf}, was calculated using Equation 3.

$$C_{nf} = 1 + \frac{R}{S+R} * \frac{4N\left(\frac{S}{D}\right)^2}{1 + \sqrt{1 + \left(\frac{2 * Lf}{C_r + C_t}\right)^2}} \tag{3}$$

Where R is the radius of the rocket body, S is the semi span of the fins, N is the number of fins, and L_f is the length of fin mid-chord line. The center of pressure as measured from the tip, X, was calculated using Equation 4.

$$X = \frac{C_{nn} * X_n + C_{nf} * X_f}{C_{nn} + C_{nf}} \tag{4}$$

Where C_{nn} is the coefficient for the center of pressure for the nose cone. The center of pressure was calculated to be 89.98 inches aft of the tip.

To calculate the center of gravity, cg, Equation 5 was used.

$$cg = \frac{d_n * m_n + d_p * m_{payload} + d_m * m_m + d_d * m_d + d_b * m_b}{M} \tag{5}$$

Where d_n is the distance from the center of mass of the nose cone to the tip, m_n is the mass of the nose cone, d_p is the distance of the center of mass of the payload section to the tip, $m_{payload}$ is the mass of the payload section, d_m is the distance of the center of mass of the main parachute section to the tip, m_m is the mass of the main parachute section, d_d is the distance of the center of mass of the drogue section to the tip, m_d is the mass of the drogue section, d_b is the distance of the center of mass of the booster section to the tip, m_b is the mass of the booster section, and M is the total mass of the rocket.

The center of gravity was calculated to be 68.99 in. aft of the tip.

To calculate the flight apogee, the altitude at which the motor burnout occurs must first be calculated. To calculate the burnout altitude, first the average mass, m_a, must be calculated. The average mass was calculated using Equation 6.

$$m_a = m_r + m_e - \frac{m_{prop}}{2} \tag{6}$$

Where m_r is the mass of the rocket without a motor, m_e is the mass of the motor, m_{prop} is the mass of the propellant. The aerodynamic drag coefficient, k, was calculated using Equation 7.

$$k = \frac{1}{2} * \rho * C_d * A \tag{7}$$

Where ρ is the density of air, C_d is the drag coefficient, and A is the cross-sectional area of the rocket. The burnout velocity, q_1, was calculated using Equation 8.

$$q_1 = \sqrt{\frac{T - (m_a * g)}{k}} \quad (8)$$

Where T is the average thrust of the motor, ma is the average mass of the rocket, and g is the gravitational constant. The burnout velocity decay coefficient, x_1, was calculated using Equation 9.

$$x_1 = \frac{2 * k * q_1}{m_a} \quad (9)$$

The burnout velocity, v_1, was calculated with Equation 10.

$$v_1 = q_1 * \frac{1 - e^{-x_1 * t}}{1 + e^{-x_1 * t}} \quad (10)$$

Where t is time at motor burnout. Finally, the altitude at which the motor burnout occurs, y_1 was calculated using Equation 11.

$$y_1 = -\frac{m_a}{2 * k} * \ln\left(\frac{T - (m_a * g) - (k * {v_1}^2)}{T - m_a * g}\right) \quad (11)$$

With the burnout altitude known the total altitude coasted can be calculated. To calculate the cost distance, the coast mass, m_c, must first be calculated. The coast mass was calculated using Equation 12.

$$m_c = m_r + m_e - m_{prop} \quad (12)$$

Where m_r is the mass of the rocket, m_e is the mass of the motor, and m_{prop} is the mass of the propellant. Next, the coast velocity coefficient, q_c, was calculated using Equation 13.

$$q_c = \sqrt{\frac{T - m_c * g}{k}} \quad (13)$$

Where T is the average thrust of the motor, g is the gravitational constant, and k is the aerodynamic drag coefficient. The coast velocity decay coefficient, x_c, was calculated using Equation 14.

$$x_c = \left(\frac{2 * k * q_c}{m_c}\right) \quad (14)$$

The coast velocity, v_c, was calculated using Equation 15.

$$v_c = q_c * \frac{1 - e^{-x_c * t}}{1 + e^{-x_c * t}} \tag{15}$$

The coast distance, y_c, was calculated using Equation 16.

$$y_c = \frac{m_c}{2 * k} * \ln\left(\frac{m_c * g + k * v_c^2}{T - m_c * g}\right) \tag{16}$$

Lastly, the flight apogee altitude, PA, was calculated using Equation 17.

$$PA = y_1 + y_c \tag{17}$$

The flight apogee altitude was calculated to be 5261 ft. The code used to calculate these values can be seen in Appendix C: Verification of OpenRocket Flight Calculations.

With the results of both simulation techniques, the team compared the two sets of results. A comparison to of the OpenRocket results and the MATLAB results can be seen in Table 21.

Table 21. Simulation Results Comparison

	OpenRocket	MATLAB
Center of Pressure (inches from tip)	89.98	89.49
Center of Gravity (inches from tip)	70.35	68.99
Static Stability (Calibers)	3.5	3.65
Altitude at Apogee (feet)	5291	5261

The results were very similar, yet not identical. This change is likely due to the estimated drag coefficient being different. Despite this discrepancy, the two outcomes had a very low margin of error. To calculate the margin of error the following equation is used:

Margin of error = |(OpenRocket - MATLAB) / OpenRocket| * 100

The margins of errors can be seen in Table 22.

Table 22. Margin of Error

	Margin of Error
Center of Pressure	0.545%
Center of Gravity	1.93%
Static Stability	4.29%
Altitude at Apogee	0.567%

All the margins of error are less than 5%, this indicates that the simulations used in OpenRocket are highly accurate.

Kinetic Energy Calculations

LTRL's MATLAB rocket descent simulation program runs a recovery model in which the force balance between gravity and drag is integrated over time with separate phases for drogue and main. The model also assumes that the parachutes do not deploy instantaneously, but rather in a linear fashion, as the area increases linearly with respect to time until the deployment time is complete. The parameters of the parachute's coefficients of drag are based on both the manufacturer's specifications and the experimentally derived values. The experimental results are from previous USLI competition launches and they indicate that the manufacturer provided values for main parachutes are generous. This trend has lead LTRL to make conservative choices regarding the main parachute sizing until more data is gathered from this season's fullscale test launches. The result of a conservative main parachute selection is a parachute that is one size larger than that which is minimally sufficient to manage the kinetic energy. In this case, an 84" main parachute was chosen over a 72" parachute. Using the conservative coefficient of drag, 2.0, a main of 72" results in a maximum kinetic energy at landing exceeding 75 ft-lb, while an 84" man results in 68 ft-lb. The manufacturer's coefficient of drag, 2.2, puts the kinetic energy under the 84" at a more reasonable 62.5 ft-lb. Figure 17 and Figure 18 display the function of maximum kinetic energy versus parachute size for each of the coefficients of drag. A full-scale launch under the 84" parachute will provide information about where the coefficient of drag falls between these values.

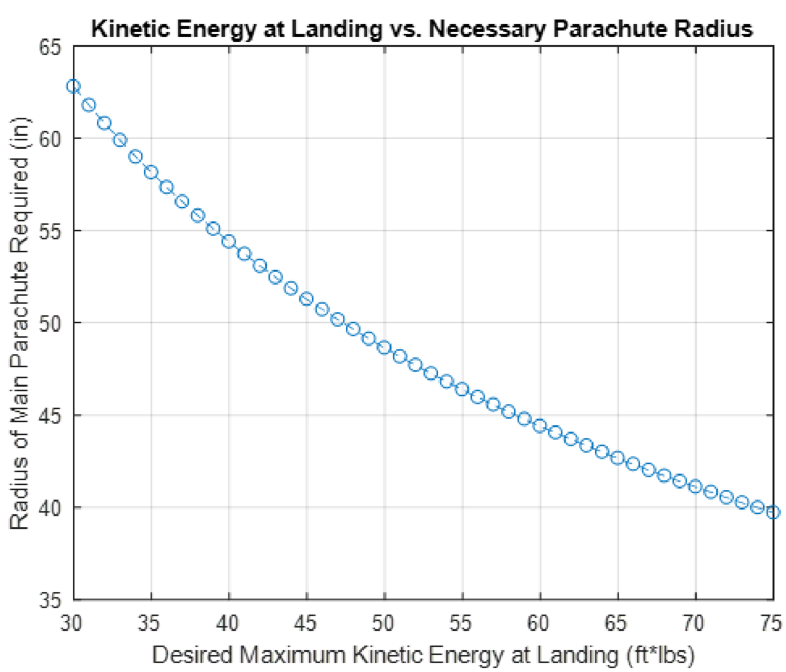


Figure 17. MATLAB Model of Kinetic Energy vs. Parachute Radius with CD = 2.2

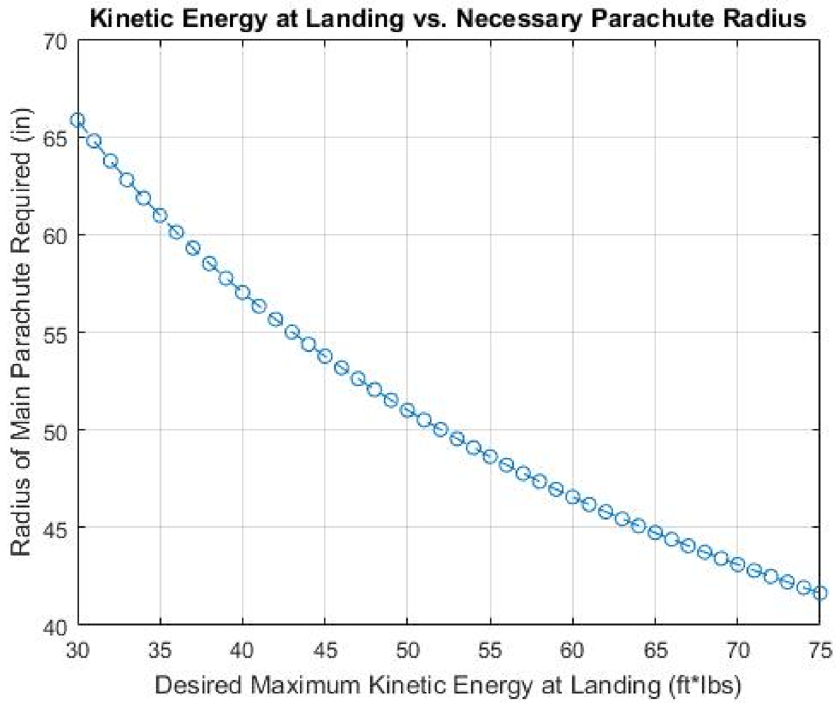


Figure 18. MATLAB Model of Kinetic Energy vs. Parachute Radius with CD = 2.0

The MATLAB simulation's predicted landing velocity of the rocket is 18.83 ft/s with a coefficient of drag of 2.2 and 17.98 ft/s with a coefficient of drag of 2.0. Calculations of kinetic energy can then be done by simply using the kinetic energy equation, which is a function of velocity and mass. The rocket's descent speed is plotted below for both coefficients of drag. The kinetic energy results for each section are shown following in table below for each coefficient of drag.

Table 23 and Table 24 show the kinetic energy of different components of the rocket throughout descent at both Cd values in question. Both tables show that the rocket will be significantly above kinetic energy limits before the main parachute deploys but at the landing, the rocket will be below the kinetic energy limit. The data shows that even if the parachute coefficient of drag is lower than the manufacturer states, the rocket will still land within the safe kinetic limit.

Table 23. Kinetic Energy of Parts During Descent Using a 2.2 Cd Main Parachute

Section	Mass (oz)	KE at Main Deployment (ft-lb)	KE Right Before Landing (ft-lb)
Nose cone	146.7	1778	46.06
Avionics bay	152.7	1854	47.97
Booster	199	2416	62.50

Table 24. Kinetic Energy of Parts During Descent Using a 2.0 Cd Main Parachute

Section	Mass (oz)	KE at Main Deployment (ft-lb)	KE Right Before Landing (ft-lb)
Nose cone	146.7	1780	50.55
Avionics bay	152.7	1855	52.63
Booster	199	2416	68.57

This data can be further visualized in Figure 19 and Figure 20. These figures show the expected altitude and velocity vs time for both Cd values, 2.2 and 2 respectively. In addition, the accuracy of the model can be seen due to its ability to consider factors such as varying air density and parachute deployment speed. These can be seen by a drop in velocity during stable descent and a curved (non-instantaneous) change in velocity at main deployment.

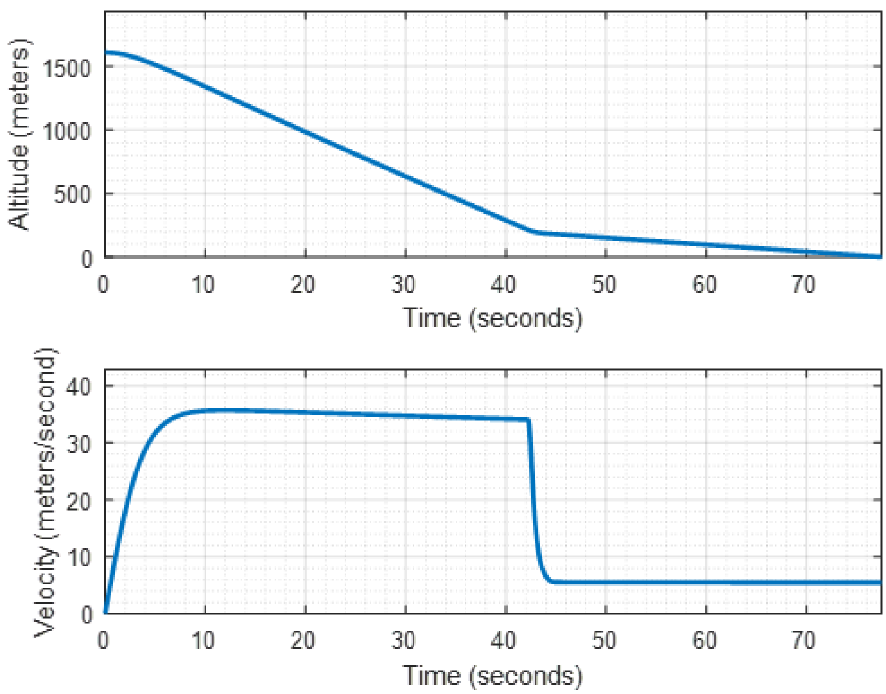


Figure 19. MATLAB Models of Descent and Altitude vs. Time with C_D = 2.2

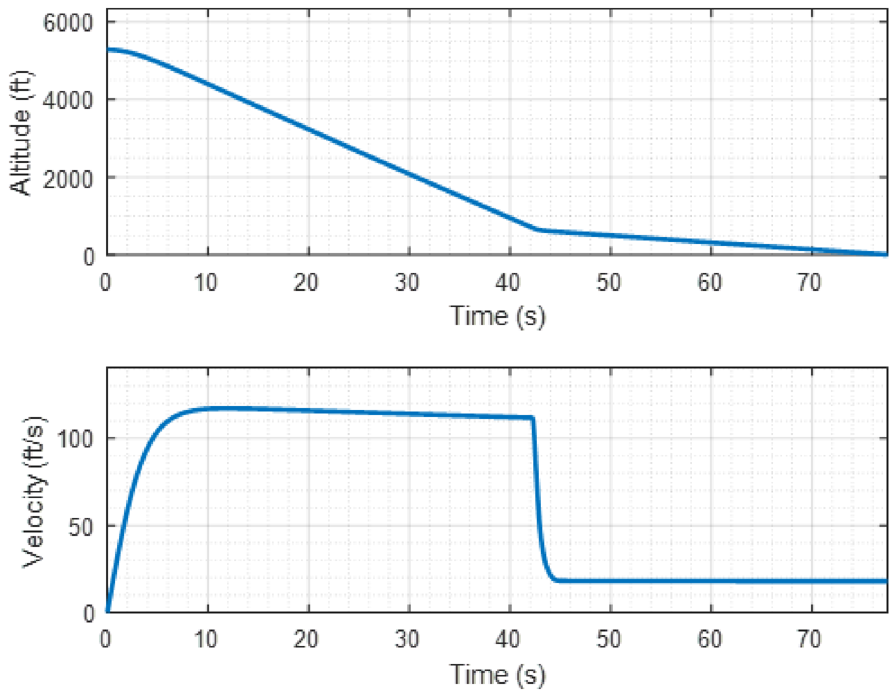


Figure 20. MATLAB Models of Descent and Altitude vs. Time with C_D = 2.0

A secondary method of determining kinetic energy is through OpenRocket's descent velocity predictions. The results for a coefficient of drag of 2.0 is a landing velocity of 19.19 ft/s and for 2.2 is 18.44 ft/s. Calculations of kinetic energy can then be done by simply using the kinetic energy equation. The rocket's altitude, speed, and acceleration are plotted in Figure 21 for a coefficient of drag of 2.2. The kinetic energy results for each section are shown following in Table 25 for each coefficient of drag.

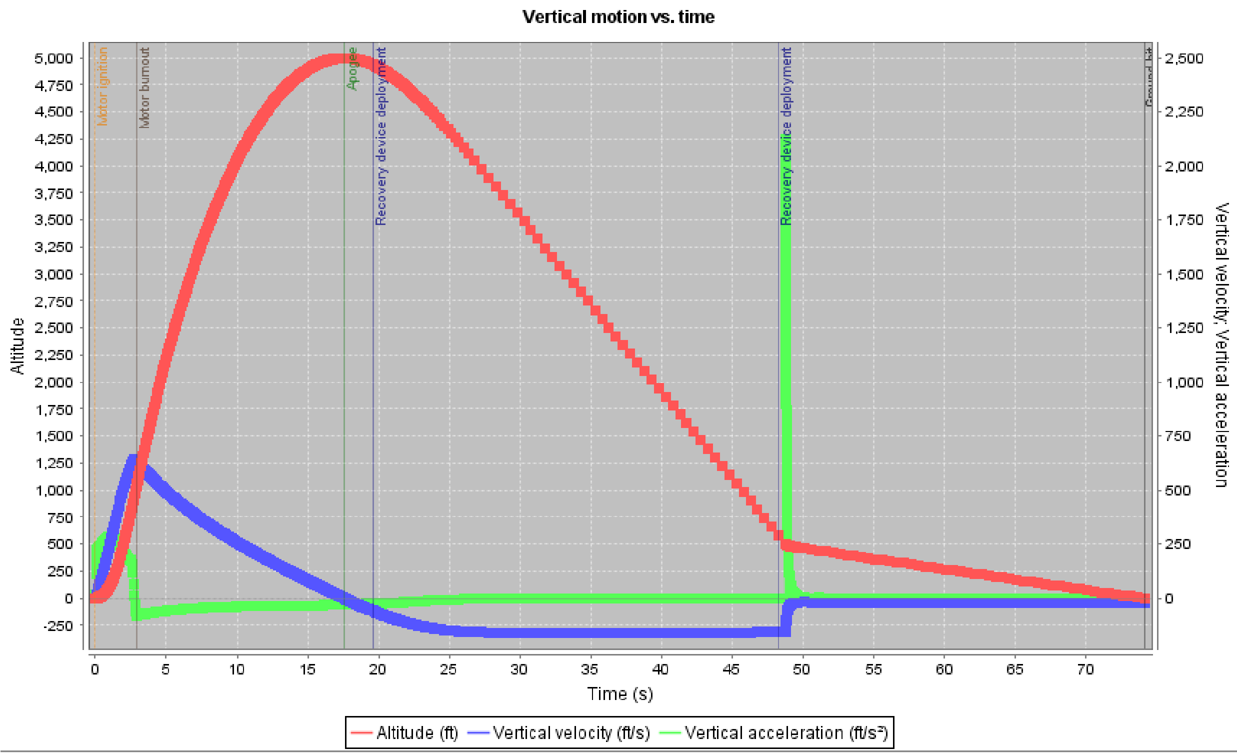


Figure 21. L1390 Flight Simulation

Table 25. Kinetic Energy upon Landing of Each Component

Section	Mass (oz)	Kinetic Energy (ft-lb) C_D = 2.0	Kinetic Energy (ft-lb) C_D = 2.2
Nose cone	146.7	52.48	48.44
Avionics bay	152.7	54.62	50.42
Booster	199	71.20	65.71

The conclusion has been reached that the predictions for descent speed and therefore kinetic energy differ because OpenRocket does not account for the drag of the rocket body while under drogue. It makes sense that the descent velocity and kinetic energy would then be greater than the predictions of the MATLAB program.

Drift Calculations

The calculation for the drift of the rocket is straightforward in that it is just the product of the descent time and the wind velocity. Based on the MATLAB program's predicted landing velocity a smaller drogue of 12" and a main deployment height of 700 ft are needed to compensate for the increased drift under a conservative main of 84". The drift distances at specific wind velocities are displayed in Figure 22. The coefficient of drag for this plot is 2.2, which results in the slowest descent time and therefore greater drift distances.

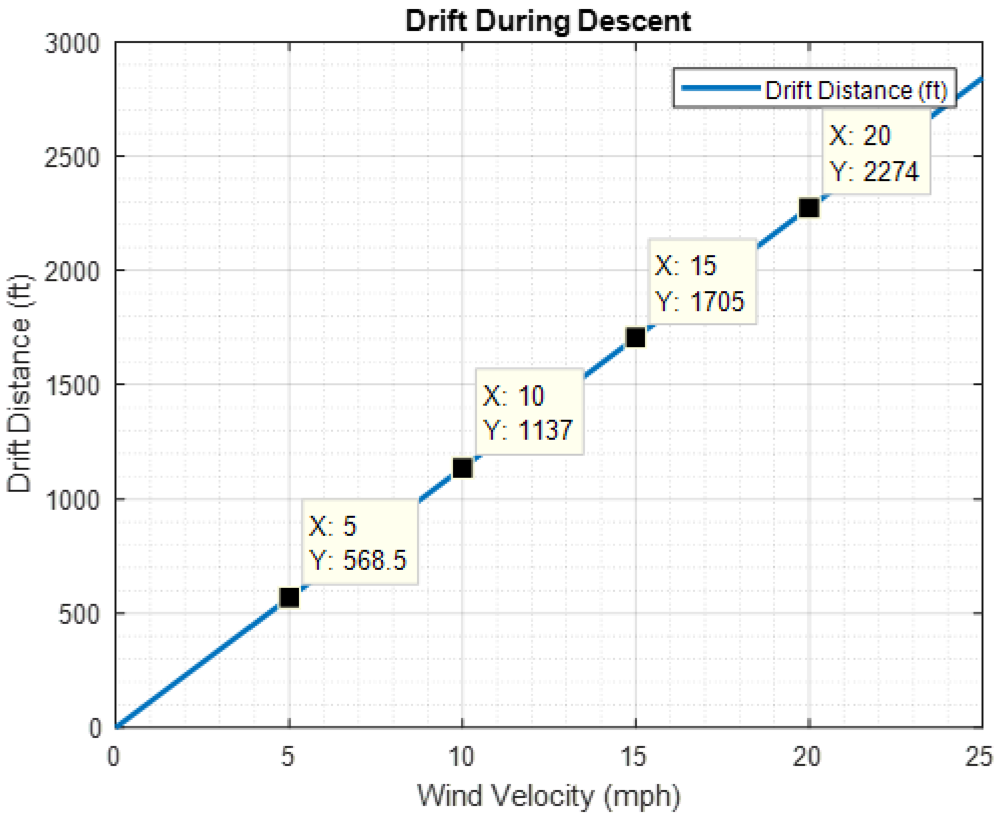


Figure 22. Drift Distance vs. Wind Speed for coefficient of drag of 2.2

OpenRocket reports descent times of 77.5s for a simulation with a coefficient of drag for the main parachute of 2.2. Given this descent time, the longer of the two coefficients of drag, the calculations reflect the largest drift distance. Table 26 gives the drift distances at each specified wind velocity.

Table 26. Drift Speed of Rocket at Various Wind Speeds

Wind Speed (mph)	**Drift Distance (ft) C_D = 2.2**
0	0
5	568.5
10	1137
15	1705
20	2274

The values differ as they do, because of the difference in the prediction of descent speed under main by the two methods. Since the MATLAB program has a slower descent than OpenRocket, it will slow a greater drift distance. Regardless of the varying drift values, the least ideal conditions of 16.8 ft/s descent due to a coefficient of drag of 2.2 still result in a greater drift distance below 2500 ft.

4 Safety

LTRL understands that there are inherent dangers in building and flying high powered model rockets. In the safety plan below, LTRL outlines the risks identified, and the preliminary steps taken to mitigate them.

4.1 Pre-Launch Procedures

Rover

Thoroughly check the rover to make sure that all the correct components are in place and working correctly. There should be no loose wires or electrical components. Communication between the ground station and rover can be tested before the rover has been placed inside the payload bay. Once all the components of the rover are operating correctly, begin assembling the CO_2 cartridge container. Place the spring inside the black cylinder. Pack the black powder into the bowl-shaped piece of the container and place an initiator inside. *CAUTION: Use gloves when handling the black powder.* Cover the packed black powder with 1 layer of clear tape. Insert the pieces into the black cylinder. Insert the CO_2 cartridge into the black cylinder. Screw the lid to the black cylinder on. Insert the black cylinder into the shelf and secure it by using I-bolts and bolts to secure underneath the shelf. Then connect the wire from the black cylinder to the rover. *CAUTION: Once the wire is connected, pyrotechnics are now loaded.* Place the rover inside of the rocket with the latching mechanism on the rover going in first. Check to make sure that the rover is secured to the inside of the rocket. Slide the nose cone onto the payload bay and attach the 8 shear pins at the separation point. After this step, the payload team will no longer be involved in assembling the rocket. Confirmation tests will be executed to ensure that the rover and ground station maintain communication if the rocket is on the launch pad for an extended period. After a successful launch and landing, the signal will be sent for the rover to trigger the CO_2 ejection for separating the rocket. The autonomous sequence will commence after a time delay. The rover will be recovered once it has completed its course.

Rover Launch Checklist

Pre-Mission Checklist

___ Double check that all rover components are assembled and secure. The rover will be taken to the launch fully assembled.

___ Begin assembly of the CO_2 cartridge by placing the spring in first to the black cylinder.

___ Pack the .25 grams of black powder into the CO_2 cartridge with the initiator.

___ Put 1 layer of clear plastic tape over the packed black powder to keep it from falling out.

___ Secure CO_2 cartridge to shelf using U-bolts. Make sure the cartridge does not move at all.

___ Connect CO_2 initiator wire to the rover.

___ Make sure there are no personnel at the exploding end of the CO_2 cartridge. Turn the rover on.

___ Place the rover inside of the rocket.

___ Double check that the rover is secured to the rocket.

___ Attach nose cone.

___ Insert 8 shear pins into the nose cone separation point.

Post-Mission Checklist

___ Once the ground station receives the “mission complete” signal, recover the rover.

Avionics Bay

To launch the rocket, the rocket must be tested in three different ways. Each test verifies the safety of the rocket and guarantees that all system will function as expected during launch.

Port-Hole Size Verification

The first test is the verification of the port-hole size. This test requires that the sealed avionics bay coupler be placed into the Mark II Test Chamber. The test chamber creates a vacuum that simulates the decrease in pressure during flight. This is used to verify that the port-hole size is sufficiently large for the altimeters to read the altitude correctly.

To complete the porthole verification test, the avionics bay must be placed in the avionics coupler and sealed on both ends by the bulkheads. The switches must be in the ON position. *(Safety note: there should not be any initiators connected or ejection charges loaded)* Then, the avionics coupler must be placed in the Mark II Test Chamber. Seal the test chamber and turn on the air pumps. After a minute, check the pressure gauge and take note of the maximum pressure inside the chamber. This will be used to determine the simulated altitude at that pressure. Turn the air pumps off and open the valves of the test chamber. Once the pressure inside of the test chamber matches the pressure outside of the test chamber, the altimeters will beep their maximum reached altitude. The altitude calculated from the pressure gauge should match the altimeter data. If the altimeter data is incorrect, then the porthole will need to be enlarged.

Ejection Charges Verification

The second test is a ground test for the black powder charges that will separate the charges. The purpose of this test is to ensure that the black powder charges will separate the rocket given the amount of shear pins used.

To complete the ground test, the ejection charges must be loaded, and the initiators must be connected to a 40 ft wire extender. Then, the rocket must be assembled and the shear pins must be installed. From a safe distance, a 9V battery can be connected to the wire extender. *(Safety note: make sure that everyone is a safe distance away from the rocket and that no one is standing in line with the nose cone or booster section of the rocket.)* This will cause the charge to detonate and should separate the rocket. If the rocket does not separate, then the amount of black powder will need to be increased on that section. If the ejection charge test for the drogue parachute charge also separates the main parachute section, then the amount of black powder in the drogue parachute section will need to be decreased. *(Safety note: If any charges do not detonate, then only the lead and safety officer can approach the rocket with the utmost care to disarm the rocket.)*

Altimeter Continuity Test
The third test is the altimeter continuity test. This verifies that the altimeters work and are connected to the drogue and main parachute charges. This must be done before every flight and is crucial to ensuring the safe landing of the rocket.

The altimeter continuity test is done by turning the switch for one altimeter at a time. After the initial beeps from the altimeter, there should be a repetitive sequence of three beeps. If there is only a repetitive sequence of one or two beeps, then the charges for the drogue and/or main parachute are not connected properly. The avionics bay will have to be taken out and the wires will have to be reconnected. After ensuring continuity for the first altimeter, turn the altimeter off and repeat the test for the second altimeter.

4.2 Launch Procedures

Motor preparation

Hardware List
Quantity is one of each item unless otherwise specified ([N] Item)

- 75mm Cesaroni 3-Grain Motor Case
- 75mm Aft Closure
- 75mm Forward Closure
- 75mm Forward Seal Disk (FSD)
- Liner
- Nozzle
- Nozzle Cap
- [3] Propellant Grains
- [2] Forward and Aft O-rings (⅛” thick x 2 ¾” O.D.)
- FSD O-ring (3/32” thick x 2 9/16” O.D.)
- [2] Grain Spacer O-rings (1/16” thick x 2 ½” O.D.)

Pre-Assembly

1. Apply a light coat of grease to all threads and O-rings (except the grain spacer O-rings).

Case Assembly

2. Use a sharp blade to deburr the forward and aft inside edges of the liner tube to provide more friction for the fit of the nozzle and forward closure assembly.
3. Insert the larger diameter portion of the nozzle into the aft end of the liner and slide the nozzle all the way in to the point that the flange is in contact with the aft edge of the liner.
4. Ensure that all following procedures are carried out with the assembly in the horizontal position.
5. Install the propellant grains into the liner, sliding them in from the forward end. Place a Grain Spacer O-ring between each propellant grain, and again ensure that they are not lubricated with grease.

6. Once the propellant grains are installed in the liner, avoid letting any personnel stand directly in line with either end of the case assembly.
7. Place the lubricated FSD O-ring into the groove in the FSD.
8. Insert the end of the disk with a smaller cross-sectional area into the forward end of the liner so that the FSD O-ring is no longer visible and the flange on the FSD is in contact with the forward edge of the liner.
9. Apply a light coat of lubricating grease to the outside of the liner to facilitate liner assembly removal from the case after launch.
10. Insert the liner assembly into the aft end of the motor case until the nozzle protrudes from the aft end of the case by 1 ¾”.
11. Place the greased Forward O-ring into the forward end of the motor case until it is in contact with the forward end of the FSD.
12. Thread the (empty) Forward Closure Assembly into the forward end of the motor case until it is firmly in contact with the Forward O-ring.
13. Place the lubricated Aft O-ring into the groove on the aft end of the nozzle.
14. Thread the Aft Closure into the aft end of the motor case until the flange is firmly in contact with the aft edge of the motor case.

Setup on launcher

Transportation to Launcher

1. Assemble the launch team, which consists of the Flight Systems Engineer, A&R Lead Engineers, and Propulsion Lead Engineer, to carry the rocket to the launcher and set it up.
2. Ensure that all launch team members leave cell phones and other electronic devices capable of radio frequency emissions with someone who is not going out to the launcher.
3. Make sure all members of the team have a firm grasp on the rocket, and lift the rocket to a comfortable carrying height. Make sure the rocket stays as close to horizontal as possible at all points during transportation.
4. Walk the rocket out to the launcher, ensuring that no people are too near or directly in line with the aft end of the rocket

Setup on Launcher

1. Have a member or two of the launch team bring the launch rail from vertical to horizontal and hold it in that position.
2. Align the rocket’s rail buttons so that they are pointed directly down towards the ground.
3. Slide the aft rail button into the launch rail so that the weight of the rocket is resting on the rail buttons. Make sure the rocket is not “hanging” off the rail only attached at the rail buttons.
4. Slide the aft rail button towards the flame deflector at the base of the launch rail, minimizing twisting of the rocket relative to the launch rail and scraping of the rocket airframe against the leading edge of the launch rail.
5. Once the forward rail button is securely inserted into the launch rail, slide the rocket towards the flame deflector until it makes contact.
6. Several members of the team should then push the launch rail into a vertical position while the rest of the team stabilizes the rocket on the rail to prevent twisting relative to the rail.

7. Once the launch rail is in a vertical position, lock the rail into this position with a bolt or screw.

Initiator Installation

After initially separating the initiator leads, do not allow them to come into contact with each other.

1. Verify that:
    a. The rocket is secured to the launch rail.
    b. The launch rail is secured in the upright position.
    c. The altimeter is correctly and completely initialized.
2. Have several team members raise the rocket a few inches so that it no longer rests on the flame deflector and ensure that the team members can hold the rocket in this position for as long as it takes to install the initiator.
3. Thread the initiator through the pre-cut hole in the wall of the nozzle cap. For now, ignore the nozzle cap but make sure it does not slide off the initiator wire.
4. Insert the end of initiator that contains the charge into the nozzle of the rocket and continue to slide the initiator upwards through the propellant grains.
5. When you feel the initiator contact the aft end of the FSD, stop feeding the initiator into the motor.
6. Secure the initiator wire to the nozzle with tape, making sure the initiator stays in contact with the aft end of the FSD.
7. Secure the nozzle cap over the end of the nozzle, again making sure not to pull the initiator wire any further out of the motor.
8. Separate the initiator wire leads as far apart as possible without damaging the wire.
9. Take one alligator clip from the power supply extension and connect it to one lead on the initiator wire.
10. Secure this connected wire to the launcher a safe distance from the second lead.
11. Take the second alligator clip from the power supply extension and connect it to the remaining lead on the initiator wire.
12. Secure this second wire to the launcher a safe distance from the first wire.

4.3 Safety Officer Responsibilities

The person responsible for drafting and maintaining the LTRL safety plan is the Safety Officer. During the 2017-2018 project cycle, the Safety Officer is Laura Reese. The safety officer's responsibilities are as follows:

- monitor team activities to ensure safety during design, assembly and ground testing of the rocket and payload
- monitor team activities to ensure safety during subscale and fullscale launches and recoveries
- monitor team activities during launch day to ensure safety
- manage and maintain current versions of the team's hazard analyses, failure modes analyses, and Safety Data Sheet (SDS) data
- manage and maintain a database of the Penn State safety certification status of all club members
- write and develop the team's hazard analyses
- assist in the writing and development of the team's failure modes analyses

4.4 Safety Statement

LTRL will comply with all National Association of Rocketry (NAR), Federal Aviation Authority (FAA) and National Fire Protection Association (NFPA) regulations pertaining to high powered model rocketry. For convenience, and to help ensure the safety of LTRL members and the public, LTRL will only launch at NAR or Tripoli Rocket Association certified club launches. LTRL and its members will comply with all instructions and guidance issued by the Range Safety Officer (RSO) of these launches. LTRL and its members will also comply with all instructions and guidance issued by the RSOs at the USLI launch in Huntsville.

4.5 Lab Safety

Design and construction of the rocket requires use of power tools, such as a dremel and drill, as well as use of chemicals, primarily epoxies. These create hazards, which can be mitigated by wearing proper personal protective equipment (PPE), as well as exercising caution and proper shop safety. To foster a "safety-first" attitude, and to educate members about proper chemical safety, basic laboratory safety, and proper use of PPE, all members are required to take safety training that is offered through Penn State's Environmental Health and Safety (EHS). In addition, safety and emergency equipment is available to LTRL members in the lab and at launches.

Safety Training

All LTRL members are required to take a four-part Initial Lab Safety and Hazards Awareness training course offered online by Penn State's EHS. The course consists of four training videos: Introduction to Safety, Chemical Safety, Hazardous Waste Management and Disposal, and Emergency Preparedness. Each training video concludes with a quiz. Members must score at least an 80% to pass that portion of the training. The website then generates a certificate, which is submitted to the Safety Officer. LTRL Members who have already completed the initial course can take a refresher course instead. The refresher course is also offered online, in a similar training video format. Members must score an 80% to pass the quiz at the end of the video, and are then issued a certificate, which is submitted to the Safety Officer. The Safety Officer keeps an electronic database recording which members have completed their safety training. The Safety Officer also keeps physical copies of all members' safety certificates in a binder that is stored in the lab. Subsystem leads are notified about which members are not compliant with the Safety Training requirement. Members who have not completed safety training are not allowed to work in the lab.

Safety and Emergency Equipment

Safety glasses, dust masks, and gloves are available in the LTRL lab. They are also brought to launches and used as necessary. In case of an emergency, a first aid kit is available in the lab. Fire extinguishers, both dry chemical and CO_2 types, are available in the hallway directly outside of the lab.

4.6 Launches and Motor Handling

For the LTRL subscale rocket, a J-class motor was used. The fullscale rocket will use an L-class motor. The rocket motors are purchase, handled and transported by the club president, who has NAR Level 2 certification. They are stored in the High Pressure Combustion Lab (HPCL) when not in use. The HPCL has storage magazines for H/D 1.1 and H/D 1.3 energetic materials and propellants. These magazines are sited, licensed, and operated in compliance with all local, state, and federal regulations.

LTRL does not currently hold its own launches. Instead, the club attends launches organized by the Maryland and Delaware Rocket Association (MDRA) and the Pittsburgh Space Command (PSC) respectively. The PSC is an NAR registered club. Both launches require the presence of a member holding either Level 1 or Level 2 NAR certification, depending on the class of motor used.

4.7 Hazardous Materials

During the project, construction and launching of the rocket will entail the handling and use of hazardous materials. Efforts to mitigate the risks posed by these hazards have been undertaken by the club.

Motor Storage

To reduce the risk of fires and explosions in the lab, all the motors LTRL uses are stored in the HPCL storage magazines.

Hazardous Materials Mitigations

LTRL maintains a chemical inventory, and SDS records for all hazardous chemicals used during the project. The current list of chemicals and hazardous materials, the hazards that they pose, and the mitigations in place to lower the risk placed by those hazards is given in Table 27. This list will updated throughout the course of the project, if additional hazardous materials are used by LTRL during construction or launch operations. The hazards outlined in Table 27 are based on the hazards listed in SDS for each hazardous material. These safety data sheets are attached in Appendix A: MSDS Sheets.

Table 27. Hazardous Materials

Material	Hazards	Mitigations
JB Weld Professional	Causes skin and eye irritation	Wear protective gloves and eye protection. Wash hands thoroughly after working with epoxy.
JB Kwik	Causes skin and eye irritation	Wear protective gloves and eye protection. Wash hands thoroughly after working with epoxy.
Black powder	Explosions, fire, can also cause skin, eye, respiratory irritation	Protect black powder from flame, heat, and electrical discharge.

Fiberglass bulkheads	Skin and eye irritation, potentially severe respiratory tract irritation	Wear gloves, eye protection, and dust mask. Clear dust using a shop vacuum.
Carbon fiber wrapping	Airborne fibers can cause severe respiratory irritation. Electrically conductive airborne fibers can cause short circuits in electrical systems.	Limit airborne fiber production during machining operations. Wear a dust mask when machining carbon fiber wrapping.
Spray paint	Can explode or catch on fire. Causes serious eye irritation, skin irritation and serious respiratory tract irritation. Can be carcinogenic and is a narcotic when fumes are inhaled.	Paint only in a well ventilated area, preferably outside. Store cans away from any potential sources of heat or flame.
No. 2 Mystik high temp grease	No known hazards	Wear gloves while handling.
Talcum powder	May cause eye and skin irritation. Causes respiratory tract irritation which over long periods of time may lead to cancer.	Use only outside in well ventilated areas.
FibreGlast 2060 60 minute epoxy cure	Causes serious eye damage. Toxic if swallowed or inhaled. Can cause skin and respiratory tract irritation. Chronic exposure can result in harm to the liver, kidneys, eyes, skin or lungs.	Always wear gloves when applying the epoxy and epoxy cure.
FibreGlast 2000 epoxy resin	Skin and eye irritation	Wear gloves while handling.
Flexseal	Causes skin and eye irritation. Is a potential carcinogen	Wear gloves while handling.
Isopropyl alcohol	Can cause flash fire or explosion. Causes skin and respiratory irritation. Causes serious eye irritation.	Store away from potential sources of flame or heat.

4.8 Risk Assessment

To reduce the risks inherent in building and flying the rocket, the Safety Officer and Subsystem Leads have undertaken multiple risk assessments. These assessments outline personal risks to club members and environmental hazards. Failure modes of the rocket and its subsystems, their causes and effects and mitigations of these potential failures are also outlined. Lastly, risks to the overall project and club are outlined, along with mitigations of these risks.

To provide a scale of how hazardous each risk or failure is, the likelihood and severity of each risk were tabulated, and used to calculate a combined risk factor. This combined risk factor was then used to rank the risks or hazards within each table from most to least hazardous. The methodology used to assign numerical values to the likelihood and severity, and the methodology used to calculate and rate the combined risk factor is outlined below.

Explanation of Risk Assessment Quantifiers

The explanation below shows how the likelihood and severity values were assigned for risks, hazards, and failure modes.

LIKELIHOOD

1: The risk is highly unlikely. Over the historical legacy of the risk, the failure has never occurred.
2: The risk is unlikely. Over the historical legacy of the risk, the failure has never occurred, but there may have been close calls, where the risk nearly did occur.
3: The risk is moderate. Over the historical legacy of the risk, the failure has occurred at least once.
4: The risk is likely. Over the historical legacy of the risk, the failure has occurred at least once during last year's project, or has recurred repeatedly in multiple years.
5: The risk is highly likely. Over the historical legacy of the risk, the failure has occurred more than once over the course of a past project, or has recurred each year during the project's duration.

Historical legacy refers to the time period over which current active club members have been a part of the club. Some risks have long historical legacies, whereas others may have only begun to occur during this project cycle. If the design responsible for a risk has changed substantially, the likelihood for that risk also was changed to reflect the impact of the design on the risk's likelihood.

SEVERITY:

1: The risk is moderate. The rocket performs more poorly than expected, or does not operate within the expected parameters, the payload does not operate within the expected parameters, and/or the environment is temporarily impacted.
2: The risk is not very severe. The occurrence of the risk could result in: moderate damage to the rocket necessitating repairs on the field, portions of the payload do not operate as expected, and/or the environment is impacted.
3: The risk is severe. The occurrence of the risk could result in: severe damage to the rocket necessitating repairs of significant portions of the rocket, the payload fails completely in its mission, and/or the environment is damaged.

4: The risk is quite severe. The occurrence of the risk could result in: injuries to a club member or bystander, catastrophic damage to the rocket, and/or significant damage to other structures or facilities and the environment.
5: The risk is very severe. The occurrence of the risk could result in catastrophic damage to the rocket, severe injuries to a club member or bystander, the disbandment of LTRL by Penn State, and/or severe damage to other structures or facilities and the environment.

Severity and likelihood values were then added together to generate the combined risk factor. In Table 28 a combined risk factor matrix is given, which also ranks the combined risk factor as low, moderate, or high.

Table 28. Combined Risk Factor Matrix

	Likelihood					
		1	2	3	4	5
Severity	1	Low	Low	Low	Moderate	Moderate
	2	Low	Low	Moderate	Moderate	Moderate
	3	Low	Moderate	Moderate	Moderate	High
	4	Moderate	Moderate	Moderate	High	High
	5	Moderate	Moderate	High	High	High

The likelihood, severity and combined risk factor were then used to quantify the risks, hazards and failure modes.

Personal Hazard Analysis

Risks to LTRL members were analyzed along with their causes, and effects, and the likelihood and severity and combined risk analysis were assigned to each of the risks. This work is shown in Table 29 below.

Table 29. Personal Hazard Analysis

Hazard	Cause	Effect	Likelihood	Severity	Combined Risk Factor	Mitigation	Verification
Free falling debris	Improper parachute deployment or linkages, structural failure of parachutes or parachute harnesses, no parachute deployment	Blunt force trauma, cuts or lacerations to the skin, eye damage	4	5	9, High	All LTRL personnel will maintain a "heads-up" stance at all times while the LTRL rocket, or other rockets, are in the air.	The safety officer will ensure that LTRL personnel maintain a "heads-up" stance while rockets are in the air
Flying debris generated by explosives during launch operations	Catastrophic explosions before or during liftoff	Cuts or lacerations to the skin, eye damage, blunt force trauma, burns	3	5	8, High	All LTRL personnel will remain a safe distance from the pad, as determined by RSO. Only necessary personnel will go out to mount the rocket on the launch rail.	The RSO and the LTRL safety officer will ensure that no one approaches the pad too closely.
Free falling debris generated during rocket flight	Structural failure during rocket flight, due to the forces experienced during launch and parachute deployment.	Cuts or lacerations to the skin, eye damage, blunt force trauma	3	5	8, High	All LTRL personnel will maintain a "heads-up" stance at all times while the LTRL rocket, or other rockets, are in the air.	The safety officer will ensure that LTRL personnel maintain a "heads-up" stance while rockets are in the air
Cuts and Lacerations from improper power tool usage	Improper use of power tools	Cuts and lacerations, potential serious injuries	3	5	8, High	All instructions and best practices for the use of power tools will be followed. No one will work in the lab alone. Inexperienced members will always be guided by club members that are more experienced in machining protocols	Only subsystem leads and officers have access to the lab. Leads will remain in the lab at all times while general body members are working.

Eye irritation due to particulates	Eye exposure to irritating particulates	Discomfort, possible permanent eye damage	2	5	7, Moderate	Eye protection will be worn when members are cutting fiberglass or carbon fiber	LTRL personnel wear eye protection when cutting fiberglass or carbon fiber. Safety glasses are provided by the club.
Flying debris from cutting or drilling	Flying debris is generated by machining operations such as drilling or cutting.	Cuts or lacerations to the skin, eye damage	2	5	7, Moderate	A safe distance between any member cutting or drilling material and everyone is maintained. Any member cutting or drilling material wears safety glasses.	LTRL personnel will notify anyone else in the lab before cutting or drilling material. LTRL personnel will wear safety glasses when cutting or drilling.
Fire in the lab	Fire begins in the lab, or spreads from another portion of the building into the lab	LTRL equipment destroyed, LTRL facility destroyed, LTRL members injured	2	5	7, Moderate	Maintain all electrical cables properly, greasy or solvent soaked rags will not be stored in the lab, e-matches will be stored away from flammable materials, only solvents needed for building the rocket will be stored in the lab, rocket motors will be stored in the HPCL. A fire extinguisher is located in the hallway directly across from the entrance to the lab.	The fire extinguisher is tested regularly by Penn State. The safety officer will ensure that no greasy or solvent soaked rags are stored in the lab. E-matches are stores in a separate box from all explosives, which are stored in an explosives rated box.
Trips and falls in the lab	LTRL member trips or falls because of obstacle in the lab	Cuts and lacerations, contusions, broken bones	3	4	7, Moderate	Keep extension cords and electrical cables coiled and placed under desks or tables, keep backpacks in the hallway when there are more than five people in the lab	The safety officer will ensure that all extension cords and electrical cables are properly stored and not stretched across the floor.

Trips and falls during launch and recovery operations	Uneven ground at the launch site	Cuts and lacerations, contusions, broken bones	3	4	7, Moderate	Exercise caution while retrieving the rocket	LTRL members will be advised to be cautious when retrieving the rocket.
Burns from motor retainers	Touching the motor retainer before it has cooled after launch	Skin damage, potentially severe	1	5	6, Moderate	Members will not approach the rocket for at least sixty seconds after the motor has been fired.	The safety officer will ensure that members do not approach the rocket for at least sixty seconds after the motor has been fired.
Skin irritation from particulates	Skin exposure to irritating particulates	Discomfort, potential injuries, potential long term chronic illness	2	4	6, Moderate	Gloves will be worn when members are machining hazardous material	Gloves are provided for LTRL personnel.
Respiratory irritation from particulates	Respiratory system exposure to irritating particulates	Discomfort, potential long term chronic illness	2	4	6, Moderate	Masks will be worn when members are machining hazardous materials. A shop vacuum will be used to limit the spread of the particulates.	Face masks are provided for LTRL personnel and will be worn by LTRL members while machining fiberglass or carbon fiber
Electrical shock	Electrical shock from power tools or cords, electrical shock from extension cables	Deep skin damage from electrical burn, potential nerve damage, potential deeper tissue damage, can cause a heart attack	1	5	6, Moderate	Ensure all power tools and their cords and that all extension cords are well maintained and contain no exposed or frayed wires, or large nicks in the insulation	The safety officer will periodically check power tools and extension cords for exposed wires.
Black powder explosions - while handling	Black powder explodes or catches fire during measurement or transport operations	Burns and injuries from explosion	1	5	6, Moderate	No open flame, electrical spark or heat source will be used near the black powder operations	Black powder is stored in an explosives box. No smoking or open heat sources will be permitted at the launch sites.

Black powder explosions - while loaded in the rocket	Black powder charges explode prematurely, or explode after the rocket has landed	Burns, blunt force injuries from explosion and potential flying rocket debris	1	5	6, Moderate	Firing circuit will not be engaged until the rocket is on the pad, exercise "muzzle awareness" around both ends of the rocket after charges have been loaded, exercise "muzzle awareness" around both ends of the rocket until it has been determined by an A&R lead that all charges have deployed. Wait sixty seconds before approaching the rocket during ground testing of charges.	The safety officer will ensure that LTRL personnel maintain "muzzle awareness" around both ends of the rocket after charges have been loaded. An A&R lead will approach the rocket first to ensure that all charges have deployed properly.
Skin irritation from chemicals	Skin exposure to irritating chemicals	Discomfort, potential injuries, potential long term chronic illness	1	4	5, Moderate	Gloves will be worn when members are working with hazardous chemicals	Gloves are provided to LTRL personnel. Subsystem leads and the safety officer will ensure that LTRL members wear gloves when handling hazardous chemicals, such as epoxies.
Respiratory irritation from chemicals	Respiratory system exposure to volatile chemicals	Discomfort, potential long term chronic illness	1	4	5, Moderate	All operations utilizing volatile chemicals will be performed in areas with sufficient ventilation	All spray painting will be done outdoors. Subsystem leads and LTRL officers will ensure that the lab is well ventilated whenever solvents are being used in the construction of the rocket.

Environmental Hazards

One of the main environmental concerns includes the disposal of toxic substances, due to use of such substances in rocket construction. All toxic substances will be disposed in accordance with local laws and regulations by Penn State Environmental Health and Safety (EHS). During a launch, measures will be taken to minimize changes to the local environment due to the emission of hot, toxic gases from the rocket motor during launch. A safe radius around the pad will be cleared of combustible materials. High winds during rocket flight could adversely impact the landing guidance system. Table 30 below summarizes these risks.

Table 30. Environmental Hazards

Hazard	Cause	Effect	Likelihood	Severity	Combined Risk Factor	Mitigation	Verification
Direct midday sunlight harms electronics	Heating of rocket body	Electronics could malfunction due to overheating	5	3	8, High	Use electronic components designed to withstand a range temperatures. Keep the rocket in the shade until it is moved to the launch pad.	High quality electronics will be used in the rover.
Ground pollution from unrecovered rockets	Unrecovered rockets on the ground	Residual motor components, ejection charges and electronic and structural components leach out of the submerged rocket and cause soil pollution.	4	3	7, Moderate	LTRL will always make every attempt to retrieve the rocket. A GPS transmitter will be placed in the rocket so that the team can locate the rocket.	The A&R leads will ensure that a working GPS is placed in the rocket.
Wind carries away trash from launch site	Gusts of wind at launch site	Loose objects blow away from launch prep site polluting the environment	4	3	7, Moderate	Keep all tools and components stored in storage boxes when not in use. Keep trash cleaned up while working.	The safety officer will keep tools and trahs picked up during launch preparations.
Flooding in the lab	The lab floods	Equipment, rocket parts, and supplies are ruined, risk of electrical shock from submerged electric cords and outlets.	3	4	7, Moderate	If a severe rainfall event is predicted, the club will move critical components, extension cords and equipment to higher places in the lab. Most components and equipment are stored in plastic boxes and are stored off the floor on shelving units.	Components and equipment is stored in plastic boxes in shelving units.

Brush fire	Hot motor gases	Hot motor gases ignite grass or brush	1	5	6, Moderate	LTRL will always use a blast deflector and ensure that dry grass and plant matter is cleared from the launch pad	The RSO propulsion leads will ensure that the blast deflector is in place and that no dry grass or plant matter remains on the launch pad.
Brush fire	Ejection charges	Ejection charges ignite grass or brush causing a fire	1	5	6, Moderate	LTRL will not use more black powder than necessary for ejection charges. Ejection charges will be contained within the rocket, ejection charges will be deployed using an altimeter and so will explode in the air, not on the ground	The A&R leads will calculate the correct amount of black powder necessary. Redundant altimeters will be used so that the ejection charges will be deployed properly.
The rocket drifts out of the landing zone	High winds during parachute deployment	The rocket drifts out of the landing zone, and/or into hazards such as buildings, trees or power lines.	3	3	6, Moderate	The main parachute will be deployed at 700ft to limit drift, drift has been calculated to fall within the proper range for up to 20 mph wind speeds. The rocket will be not be launched in winds over 20 mph.	The A&R leads will perform calculations to determine the drift rate of the rocket, and will select parachutes accordingly.
Falling rocket injures animals	Rocket lands on animals	Animal is injured, rocket is trampled	2	4	6, Moderate	Launch in area free from livestock. Limit drift in order to land the rocket in the cleared landing area. Limit kinematic energy of rocket on landing so that potential injuries to livestock or wildlife are minimal.	The A&R leads will ensure that the rocket's kinetic energy remains at safe levels. LTRL will only launch at approved events under the supervision of the RSO.

Crop debris limits rover operation	Crop debris interferes with rover operations	Crop debris prevents the rover from exiting the rocket, or from moving forwards	3	3	6, Moderate	The rover is designed to have high ground clearance. The release mechanism for the rover allows the rover to freely exit the rocket, so that crop debris will not trap the rover in the rocket. Tests will be conducted in fields with soybean and/or corn crop debris to test the functionality of the rover.	The rover's ground clearance will be tested in fields with soybean or corn residue.
Water pollution caused by rocket parts	Unrecovered rockets in bodies of water	Residual motor components, ejection charges and electronic and structural components leach out of the submerged rocket and cause water pollution.	2	4	6, Moderate	LTRL will always make every attempt to retrieve the rocket from bodies of water. The team will always launch the rocket in a manner such that its flight path will not take it over large bodies of water.	The A&R leads will perform calculations to determine the drift rate of the rocket, and will select parachutes accordingly. The A&R leads will ensure that a working GPS is placed in the rocket.
Water pollution from chemicals used during rocket construction	Improper disposal of lab chemicals	Poisonous chemicals could cause fish kills and pollution of waterways.	1	4	5, Moderate	All chemicals will be picked up by Penn State EHS and safely treated and disposed.	The safety officer will ensure that all hazardous chemicals are disposed of through Penn State EHS chemical pickup.
Ground pollution from litter	Littering	Trash such as plastic bags, wires, and cardboard is left behind at launch prep site.	2	3	5, Moderate	LTRL will always pick up all of the trash at the launch prep site.	. The safety officer will check to see that all trash has been removed before the team leaves.

Ground Pollution from chemicals used during the construction of the rocket	Improper disposal of lab chemicals	Poisonous chemicals could cause soil contamination.	2	3	5, Moderate	All chemicals will be picked up by Penn State EHS and safely treated and disposed.	The safety officer will ensure that all hazardous chemicals are disposed of through Penn State EHS chemical pickup.
Wind catches the parachute after the rocket has landed	Gusts of wind after rocket lands	Parachute drags rocket across the ground, causing potential damage to the rocket body	3	2	5, Moderate	Use a parachute no larger than necessary to land the rocket safely.	The A&R leads will select the smallest parachute necessary to bring the rocket down safely
Rain causing launch cancellation	Rain during launch window	Launch is cancelled, causing LTRL to waste time and money travelling to the cancelled launch	4	1	5, Moderate	Check weather reports before leaving for the launch.	The president, or designated launch leader will check the weather in the launch area, and call the launch organizers if the weather appears to be inclement.
Low level clouds or fog cause launch cancellation or delay	Low level clouds or fog at launch site	Launch is cancelled or delayed, causing LTRL to waste time and money	4	1	5, Moderate	Check weather reports before leaving for the launch.	The president, or designated launch leader will check the weather in the launch area, and call the launch organizers if the weather appears to be inclement.

Rain damages rocket components	Rain at launch site	Explosives get wet and do not ignite properly, electronics are damaged	1	3	4, Low	Protect explosives from rain until their placement in the rocket. Rocket is designed to protect explosives and electronics from the elements	The A&R leads will ensure that explosives are prepared in a place sheltered from the rain.
Excessive humidity causes electronics to malfunction	Humidity is high enough to interfere with electronics operation	Malfunctioning electronics cause the rover to malfunction	1	3	4, Low	Use quality electronic components less likely to be affected by humidity. If problems are experienced, use desiccants to lower the humidity near the problematic electronic components.	High quality electronics will be used in the rover.
Cold temperatures cause electronics to malfunction	The temperature is below the range which the electronic components are designed to handle	Malfunctioning electronics cause the rover to malfunction, or be unable to complete its mission	1	3	4, Low	Use electronic components designed to withstand a range of temperatures. Keep the payload and avionics bays in a warm environment as long as possible.	High quality electronics will be used in the rover.

Failure Modes and Analysis

To ensure a safe and effective launch, an assessment of possible failures has been made. After analyzing the cause of the potential failure, mitigations were also proposed. Table 31 shows the preliminary set of failure modes.

Table 31. Failure Modes and Analysis (FMEA)

PAYLOAD						
Failure	Cause	Effect	Likelihood	Severity	Combined Risk Factor	Mitigation
Premature activation of CO2 canisters	Control software malfunction	Nose cone of the rocket separates prematurely during flight - can cause massive instability during launch, and free-falling body sections pose a serious danger to bystanders on the ground	2	5	7, Moderate	Perform thorough rigorous testing on the control software to prevent premature triggering
Rover tips over and is unable to right itself	Uneven terrain	Rover will be unable to move and complete the mission	4	3	7, Moderate	Rigorously test the self-righting mechanism with various terrain
Shear pin failure	Manufacturing defect	Nose cone of the rocket separates prematurely during flight - can cause massive instability during launch, and free-falling body sections pose a serious danger to bystanders on the ground	1	5	6, Moderate	Manually inspect shear pins before flight to ensure integrity
Premature activation of CO2 canisters	Physical damage to canister/trigger	Nose cone of the rocket separates prematurely during flight – can cause massive instability during launch, and free falling body sections pose a serious danger to bystanders on the ground	1	5	6, Moderate	Build guards for the separation trigger to prevent accidental activation

CO2 canisters fail to activate	Control software malfunction	Rover will be unable to deploy from the rocket	3	3	6, Moderate	Perform rigorous testing on the control software to ensure that canister is triggered
Discharged battery pack	Not following pre-flight/charging procedures	Loss of power to rover and associated electronics – payload section of the rocket will be unable to separate, leaving the rover unable to execute its mission	3	3	6, Moderate	Develop and implement thorough preflight guidelines to ensure that the batteries are charged before launch
Structural damage to payload bay	Forces sustained during launch or landing exceed strength of the payload bay	A breach in the wall of the body tube would prevent the CO2 canister from creating enough pressure to separate the nose cone from the rocket body	2	3	5, Moderate	Check parachute deployment mechanism with A&R subsystem to ensure that the rocket does not land a high rate of speed
Ultra-sonic sensor failure	Control software malfunction	Rover will be unable to detect and avoid obstacles in its path	3	2	5, Moderate	Thoroughly test control software to ensure that obstacles are able to be detected and avoided
Ultra-sonic sensor damaged	Acceleration experienced during launch or landing	Rover will be unable to detect and avoid obstacles in its path	2	2	4, Low	Perform ground testing to ensure that ultra-sonic sensor can withstand forces sustained during launch and landing

CO2 canisters fail to activate	Trigger mechanism becomes physically disconnected/damaged due to acceleration experienced during launch or landing	Rover will be unable to deploy from the rocket	1	3	4, Low	Double check integrity of physical mount points for the activation trigger and soldered wires between the control board and trigger
Discharged battery pack	Faulty battery	Loss of power to rover and associated electronics - payload section of the rocket will be unable to separate, leaving the rover unable to execute its mission	1	3	4, Low	Thoroughly test all batteries (primary and any backups) before launch to ensure that they can hold sufficient charge
Physical damage to the rover	Forces sustained during launch or landing exceed strength of the rover	Rover is damaged during launch or deployment - if damage sustained is severe enough, rover may be unable to operate correctly	2	2	4, Low	Construct the rover out of materials durable enough to withstand launch forces, minimize rover weight to minimize force transferred to rover components
Structural damage to payload door	Forces sustained during launch or landing exceed strength of the payload door	A breach in the wall of the body tube would prevent the CO2 canister from creating enough pressure to separate from the rocket body	1	3	4, Low	Check parachute deployment mechanism with A&R subsystem to ensure that the rocket does not land at a high rate of speed

STRUCTURES						
Failure Mode	Cause	Effect	Likelihood	Severity	Combined Risk Factor	Mitigation
Fin Separation from fin brackets	loosening of bolts due to excess vibrations experienced during launch, flight, parachute deployment, descent and landing	Potential free falling sky debris	1	5	6, Moderate	Vibrational simulations of the most extreme cases expected will be conducted. Material testing will be performed to determine the material properties. Thread lock may be used if necessary. A visual inspection will be conducted prior to and after every launch/landing cycle. Missing/damaged parts will be replaced if necessary.
Eyebolts Separation from bulkheads	Extreme stress from shock cord, insufficient thread strength on bulkhead. Loosening of eyebolt due to excess vibrations during launch, flight, parachute deployment, descent, and landing	Unwanted separation of rocket, potential free falling sky debris	1	5	6, Moderate	Stress and vibration simulations of the most extreme cases expected will be conducted to determine the maximum possible forces seen during launch to landing process. Material testing will be performed to determine the material properties. If the material is incapable of withstanding any posible forces or stresses seen during the flight process, a new material will be selected and tested. This process will be continued until a material is found to be able to withstand any possible forces seen during launch to landing process. Thread lock and a nut will be used to ensure loosening of the eyebolt does not occurred. A visual inspection will be conducted before and after every launch/landing cycle. Damaged parts will be replaced as necessary.

Bulkhead Separation from body tube	Insufficient Epoxy strength	Unwanted separation of rocket, potential free falling sky debris	1	5	6, Moderate	Simulations of the most extreme cases expected will be conducted to determine the maximum possible forces seen during the launch to landing process. Material testing will be performed to determine the material properties. Enough epoxy will be used to ensure a factor of safety of at least 1.5. A visual inspection will be conducted before and after every launch/landing cycle. Damaged parts will be replaced as necessary.
Cascading Fracture, body tube	Extreme stress due to sudden change in acceleration due to takeoff, parachute deployment , and landing localized around bolt hole	Functional/Structural inadequacy	1	4	5, Moderate	Simulations of the most extreme cases expected will be conducted. Material testing will be performed to determine the material properties. Additional carbon fiber layers will be added to the bluetube body tube to ensure that the rocket body has a minimum factor of safety of 1.5.
Crack along inner/outer seam, body tube	Extreme torsional stress or bending moment due to extreme rotational acceleration	Functional/Structural inadequacy	2	3	5, Moderate	Simulations of the most extreme cases expected will be conducted. Material testing will be performed to determine the material properties. Additional carbon fiber layers will be added to the bluetube body tube to ensure that the re rocket body has a minimum factor of safety of 1.5.
Unwanted coupler separation from body tube	Premature Shear pin fracture due to extreme axial or torsional stress caused by extreme jerk or excess rotational acceleration	Parachutes do not deploy, incorrectly timed parachute deployment, incorrect descent	3	2	5, Moderate	Simulations of the most extreme cases expected will be conducted. Shear pin locations will be optimized using stress analysis so that a minimum value of shear pins can be employed. Total shear pin stress resistance will be rated at a minimum of 1.2 times the maximum stresses simulated.
Premature nose cone separation	Premature Shear pin fracture due to extreme axial or torsional stress caused by extreme jerk or excess rotational acceleration	Aerodynamic inconsistency/ Instability, sky debris	1	4	5, Moderate	Simulations of the most extreme cases expected will be conducted. Shear pin locations will be optimized using stress analysis so that a minimum number of shear pins can be employed. Total shear pin stress resistance will be rated at a minimum of 1.2 times the maximum stresses simulated.

Fin bracket fracture	Extreme or repeated impact, bending moment	Aerodynamic instability, Structural failure, potential free-falling sky debris	1	4	5, Moderate	Simulations of the most extreme cases expected will be conducted to determine the maximum possible forces seen during the launch to landing process. Material testing will be performed to determine the material properties. Stress analysis will be conducted on the geometry, and design iterations will be conducted until the fin brackets are able to withstand any and all expected forces. A visual inspection will be conducted before and after every launch/landing cycle. Damaged parts will be replaced as necessary.
Coupler Fracture crack	Extreme torsional stress or bending moment due to extreme rotational acceleration	Aerodynamic inconsistency/Structural Failure	2	2	4, Low	Simulations of the most extreme cases expected will be conducted. Material testing will be performed to determine the material properties. If the couplers fail to be able to withstand the extreme cases, a higher durability material will be selected and tested. This process will continue until a coupler design is able to withstand any forces that can be expected.
Body tube Fracture crack	Material Defect, Repeated impact	Aerodynamic inconsistency/Structural Failure	2	2	4, Low	A visual inspection will be conducted for each piece of the body tube before and after each launch/landing cycle. If any parts are damaged beyond repair, a new replacement part will be fabricated.
Fin fracture crack	Extreme or repeated impact, bending moment	Aerodynamic instability, Structural failure	2	2	4, Low	Simulations of the most extreme cases expected will be conducted. Material testing will be performed to determine the material properties. Design iterations will be conducted until a design is able to withstand all forces and stresses that may be present on launch day, with a factor of safety of at least 1.2. Visual inspection will be conducted before and after every launch/landing cycle. New parts will be fabricated if necessary.

Bulkhead Fracture crack	Material Defect, stress on eyebolt threads,	Structural Failure, pressure leakage	1	2	3, Low	Simulations of the most extreme cases expected will be conducted to determine the maximum possible forces seen during launch to landing process. Material testing will be performed to determine the material properties. If the material is incapable of withstanding any possible forces or stresses seen during the flight process, a new material will be selected and tested. This process will be continued until a material is found to be able to withstand any possible forces seen during launch to landing process. A visual inspection will be conducted before and after every launch/landing cycle. Damaged parts will be replaced as necessary.

PROPULSION						
Failure	Cause	Effect	Likelihood	Severity	Combined Risk Factor	Mitigation
Motor CATOs	Motor casing or components rupture	Catastrophic damage to rocket	2	5	7, Moderate	Inspect motor grains prior to installation. A certified member will assemble the motor according to the assembly instructions with another observing. Develop an internal checklist.
Motor does not stay retained	Motor thrust pushes the motor into the rocket	Catastrophic damage to rocket	2	5	7, Moderate	Verify that the motor retention system can handle the motor thrust, with a safety margin

Motor does not stay retained	Ejection charges push motor out of rear of rocket	Motor does not remain in rocket	2	5	7, Moderate	Use of active motor retention, Use of lower impulse motor
Motor does not ignite	Motor does not ignite on launch day	Rocket does not lift off pad	3	1	4, Low	Use recommended igniters. Store motors properly to avoid oxidation. Verify that the initiator is inserted all the way to the top of the motor grains.

Avionics and Recovery

Failure	Cause	Effect	Likelihood	Severity	Combined Risk Factor	Mitigation
Altimeter has complete or partial power loss in flight due to faulty wiring of battery or switch	Wiring of switch and/or battery is not secure	Parachutes may not deploy, rocket descends at terminal velocity, rocket body and/or payload components are damaged	3	5	8, High	Perform sharp, forceful 'tug' test on wires, make connections with snapping and/or pinching mechanisms, not twisting
Altimeter fails to detect outside pressure accurately	Pressure port into avionics bay is not sufficiently large to allow outside pressure to be measured	Late or no deployment of parachutes, rocket descends at terminal velocity, rocket body and/or payload components are damaged	3	5	8, High	Ensure pressure port is at least the size of a grape
Main and drogue charges fail to separate the rocket	Use of too many shear pins, too little black powder	Parachutes do not deploy; the rocket descends at terminal velocity	3	5	8, High	Perform ground testing to determine the number of shear pins and proper amount of black powder.

Drift distance from launch pad is greater than required safety range	Main parachute is too large and/or deployment height is high	Rocket falls outside of launch boundaries, may cause damage to property, vehicles or people	3	4	7, Moderate	Select parachute sizes based on models of minimum descent speed, given various wind conditions
Altimeter loses continuity	Wiring of leads from altimeter and/or connection to initiators is not secure	Altimeter cannot ignite initiator, rocket descends too quickly	3	4	7, Moderate	Perform sharp, forceful 'tug' test on wires, make connections with snapping and/or pinching mechanisms, not twisting
Main side charges fail to separate rocket	Ejection charge strength is not matched to shear pin strength	Rocket descends and lands too quickly, damage may be inflicted onto rocket body	3	4	7, Moderate	Ground testing to determine ratio of shear pins to black powder
Drogue parachute undergoes fire damage due to ejection charge detonation	Parachute is damaged and may fail upon deployment	Rocket descends too quickly, main parachute may be damaged or cause damage to body tube upon deployment	3	3	6, Moderate	Standard operating procedure for parachute packing, included wrapping with fire retardant blanket
Main parachute undergoes fire damage due to ejection charge detonation	Parachute is damaged and may fail upon deployment	Rocket descends and lands too quickly, damage may be inflicted onto rocket body	3	3	6, Moderate	Standard operating procedure for parachute packing, included wrapping with fire retardant blanket
Fire retardant blanket slides up shroud lines of parachute and prevents it from opening fully	Fire retardant blanket is attached by running shroud lines through the hole in blanket as opposed to directly to the quicklink	Parachute's effectiveness is diminished, rocket descends and/or lands too quickly, damage may be inflicted on rocket body	3	3	6, Moderate	Secure fire retardant blanket to quicklink

Drogue side charges fail to separate the rocket	Ejection charge strength is not matched to exceed shear pin strength	Rocket descends too quickly, main parachute may be damaged or cause damage to body tube upon deployment	3	3	6, Moderate	Ground testing determine ratio of shear pins to black powder
Electromagnetic field trigger altimeter to detonate early	Faraday cage is not constructed to effectively shield altimeter	Rocket experiences explosive separation while on the ground and/or while being handles	2	4	6, Moderate	Construct faraday cage so that it is sufficiently thick and has complete coverage, testing
Main parachute either does not leave body tube or does not unfurl	Parachute, fire retardant blanket, and/or shock cord are not packed correctly	Rocket descends too quickly, damage may be inflicted on the rocket body	1	4	5, Moderate	Standard operating procedure for parachute packing
Main parachute deploys at apogee with the drogue parachute	Main side shear pin strength is not matched to exceed drogue side ejection charge strength; main and drogue parachutes are mistakenly swapped	Rocket descends too slowly, drift distance exceeds maximum	3	2	5, Moderate	Ground testing to determine ratio of shear pin to black powder; standard operating procedures for assembling recovery harnesses and parachutes
Jostling of rocket vertically triggers altimeter to detonate early	Altimeter detects changes in pressure that resemble apogee and detonates drogue charges	Rocket experiences explosive separation while on the ground and/or while being handles	1	4	5, Moderate	Setting minimum detonation height of altimeter to at least 100 ft above ground level, only enabling altimeters with charges on the launch pad
Body tube of the rocket is zippered by shock cord during parachute deployment	Rocket is falling too quickly when parachute is deployed	Permanent damage to body tube, which may need to be replaced	3	2	5, Moderate	Select parachute sizes based on models of maximum descent speed, use cushioned ball around shock cord to prevent damage

Kinetic energy at landing is above required safety threshold	Main parachute is not sufficient large to slow descent	Rocket lands with too much force, rocket body and/or payload components are damaged	2	3	5, Moderate	Select parachute sizes based on models of maximum descent speed, ensure masses of rocket section are accurate and up to date
Drogue parachute either does not leave body tube or does not unfurl	Parachute, fire retardant blanket, and/or shock cord are not packed correctly	Rocket descends too quickly, main parachute may be damaged or cause damage to the body tube upon deployment	1	3	4, Low	Standard operating procedure for parachute packing
Main parachute deploys below drogue parachute and tangles	Shock cord lengths are incorrectly proportioned	Rocket descends and lands too quickly, damage may be sustained by rocket body	1	3	4, Low	Designating specific lengths based on rocket section lengths, weights, and parachute locations

Explanation of Project Risk Assessment

The risks to the overall project were assessed, not with numerical values, but with descriptors such as “low”, “moderate”, and “high” for Likelihood and Impact. These were assigned based on list given below.

LIKELIHOOD:
Low: The risk is unlikely. Over the historical legacy of the risk, it has never occurred.
Moderate: The risk is likely. Over the historical legacy of the risk, it has occurred at least once.
High: The risk is very likely. Over the historical legacy of the risk, is has occurred several times.

IMPACT:
Low: The risk will cause disruption within the club, and could delay the progress of the project.
Moderate: The risk could cause the project to be severely delayed and/or reduce the quality of the finished product.
High: The risk could cause the project to fail, cause the team to be unable to make it to Alabama, or cause the club to be disbanded by Penn State.

Project Risk Assessment

There are several concerns with the overall project, mostly related to budget and personnel management. These are presented in Table 32.

Table 32. Project Risks

Risk	Cause	Effect	Likelihood	Impact	Mitigation
Club loses funding	One or more sources can no longer provide funding	There is not enough money to pay for transportation or necessary parts and equipment	Moderate	High	Dedicated member to track expenses and make funding contracts possible.
Project over budget	Testing/fabrication/travel costs exceed expectations	Project cost exceeds amount of money projected	Moderate	High	Compare prices from different vendors, avoid excess shipping costs
Parts are unavailable	Parts needed for the rocket are not available commercially	Rocket cannot be completed using the planned parts	Moderate	High	Use non-exotic materials and check for availability. Order parts far in advance
Damage during testing	Accident/malfunction during testing	Catastrophic damage to the rocket	High	Moderate	Ground testing, maintain a stock of spare parts
Project falls behind schedule	Team fails to build critical components in a timely manner	Major milestones are not met in time	Moderate	Moderate	Weekly status meetings, follow project plan
Failure to acquire transportation	Transportation to Alabama not acquired	Team is unable to travel to the competition	Low	High	Carpool to Alabama if necessary

Injury of team personnel	Hazards outlined in Table 29	Team member is injured	Low	High	Inform and enforce team safety
Club loses facilities	University revokes club access to the lab	Club loses access to 46 Hammond	Low	High	Maintain clean and safe environment in the lab and store hazardous materials safely
Labor leaves/graduates	Seniors graduate or students stop attending meetings	There are no longer enough students available to perform the necessary work	Low	Moderate	Recruitment at the beginning of each semester. Team building activities.
Theft of equipment	Parts or testing equipment get stolen	Rocket construction becomes more difficult, excess cost to the club	Low	Moderate	Only subsystem leaders and officers will have card access to the LTRL lab

5. Payload Criteria

Object Avoidance

Table 33 below is a selection matrix for object avoidance method. The “Range” score of the method is determined by the distance between the rover and obstacle when the latter is detected. Since the rover will be running at a relatively low velocity, it does not need to predict obstacles from a far distance. Therefore, this is one of the less important criteria. The “Light” score is determined by how much the method of avoidance weighs. Lighter components are more desirable because of mass constraints for the payload. The “Effective” score is determined by how reliable the method of avoidance is. More reliable methods are more favorable because they decrease risk of failure. This criterion is the most important because avoiding obstacles is essential for the rover’s operation, and failure in obstacle avoidance would disrupt the rover’s mission. The “Wedge Proof” score is determined by how effective the method of avoidance is at keeping the rover from getting stuck. This criterion is the second most important because it is essential that the rover continues to its desired location. The “Low Power” score is determined by how much power the method of avoidance would take. Energy efficient methods of avoidance are important because there is limited power onboard the rover due to space constraints. However, since the different design concepts all use relatively little power, this is not as important of a criterion when comparing the different concepts. The “Small” score is determined by how much volume the method of avoidance uses. Since the inner diameter of the rocket constrains the dimensions of the rover, having small methods of object avoidance are beneficial. Therefore, this criterion is more heavily weighted.

Table 33. Object Avoidance Selection Matrix

	Weight		Sensors	Bumper Wheels	Plow
Range	0.168		4	1	3
Light	0.054		5	4	3
Effective	0.326		3	2	4
Wedge Proof	0.236		3	1	3
Low Power	0.032		2	5	4
Small	0.185		5	4	3
			3.613	**2.169**	**3.358**

The most effective method of object avoidance is using sensors. The rover will incorporate ultrasonic sensors that can determine obstacles using radio wave signals and a receiver. Ultrasonic sensors are a lightweight, small, and effective method of determining the rover’s obstacles which will allow the rover to turn in time to avoid them.

Drivetrain

The primary driving mechanism was determined from the selection matrix shown in Table 34 below. The “Maneuverable” score was determined by the ability for the rover to make turns and avoid obstacles. This criterion is highly weighted because it is important for the mission’s success that the rover can reach its destination, which it cannot do if it can’t avoid obstacles. The “Low Risk” score was determined by the likelihood of failure of the method and the likelihood that it could cause other components to fail. Since all methods were relatively low risk, this criterion was not highly weighted. The “Traction” score was determined by the method’s ability to gain traction in various expected soils. Traction was a highly weighted criterion because there is the possibility of loose soil at the landing site, therefore the drivetrain method must gain traction in loose soil. The “Torque Output” score was determined by how much torque the method produces. Torque output is an important criterion because it is the primary way that the rover moves over obstacles. Due to the rover’s small size and limited ground clearance, torque output was the most highly weighted criteria. The “Durable” score was determined by how long the method would last and how strong it was. Durability is favorable because rovers should be designed to drive extended periods of time and complete multiple missions. The “Weight” score was determined by the mass of the method. Weight is typically an important variable to keep low, however it was not weighted heavily since it is the method of the rover’s movement, which is essential.

Table 34. Drivetrain Selection Matrix

	Weight		Wheels	Treads	Auger
Maneuverable	0.259		4	2	3
Low Risk	0.064		3	3	2
Traction	0.268		4	4	3
Torque Output	0.296		3	2	2
Durable	0.080		3	4	3
Weight	0.033		4	2	1
			3.560	**2.492**	**2.841**

As seen in Table 34 above, the wheels were chosen as the drivetrain method. Due to the high level of torque and expected traction from wheels, it is the ideal design choice for the rover.

Figure 23 below shows the design of the rover’s wheels. The wheels will be 3D printed because customizability is desired for the traction method. Additionally, rubber sealant will be added to the wheels to increase friction. Additional friction is necessary because of the smooth properties of PLA plastic.

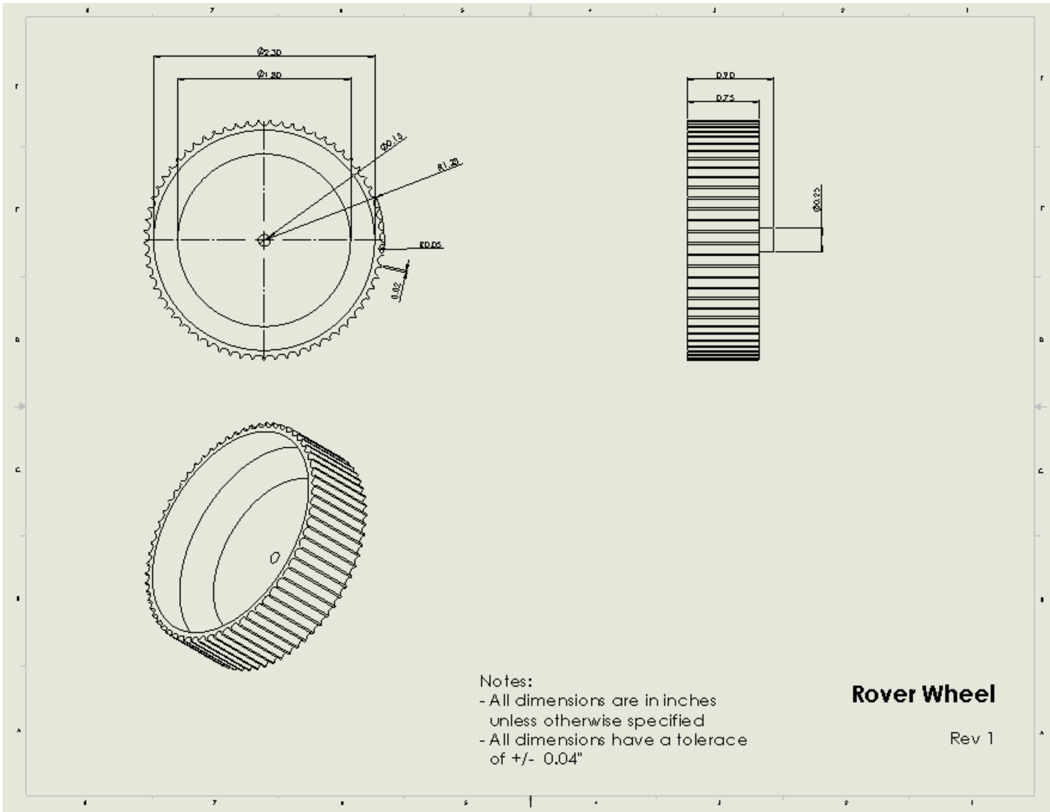


Figure 23. Rover Wheel Design

Figure 23 shows the riveted design for the wheel above to give the rover additional grip. This texture will increase the rover's traction on loose soil.

Rocket Integration

To drive the rover out of the rocket, there will be a post-landing CO_2 ejection. A CO_2 cartridge will be placed on the shelf above the rover pointed towards the nose cone. A wire will be connecting an initiator to the ejection mechanism so that the rover can trigger the ejection charge after the rocket has landed. The rover will be attached to the inside of the rocket via a locking mechanism. The system will include a 0.16 lb CO_2 cartridge in a 136 in^3 volume container which is held at 30 psi of pressure. This force will be sufficient to separate the rocket using 8 shear pins, since each shear pin can withstand approximately 25 lbf. Testing will be done to ensure that the correct amount of CO_2 and number of shear pins are used. Also, during testing, the pressure and temperature of the inside of the rocket during separation will be measured. This testing ensures that the rover and its electronics can withstand the pressure and temperature of the separation. A drawing of this set up is shown in Figure 24 below.

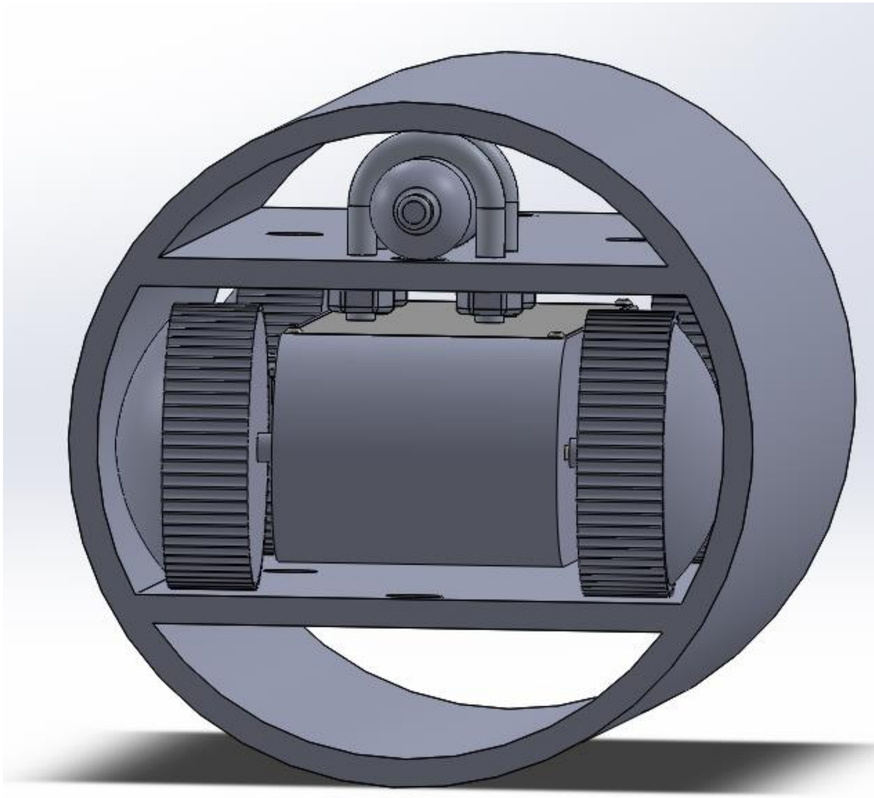


Figure 24. Rover and Ejection charge in rocket body

The 3D rendering shows the configuration of the payload bay and the CO_2 ejection mechanism. In this model, the nose cone would be facing out of the page. The mounting device is meant to hold the CO_2 cartridge in place. The holes drilled into the shelves, as seen in Figure 24, allow the pressure caused by the CO_2 cartridge's detonation to evenly distribute in the payload bay. The location of the holes were chosen to avoid direct contact with the wheels of the rover.

Software

The rover's flight computer will be an Arduino Mega microprocessor. The control software for the rover will be written in the C++ programming language and compiled to run on the Arduino microcontroller. The logic for the control software is illustrated in Figure 25 below.

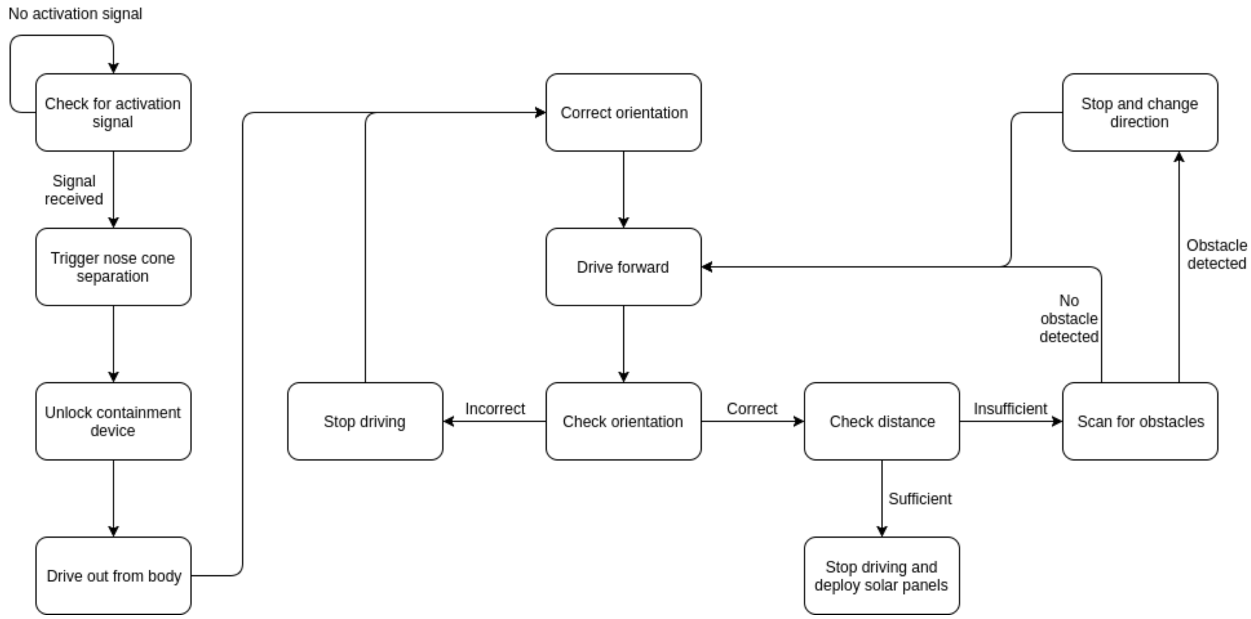


Figure 25. Rover Software Flow Diagram

When the rover is first powered on, it immediately begins listening for an activation signal to be sent from the ground station. Once the signal is received, the software activates the initiator to detonate the CO_2 charge and separate the nose cone from the rest of the rocket. After separating the nose cone, the software will then proceed to unlock the containment mechanism keeping the rover secured to the rocket and drive out from the interior of the body, correcting its orientation after exiting if needed. Since the rover only has passive corrective mechanisms (the hemispherical hubcaps), correcting orientation only involves waiting for the rover to settle on the ground due to gravity. After correcting its orientation, the software will continuously check its orientation, check the distance travelled from the rocket, and scan for obstacles. If the software detects that it has flipped, it will wait for the self-righting mechanisms to correct its orientation before resuming driving. If the software detects that it has travelled the appropriate distance, the rover will stop driving and deploy its solar panels. If the software detects an obstacle in the path of the rover, the rover will change direction and resume driving again.

The selection matrix for deciding upon the technique to be used for measuring distance traveled by the rover is shown in Table 35 below. The “Accuracy” score is determined by the accuracy of the method. This criterion is the most important for determining distance because the rover’s mission is based on the distance it travels. The “Risk” score is determined by how reliable the method of distance measurement is. Risk is the second most important criteria because if the system is unreliable and fails as a result, then the rover would not be able to complete its mission. The “Feasible” score is determined by how practical using the method is. Since all of the methods are fairly simple, this criterion is not as important for concept comparison.

Table 35. Distance Measurement Selection Matrix

	Weight		Accelerometer	GPS	Wheel Encoder	String on Pin
Accurate	0.555		3	4	3	4

Low Risk	0.370		3	4	3	1
Feasible	0.076		2	4	4	2
			2.294	**4.000**	**3.076**	**2.739**

As seen from Table 35 above, GPS is the best method for determining the rover's location. From the GPS data, the total distance from the rocket can be determined continually and quickly during the mission. The other methods of determining distance would not have the same abilities. To account for GPS error, the rover will aim for ten feet away from all parts of the launch vehicle.

Chassis/ Electronics

Figure 26 shows the chassis of the rover. The dimensions of the rover were chosen so that width could be maximized in the limited 5.375-inch inner diameter of the rocket. The dimensions are shown in the drawing below:

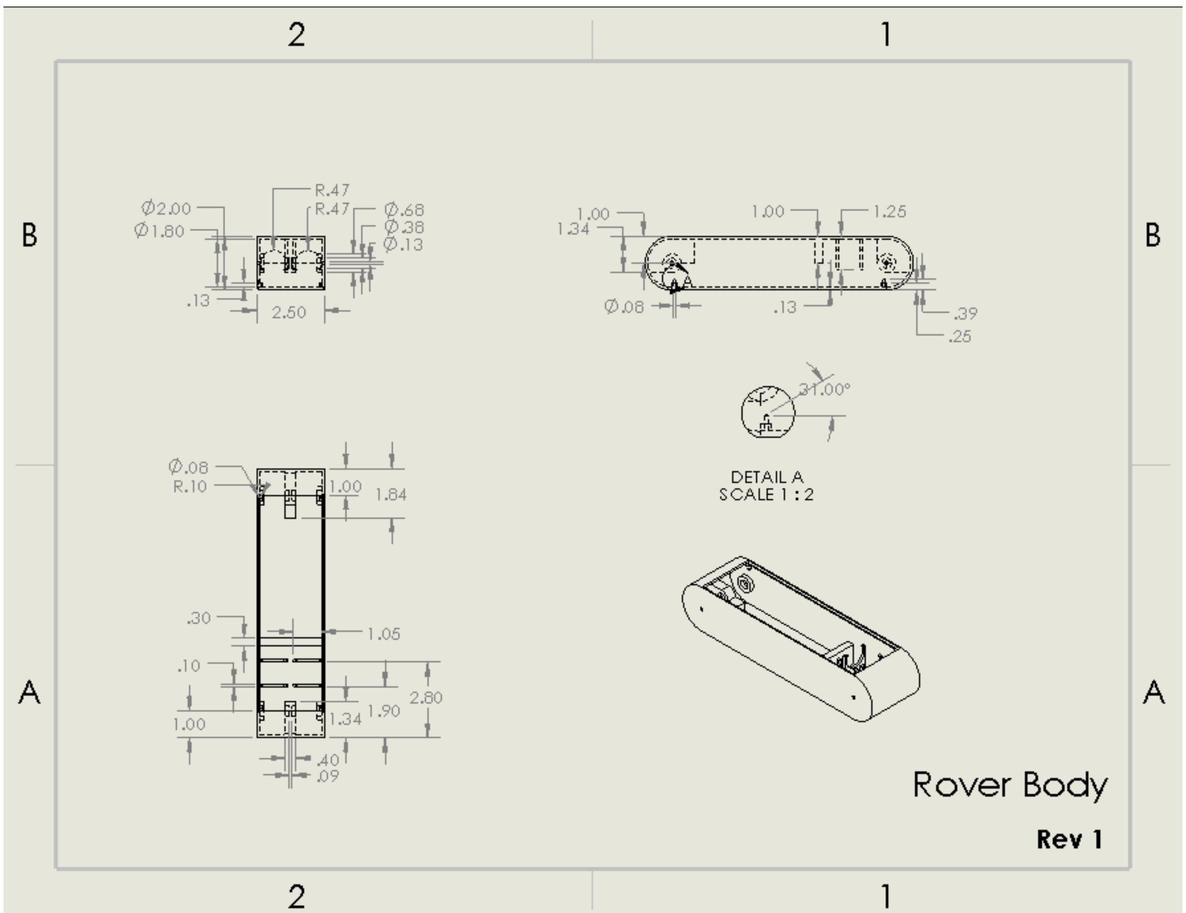


Figure 26. Rover Chassis Design

Design features include motor mounts and a section for the electronics board to be placed. To build upon last year's electronics organization, the chassis has open space for wiring and mounts. Figure 27 shows a 3D rendering of the chassis with the wheels attached.

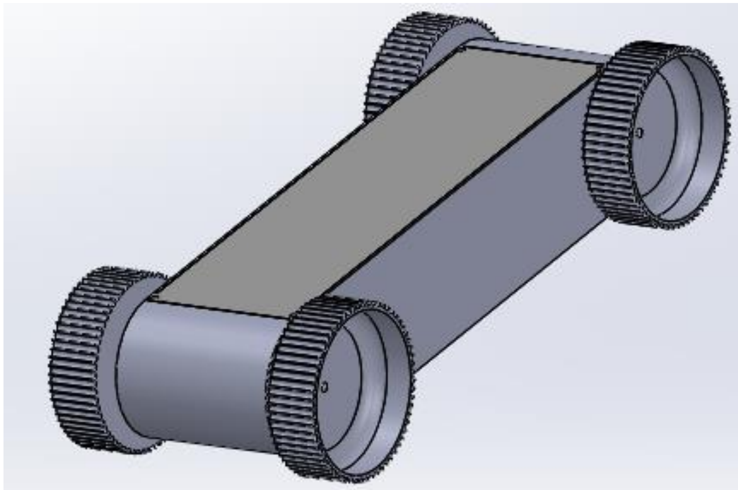


Figure 27. Rover Chassis with wheels 3D Rendering

As can be seen in the figure, the wheels are taller than the rover so that regardless of which way the rover drives out the rocket, it will be able to continue its mission. The wiring schematic for the rover's electronics, which are contained in the chassis, is shown in Figure 28.

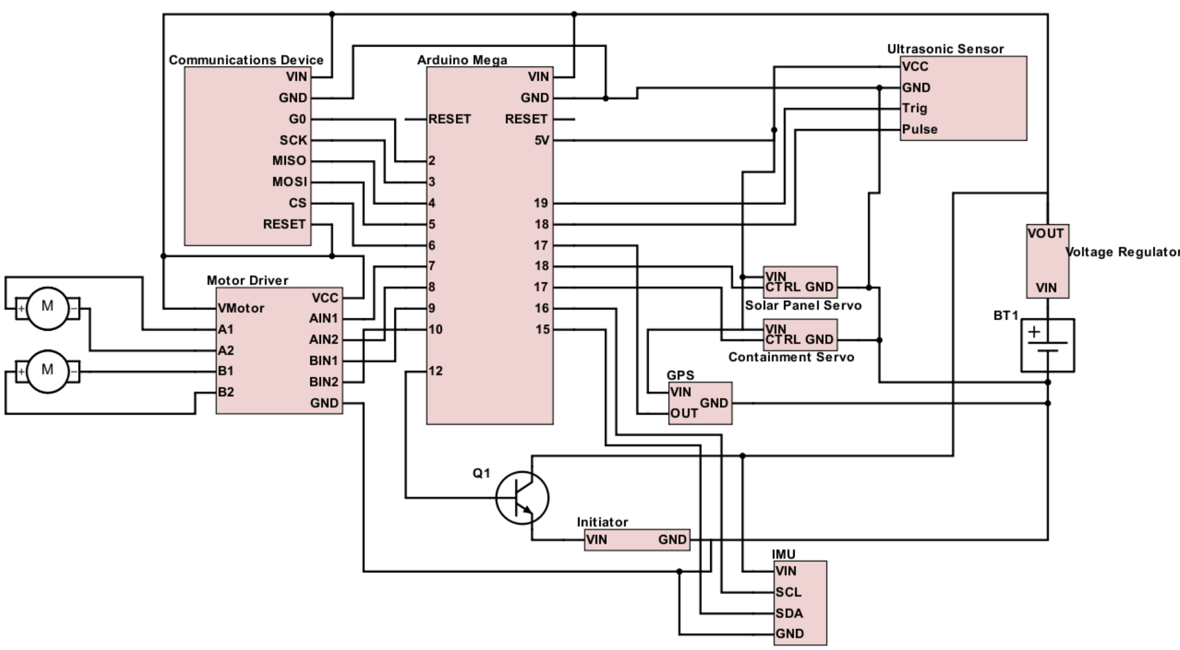


Figure 28. Rover Electrical Schematic

Rechargeable batteries are providing power to all components. The two motors power the wheels are connected to the motor driver, which is in turn wired to 4 pins on the Arduino microcontroller. The number of pins required was the primary factor in deciding to use the larger Arduino Mega instead of the smaller Arduino Nano. All power coming from the battery travels through a voltage regulator to ensure that sensitive electronic components are not subject to voltage spikes which may damage them. A digital LED display on the regulator allows the output voltage to be calibrated to the required value. To reduce the payload weight, a decision was made omit a switch from the circuit design and simply unplug the battery when the rover is not in use.

Solar Panel Deployment

The deployment of the solar panels built into the rover will be activated by the rover control software when the software detects that a sufficient distance has been travelled. The double-sided panels will be stored horizontally inside the body of the rover near the sides. Once the software decides to deploy the panels, a servo inside the rover body will pivot each panel outwards through slots in the side of the body, exposing the surface of the panels to sunlight. Because the panels will have solar cells on both sides, the solar panels will still be functional regardless of the side of the rover that faces up.

Justifications for unique aspects of the payload

PLA plastic is used for the body material of the rover because 3D printing allows for more detailed and precise components, allowing the team to make clasps for the electrical components that are contained within the chassis easily. The alternative to PLA was machining parts using hand tools and machines.

To account for not knowing the orientation of the rocket upon landing, the rover has multi-directional capabilities. Ultrasonic sensors are mounted on the front and back of the rover and the motors have the ability to move both directions so that the rover can go forward and backwards. Using an accelerometer, the rover can determine the relative direction of gravity from which it can determine which direction to drive if the rover flips over during its course.

Due to the high height to width ratio of the rocket, the rover was designed to be longer than it is wide. To maintain stability, hemisphere shaped hubcaps were implemented as a balancing mechanism.

Since the rover remains inside the rocket during descent and landing, a method of ejection was designed. CO_2 was chosen as the separation method because it has fewer safety risks than using black powder, and it is easily available. Black powder charges would release soot which could coat the rover, including wheels, hinges, and sensors, thus causing the rover to be unable to complete its mission.

Holes in the shelves were included to reduce the stress on the attachment points between the shelves and rocket. When the CO_2 charge detonates, there will be a large, rapid increase of pressure behind the nose cone and within the chamber the CO_2 charge will be stored. This pressure change will produce an impulse normal to the planar surface of the shelves that contain the rover. By including 4 small holes on each shelf, air will be able to pass between cavities and there will be no pressure gradient across the shelf. This will eliminate risk of deflection of the shelf, which would risk fracture and/or dislocation of the shelf and damage to the rover.

6. Project Plan

6.1 Testing

Payload Testing

Table 36 below describes the testing that will be conducted to verify the design of the rover. The table includes the variable being tested, the objective of the test, what defines a successful test and the justification for conducting the test.

Table 36. Planned and completed rover testing

Test	Objective	Success criteria	Justification
Communication System	Show that the rover can send status messages to the ground station	The ground station receives a message from the rover that is sent at a specified time	It is necessary for the rover to report its status to the ground station so that the team can monitor the payload for any issues that may arise during operation
Communication System	Show that the rover can receive the activation signal from the ground station	The rover receives the activation signal from the ground station and begins the ejection procedure	It is necessary for the rover to be able to receive the activation signal so that it will exit the rocket and begin executing its mission
Ejection Mechanism	Show that the rover can trigger the ejection mechanism to allow the rover to deploy from the rocket	The ejection mechanism releases the CO2 and separates the rocket	The CO2 must be released to separate the rocket and allow the rover to exit
Rover maneuvering	Show that the rover can avoid obstacles by turning based on information from the sensors	The rover successfully avoids various obstacles placed in front of it	The rover needs to be able to avoid large objects in its path to reach its desired location
Containment Mechanism	Show that the rover can stay attached to the rocket during the ejection	The rover does not prematurely exit the rocket	It is necessary to ensure that the rover remains inside the rocket until landing for mission success and for safety

The resultant data from testing will be used to determine changes that need to be made to the payload. For the communication system, if the rover fails to communicate to the ground station or vice versa, then there may need to be changes to the method of communication or the equipment. If the ejection mechanism fails to separate the rocket, then changes need to be made to either the amount of shear pins or CO_2 used. If there is a failure in the communication of the rover to the ejection mechanism, then there may need to be changes in the method of communication. If the rover is unable to avoid obstacles, then there may need to be modifications to the method of avoidance, the speed of the rover, or the software that controls how the sensors data results in the movement of the rover.

Test Plans and Procedures

To test the communication system, simple tests can be conducted in the lab to determine that signals are being received between the rover and the ground system. By sending an arbitrary signal to the rover via the communication system, the rover's Arduino will be connected to a computer to see that the message being sent by the ground station is received. The same will be done from the rover to the ground station.

To test the ejection mechanism, a full-scale model of the payload bay will be constructed using a fiberglass piece of body tube and nose cone. These parts will be recovered from previously launched rockets. The main objective is to ensure that the pressure and number of shear pins is sufficient to separate the rocket. A full-scale ground test will be conducted first without the payload. When the results of the separation are consistent, full scale ground testing will take place with the rover. While performing full scale ground tests with the rover, the main objective is to determine if the components of the containment mechanism and the components of the rover keep the rover both attached and undamaged respectively.

To test the maneuvering capabilities of the rover, various obstacles will be placed in the rover's path to see if it can avoid them. The testing area will be chosen based on the possible obstacles and terrain the rover could encounter. These include but are not limited to trees, large rocks, buildings, and vehicles. The rover will also be tested in various farming soils to predict its performance and make necessary modifications.

During the subscale launch, a door was tested as a containment mechanism for the rover. This method proved to be an unnecessary complication to the design. It will be easier, less complicated, and less massive to use a pin attachment method instead. A pin attachment will provide equal stability during launch and separation while also lowering complexity.

Vehicle Testing

One test will be performed after CDR is submitted to ensure the safety of the rocket. The rocket's airframe will be blue tube wrapped in carbon fiber. The test will determine how many layers of carbon fiber should be wrapped around the blue tube to ensure a sufficient strength of the airframe.

The launch vehicle's airframe will consist of blue tube wrapped in carbon fiber weaving. The number of carbon fiber layers that blue tube will be wrapped with will be determined by testing. The objective of the test will be to determine the tensile strength of the carbon fiber wrapped blue tube when the blue tube is wrapped with one layer, two layers, and three layers of carbon fiber weaving. This tensile strength should indicate the airframe ability resist zippering from deployment of the main parachute. A successful test is defined by obtaining a tensile strength value that is greater than the force that the shock cord from the main parachute will exhibit on the body tube. The shock cord force will be equal to the drag force that the parachute will experience once deployed. Logical results also define a successful test. A higher number of carbon fiber wrappings should result in a higher tensile strength. The variable that will be tested for is tensile strength.

This test is necessary to determine the number of carbon fiber wrappings needed to sufficiently withstand shear force that the airframe will experience from the shock cord during the parachute deployment. The zippering force will be defined by the drag force that the main parachute will experience once deployed. The lowest number of layers necessary to sufficiently withstand the zippering force and surpassing the failure value with a safety factor of at least 1.5 will be chosen to reduce the weight from the airframe.

Currently, the design of the launch vehicle includes two layers of carbon fiber wrapping the blue tube. If the current design fails to be able to withstand the expected forces seen during operation, then more layers of carbon fiber will need to be added to the design and retested. This process is to be continued until the design is able to fully withstand any and all loads encountered during flight and recovery. Full test procedures for all vehicle tests can be found in Appendix E: Testing Procedures.

Recovery Testing

Body Tube Drag

As the rocket falls under the drag of the drogue parachute the tumbling body tube sections have a significant contribution to the total drag acting on the rocket. A model for the drag of the body tube has 12 degrees of freedom as there are 2 body tube sections free to move and rotate in 3 axes each. An effective model was not able to be obtained due to the complexity of the dynamics. A model for the trajectory of the rocket was constructed to predict if the rocket's decent will satisfy NASA's requirements for drift distance and maximum kinetic energy. In this model the drag of the body tube is roughly estimated as a parachute with coefficient of drag 1.0 and radius 7.2 inches. The values of these estimated parameters will be calibrated after a test launch such that the predicted trajectory will coincide with the actual trajectory. These parameters will be used to predict the launch trajectory for the USLI competition.

BP/ CO2/ Pyrodex

Currently, most ejection charges are black powder (BP), which is reliable and cheap. However, BP has hazards associated with is as well as a questionable legal standing. Currently, to calculate BP charge sizes, A&R uses a 3rd party website that gives measurements that LTRL cannot verify. It would be ideal to create a calculator that will predict the pressures generated with certain quantities of the different charge options in different volumes. The options are BP, pyrodex (a BP substitute that is less regulated and safer), and CO2 cartridges (similar to the ones used in airsoft). This project will involve some chemistry, physics, and hopefully experimental design and execution. LTRL is currently working with faculty and nearby laboratories to establish safe testing facilities and determine what equipment is available.

Bulkhead Testing

The bulkheads are important structural components that support forces from the parachute and body tube of the rocket. They hold the avionics bay in place and cannot fail during flight, so they will be tested in SolidWorks FEA simulation. Red oak was chosen for the bulkhead since it can be laser cut to ensure a perfect fit. The bulkhead was modeled in SolidWorks, as well as the AV bay, bluetube coupler, all threads, U-bolt, screws, blast caps, nuts and washers that are attached to it. These components are fixed in their location by the design of the rocket and will affect the structural integrity of the bulkhead. The top and bottom bulkheads are built from two sections glued together with eight holes drilled through them both. Six of these holes must be drilled in certain locations so that the two all threads can go through the AV bay, and so that the U-bolts and blasting caps can be centered, the other two holes can be placed anywhere that can allow wires to connect the initiators for the black powder charges to the Avionics bay.

To find the location of these two holes, the six-hole bulkhead will be simulated under a load and the factor of safety chart will be displayed. The two extra holes will be drilled on opposite sides of the bulkhead and in the location with the highest factor of safety. The success criteria for this test is just to find the best location to place the initiator wire holes. If it is found that the best location for the holes is not a location where the wires can reach the blast caps, then the next safest spot will be chosen and so forth.

Once the all eight-hole locations are decided then the bulkhead will be remodeled and run through the same FEA simulation. The same arbitrary value for the force will be used to test the bulkhead. When checking the results, the location with lowest factor of safety will be multiplied by the force in the simulation. The simulation will then be rerun with that force to double check that the weakest point will still hold. That force value will then be compared to the expected force that drogue deployment, and main deployment are expected to exert on the U-Bolt. The test will be counted as a success if the force required to cause a failure of the bulkhead is greater than both other two values.

If the test is a failure the next option is to use plywood. Plywood has been used for rockets like the rocket for the 2018 USLI competition, including the rocket that LTRL launched for the 2017 USLI competition. Plywood has never had any type of failure and is a safe choice for bulkhead material.

Force on Nose Cone

Since Payload needs to be able to open the nose cone after the rocket has landed so the rover may exit, the nose cone is attached to the body of the rocket by shear pins, able to support up to 25 lbf each, that can be broken with a CO_2 charge. However, during flight, the rocket will experience a large drag force when the main parachute deploys so it must be ensured that the force of the parachute does not break the shear pins; by calculating this force the number of shear pins required for safety can be determined. The purpose of the measurements is to calculate an approximate maximum force exerted on the shear pins connecting the nose cone to the rest of the body.

To calculate the maximum force applied to the nose cone of the rocket is to calculate the force of drag the main parachute will create when it opens. The equation is: $F_{drag} = .5 * p * C_d * A * v_{max}^2$, where p is the density of air (1.225 kg/m3), A is the cross-sectional area of the main parachute in m^2, while C_d is the coefficient of drag of the parachute. The velocity, v_{max}, is the maximum velocity of the rocket after drogue deployment, experimentally measured to be 120 ft/s. When calculating this, the maximum drag force would be a 600 N force, which is 134 lbf. That means it would require at least 6 shear pins to prevent the nose cone from breaking off during the deployment of the main parachute. Since the CO_2 charge applies a much greater force once the rocket has landed, 8 shear pins are being used as insurance to ensure that the nose cone will not separate before the rocket is on the ground.

Parachute Test

To accurately select which parachutes to use to land the rocket, the coefficient of drag for each parachute must be verified. The testing is necessary to land the rocket safely and within the prescribed kinetic energy limits. The plan is to first, measure the diameter of the parachute to calculate area. Second, attach the altimeter and mass to the parachute. Then measure the mass of the parachute-altimeter system. Drop the parachute system from 100ft so that the parachute deploys. Use the altimeter data recorded to find the terminal velocity, if it is reached. Then, use the experimental values to calculate Cd. If terminal velocity is not reached, the coefficient of drag can still be found by using instantaneous values of velocity and derived acceleration. Make three drops for each parachute, but the measurements only need to be made once.

Equation for coefficient of drag: $C_d = 2 * m_{sys}(g - a) * A * v^2$
Equation if terminal velocity is reached (a = 0): $C_d = 2 * m_{sys} * g * A * v^2$

For the experiment to be most successful, terminal velocity should be reached. However, reliable results can still be found by calculating instantaneous velocity and acceleration for the first equation for Cd. The results of the test will be used to select the proper drogue and main parachutes for the rocket.

6.2 Requirements Verification

The following five tables explain how LTRL will meet all the requirements set forth by NASA.

Table 37. General Requirements

Requirement	Method of Verification	Verification
1.1	Inspection	The club is 100% student run, and only turns to mentors for advice and motor assembly, handling all ejection charges, and preparation and installation of electric matches.
1.2	N/A	The team has established Gantt Charts to maintain a project plan that includes but is not limited to project milestones, budget and community support, checklists, personnel assigned, educational engagement events, and risks and mitigations.
1.3	N/A	Foreign National members will be identified to NASA by PDR via email.
1.4	N/A	The team will identify all members attending launch week activities in the launch week member list to be submitted with CDR.

1.4.1	Inspection	LTRL leadership will keep track of the students who are actively engaged in the project, and only send them to launch week activities.
1.4.2	N/A	The team will bring Alex Balcher as it's mentor. (NAR Level 2 Certified)
1.4.3	N/A	The team will bring no more than two adult educators.
1.5	Inspection	The team will engage at least 200 participants in hands-on, educational STEM activities by participating in STEM events at middle and high schools in Centre County and going to visit team members' former middle and high schools to give STEM talks.
1.6	Inspection	The team has created a website on Penn State's sites server which it will continually update during the project year.
1.7	Inspection	The team will post the required deliverables to the LTRL website before the due dates specified in the NASA USLI Handbook.
1.8	Inspection	The files will be posted to the website in PDF format.
1.9	Inspection	LTRL will include a table of contents in all reports that includes major sections and subsections.
1.10	Inspection	The team will always include page numbers at the bottom of each page of each report.
1.11	Inspection	The team will ensure they have all equipment necessary for a video teleconference at the time of each review conference. LTRL will make sure they have a speakerphone that is not a cellular phone.
1.12	Inspection	The team will make sure their rocket does not require a custom launch rail, and that their rocket can be launched on the launch pads provided by the USLI launch service provider.
1.13	Inspection	LTRL will implement the Architectural and Transportation Barriers Compliance Board EIT Accessibility Standards (36 CFR Part 1194)
1.14	Demonstration	Alex Balcher is LTRL's mentor for this academic year. He maintains a level 2 certification and is in good standing through NAR. He is the designated owner of the rocket and will travel with the team during launch week.

Table 38. Vehicle Requirements

Requirement	Method of Verification	Verification
2.1	Analysis	Accurate simulations using Openrocket have been performed to ensure that the rocket design can reach an apogee altitude of 5,280 feet above ground level. Other calculations will be performed using the club's own equations to ensure that the rocket is as close to 5,280 ft as

		possible. Test launches will be conducted to test Openrocket and the club's own equations. Up to 10% of ballast will be added to the rocket to get the specific weight needed to get to a mile high.
2.2	Inspection	A visual inspection of the official barometric altimeter will be conducted to ensure that it is installed properly and a continuity test will be conducted prior to flight to ensure that the altimeter is functional.
2.3	Demonstration	The rocket will be designed to use key switches to ensure that the arming switches cannot be armed without purposeful intent to do so.
2.4	Inspection	A visual inspection will be conducted prior to launch to ensure that each altimeter is powered by a dedicated 9V battery.
2.5	Demonstration	Key switches that lock in the ON position will be used. A visual inspection and functionality test will be conducted prior to launch to ensure that the key switches are functioning properly.
2.6	Demonstration / Testing	Durable materials will be used for all rocket parts to ensure that the rocket can survive flight without damage. Test flights will be conducted before launch day to further verify that chosen materials will withstand flight conditions. Specifically, the airframe made out of blue tube will be wrapped in carbon fiber to withstand possible zippering, buckling, or abrasion.
2.7	Demonstration	The rocket is designed to have only four (4) independent sections. A visual inspection will be conducted prior to launch to ensure that the rocket meets this requirement.
2.8	Analysis	The rocket will be designed to use a single stage motor. Proper documentation will be collected and recorded. A visual inspection will be conducted prior to launch to ensure that the rocket meets this requirement.
2.9	Demonstration	The rocket will be designed so that minimal assembly will be needed on launch day. Three sections of the rocket will be independent of each other and each subsystem will be able to work on there specific section independent of other subsystems to allow a quicker construction time. The rocket will be launched prior to launch day to ensure that the time needed to assemble the rocket meets this requirement.
2.10	Analysis	Energy consumption calculations will be performed for all on-board components. Power supplies that meet this requirement will be selected.
2.11	Testing	Tests will be performed on a fullscale primary motor prior to the fullscale test launch to demonstrate that the motor can be ignited with a 12-volt direct current firing system. These tests will be part of the larger test goal to gather operational

		and performance characteristics of the primary fullscale motor before the fullscale test launch.
2.12	Demonstration	All electronics will be contained within the launch vehicle except for the initiator required to light the motor upon launch.
2.13	Demonstration	The motor used for competition launch will be from a trusted manufacturer (Ceseroni or Aerotech), using NAR approved APCP propellant.
2.13.1	Analysis	In-depth mass analysis of the rocket using OpenRocket and SolidWorks will be performed to ensure mass estimates are accurate by CDR therefore, ensuring a proper motor selection.
2.13.2	N/A	Motor selection will be finalized before CDR. If any change to the motor is necessary, proper steps will be followed to ensure that the change in decision is done so as to be in accordance with this requirement.
2.14.1 - 3	N/A	The final flight vehicle will not contain any custom pressure devices except for possible CO_2 cartridges which will be commercially bought.
2.15	Analysis	Analysis will be conducted via OpenRocket and MATLAB models to simulate the flight profile of the vehicle, and the associated motor selection process will be limited to motors approved by the aforementioned bodies.
2.16	Analysis	Accurate simulations will be conducted to ensure that the rocket meets this requirement. The rocket is designed with the rover payload towards the front of the rocket to bring the center of gravity closer to the front of the rocket and bring the stability of the rocket up as a result. Fins are large enough to bring the center of pressure back far enough so that the stability is further increased.
2.17	Analysis	Accurate simulations will be conducted to ensure that the rocket meets this requirement. A sufficiently powerful motor will be selected that will able to accelerate the rocket to 52 fps at rail exit. Data from test launches will verify the simulations accuracy.
2.18	Demonstration	The team has launched and recovered a subscale model of the rocket prior to CDR.
2.18.1	Demonstration	The subscale rocket was designed to accurately imitate the fullscale geometry as closely as possible. All materials that will be used for fullscale were used for subscale. The same methods that were used to build the subscale rocket will also be used for the fullscale rocket.
2.18.2	Demonstration	The avionics bay will be designed to include an altimeter that will record the altitude the launch rocket reaches.
2.19	Demonstration	The rocket will be launched and recovered in its final flight configuration prior to FRR. Gantt charts along with

		deadlines in place will ensure that the team stays on schedule for a launch prior to FRR. The rocket will be built and launched multiple weeks prior to the FRR deadline so that if there is a failed flight, the team can fix any damages or issues that occurred during the failed test flight and relaunch before FRR.
2.19.1	Inspection / Analysis	After the rocket is launched, the team will inspect each system to confirm that it functioned properly. The structural integrity of the vehicle will be inspected to ensure that no part of the rocket suffered severe damages during flight, and flight data will be analyzed to ensure that recovery systems were deployed at their correct altitudes, and to determine if drift calculations were correct.
2.19.2	Demonstration	If the payload is not ready for a fullscale test launch, it will not be flown, but it should be thoroughly tested regardless.
2.19.2.1	Demonstration	A custom mass simulator will be made if the payload is not ready to be installed into the rocket for the test launch. The mass simulator will be made to be identical in mass as the final design of the payload.
2.19.2.2	Inspection	A visual inspection will be conducted prior to the test flight to ensure that either the final design of the payload or the mass simulator are installed properly.
2.19.3	Inspection	A visual inspection will be conducted prior to the test flight to ensure that all parts that affect the external surfaces of the rocket are present and installed properly.
2.19.4	Analysis	If the fullscale motor is not flown during the fullscale test flight, analysis will be performed via OpenRocket and MATLAB with the motor used during the flight to verify that major flight characteristics such as maximum velocity, maximum acceleration, and maximum altitude are as close to originally predicted as possible.
2.19.5	Inspection	A visual inspection and weight measurement will be conducted prior to test flight and launch day flight to ensure that the rocket ballast is the same for both flights. The mass will be recorded. Full scale test launch will not occur until the rocket is fully built so that the total mass of the rocket on test launch day accurately reflects test day launch.
2.19.6	Inspection	Proper documentation will be collected and recorded to ensure that all components used on launch day are identical to the components used during the full-scale demonstration flight. A visual inspection will be conducted prior to launch to ensure that this requirement is met.
2.19.7	Demonstration	A date will be selected for full-scale test flight prior to the cut-off date to be in accordance with this requirement. This selected date will be multiple weeks prior to the FRR deadline in case a re-flight is necessary. If a re-flight is

		necessary, a date will be selected for full-scale re-flight prior to the extended cut-off date.
2.20	Demonstration	The fins and camera cover will be located aft of the burnout center of gravity. Center of gravity will be recorded through multiple procedures to validate its location. The center of gravity will be moved to the front of the rocket as much as possible by having the rover payload at the front of the rocket. A visual inspection will be conducted prior to launch to ensure that the rocket complies with this requirement.
2.21.1	Inspection	The rocket will be designed to not have any forward canards. A visual inspection will be conducted prior to launch to ensure that the rocket complies with this requirement.
2.21.2	Inspection	The rocket will be designed to not have any forward firing motors. A visual inspection will be conducted prior to launch to ensure that the rocket complies with this requirement.
2.21.3	Inspection	The rocket will be designed to comply with this requirement. A visual inspection will be conducted prior to launch to ensure that the rocket complies with this requirement.
2.21.4	Inspection	The rocket will be designed to have only A visual inspection will be conducted prior to launch to ensure that the rocket complies with this requirement.
2.21.5	Inspection	The rocket will be designed to have only one motor. A visual inspection will be conducted prior to launch to ensure that the rocket complies with this requirement.
2.21.6	Inspection	The rocket will be designed to have active motor retainment via use of centering rings and a motor retainer. A visual inspection will be conducted prior to flight to ensure that the rocket complies with this requirement.
2.21.7	Analysis	Analysis will be conducted via OpenRocket and MATLAB models to simulate the flight profile of the vehicle, and the associated motor selection process will be limited to motors that do not accelerate the vehicle past Mach 1 at any point during the flight. This will primarily be achieved by ensuring that motors with higher average thrust values are not included in the selection process.
2.21.8	Demonstration	A full inventory of the rocket components will be recorded. All components will have part name, mass, and function recorded. Ballast will not exceed 10% of the total weight of the rocket. A visual inspection of the rocket will be conducted prior to flight to ensure that all components recorded on the inventory list are present. There will be no

		components missing or more than what is documented in the inventory list.

Table 39. Recovery Requirements

Requirement	Method of Verification	Verification
3.1	Demonstration	Altimeter will be programmed so that drogue will deploy at apogee, main will deploy at 700ft.
3.2	Test	LTRL will ground test ejection charges before any subscale or fullscale launch.
3.3	Analysis	The parachutes sizes will be determined by modelling so that each component of the rocket lands within the kinetic energy constraint of 75 ft-lbs.
3.4	Inspection	The recovery system wiring will be completely independent of any payload components.
3.5	Inspection	Each altimeter will have an independent, commercially available battery.
3.6	Inspection	There will be two independent, commercially available altimeters per avionics bay. Each altimeter will have independent power, ejection charges, and switches for redundancy.
3.7	Inspection	Motor ejection will not be used to separate the rocket at any point.
3.8	Inspection	Removable shear pins will be used to secure all parachute compartments until altimeters initiate separation.
3.9	Analysis	The parachutes sizes will be determined by modelling so that recovery area will not exceed a 2500 ft. radius from the launch pads in various wind conditions.
3.10	Inspection	An electronic tracking device will be installed in the launch vehicle and will transmit the position of any independent section to a ground receiver.
3.10.1	Inspection	Any rocket section, or payload component, which lands untethered to the launch vehicle, will also carry an active electronic tracking device.
3.10.2	Test	The electronic tracking device performance will be tested in a variety of scenarios, including test flights.
3.11	Demonstration	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight.
3.11.1	Inspection	The recovery system altimeters will be a separate compartment within the vehicle without any other payloads or electronic components.
3.11.2	Test	A faraday cage will be tested for ability to shield the recovery system electronics from all onboard transmitting devices.

3.11.3	Test	A faraday cage will be tested for ability to shield the recovery system electronics from all onboard devices which may generate magnetic waves.
3.11.4	Test	A faraday cage will be tested for ability to shield the recovery system electronics from any other onboard devices which may adversely affect them.

Table 40. Experimental Requirements

Requirement	Method of Verification	Verification
4.1	N/A	The team will construct a rover which will deploy from the rocket upon landing and operate autonomously
4.2	N/A	No additional experiments
4.3	N/A	No additional experiments
4.4	N/A	N/A
4.5	N/A	Deployable Rover
4.5.1	Inspection	The rover and its containment mechanism will autonomously deploy the rover from the inside of the rocket upon landing. The team will design, manufacture, and test the rover and containment system following the engineering design process.
4.5.2	Test	The communication protocols between the rover and the ground station will be tested in a variety of scenarios to ensure communication. Hardware communication components (XBee radios) will be procured and manufactured and control software will be written to establish a communications link between the rover and the ground station.
4.5.3	Test	The rover will be tested thoroughly on different terrains and in different weather conditions to prove its ability to travel the minimum required distance. The team will scout test sites on and around campus to determine potential proving grounds for the rover's travel abilities.
4.5.4	Test	The solar cell deployment mechanism will be tested thoroughly to ensure deployment after the rover has travelled to its final position. The solar panel deployment mechanism will be iteratively prototyped and tested to ensure that it can meet and exceed the given requirements.
4.6	N/A	N/A

Table 41. Safety Requirements

Requirement	Method of Verification	Verification

5.1	Demonstration	The team will use launch and safety checklists during all fullscale launches.
5.2	Demonstration	Laura Reese is identified as the club safety officer in each report.
5.3.1	Demonstration	Laura Reese will perform all of the duties of the safety officer.
5.3.2	Demonstration	The safety officer will implement the safety procedures developed by the team for construction, assembly, launch and recovery activities.
5.3.3	Demonstration	The safety officer will manage and maintain current revisions of the team's hazard analyses, failure modes analyses, and SDS data.
5.3.4	Demonstration	The safety officer will assist in the writing and development of the team's hazard analyses and failure modes analyses
5.4	Demonstration	LTRL will abide by the rules and guidance of the RSOs of the Pittsburgh Space Command, Maryland Delaware Rocketry Association, and any other launch which the club chooses to attend.
5.5	Demonstration	LTRL will only launch at locations which have been given FAA clearance for the altitude to which the rocket is projected to attain.

Team-Derived Requirements

Table 42 Table 42lists the teams derived goals for this year's competition. These goals are divided by section of the rocket to create individual milestones that the team can work towards accomplishing throughout the project.

Table 42. Team Derived Requirements

Requirement	Method of Verification	Verification
Flight Vehicle		
Launch vehicle fins will be removable	Demonstration	Fins on the launch vehicle will be able to be removed without disassembly of the launch vehicle. This will be accomplished by securing the fins into 3D printed fin brackets. These fins can be unscrewed or unbolted from the fin brackets and safely removed.
Launch fin brackets will be removable	Demonstration	Fins brackets on the launch vehicle will be able to be removed without disassembly of the launch vehicle. This is accomplished by 3D printing the fin brackets and sliding them into precut slots in the airframe. These fin brackets will then be screwed and bolted to

		the airframe which can be removed at any time.
Camera will be housed in the launch vehicle with aerodynamics in mind	Demonstrations / Testing	A 3D-printed camera cover will be screwed into the rocket so that the camera can film without disturbing aerodynamics.
Maintain a circular profile after wrapping the body tube in carbon fiber	Demonstration / Testing	The team will test different methods of wrapping the body tube with carbon fiber to ensure that the body tube will not warp after wrapping and compressing. Couplers may be put into the body tube to prevent shrinking of the airframe. Epoxy will be carefully maintained so that it does not seep into the airframe and add extra thickness.
Flush cuts between separation points to ensure structural integrity	Demonstration / Testing	The team will cut all body tubes using school supplied bandsaws to ensure straight and flush cuts. Carbon fiber weaving might warp these flush cuts after being epoxied on. Couplers may be added to the ends of these body tube sections to prevent warping so that a circular profile may be maintained.
Cut screws so that they will not interfere with parachute deployment	Demonstration	Screws will be measured and cut to a length that remains long enough to maintain structural integrity but short enough so that they do not interfere with parachute deployment.
Coupler length is twice the diameter of the rocket to ensure structural integrity	Demonstration	The team will purchase couplers that are twice the length of the diameter and measure couplers to verify length.
Rocket is designed so that assembly is optimized on launch day	Analysis / Demonstration	When finalizing the design of the rocket, separation points will be picked so that each respective subsystem can work on their section of the rocket without having to wait for other subsystems.
Camera can start recording after it is fastened into the rocket.	Demonstration	The 3D-printed camera cover design will be modified so that an external recording button can be threaded through the rocket and accessed from the outside of the rocket after full assembly.
Avionics and Recovery		
The avionics bay will be able to be assembled into a transportable state within 2 hours.	Demonstration	The avionics bay will be able to be partially assembled within two hours and be able to be transported.
Avionics bay will be able to be transformed from a	Demonstration	The avionics bay will be able to be assembled within 30 minutes on launch day.

transportable state to a launch ready state in 30 minutes.		
The detonation of charges shall not cause the pressure within the avionics bay to exceed the rated pressure for the body tube	Analysis	The charges will not overwhelm the body tube and the redundant charges will be at a two-second delay.
The pressure produced during detonation shall exceed the rating of the shear pins by a factor of at least 2.5	Test	The black powder will be tested against the amount of force it would take to release the parachute but not cause an overpressure event.
The avionics bay shall contain fully redundant parachute deployment systems	Inspection	The avionics bay will have two independent altimeters with corresponding independent charges, power supplies, and switches.
Each altimeter arming switch shall be no more than five feet up the rocket	Inspection	The avionics bay will not be more that five feet up the rocket.
The avionics bay shall utilize a simple design that allows for clear and unambiguous instructions and assembly	Demonstration	The avionics bay will be designed to be easily assembled and bulkheads will be laser cut to ensure perfect symmetry.
The faraday cage shall protect the avionics bay from both internal and external interference	Test	The avionics bay will be enclosed in a faraday cage that will protect it from interference from other electronic components.
Any load-bearing hardware in the recovery system shall have a factor of safety of at least 3	Analysis	All load-bearing hardware will be ensured to have at least a safety factor of at least 3.
Avionics bay shall have a system to easily incorporate ballast securely	Demonstration	The avionics bay and avionics bay coupler will allow a ballast to be incorporated in the coupler.
Payload		
Maintain constant communication between the ground station and the rover throughout the mission	Test	Test the maximum range of the communications system to show that it is greater than the maximum drift range of the rocket. Find a test location where launch conditions can be most accurately replicated (including distance, duration of operation, and line of sight to the vehicle).

Design the rover to be self-righting in case it is overturned while maneuvering	Test	Places the rover in different orientations on different terrains and ensure that it can return to a drivable orientation without human intervention. Find various terrain and determine if the rover's self-righting capability can adequately perform on all terrains for any given orientation.
Avoid obstacles on the ground and navigate around terrain during operation	Test	Test the rover's navigational abilities by placing various sized obstacles in its path and driving it over various types of terrain. Find various terrain and determine if the rover's obstacle detection and avoidance system can accurately detect and avoid various sized and shaped obstacles
Deploy solar panels so that they are able to collect sunlight	Inspection	Confirm that the solar panels are exposed to sunlight when deployed. Design the solar panel deployment mechanism so that the solar panels will be exposed to sunlight (parallel to the ground) regardless of the rover's orientation.
Safely deploy the rover from the rocket body	Demonstration	Show that the CO_2-powered ejection of the nosecone does not harm the rover or hinder its operation. Conduct ground testing of the nosecone ejection to determine the maximum force able to be sustained by the rover

6.3 Budget Plan

Table 43 displays the expected costs of the 2017-2018 with the updated design. This table includes every individual item that has been purchased so far and all the projected costs.

Table 43. Expected Line Item Outflow 2017-2018

Fullscale			
Payload			
Arduino	5	$15.99	$79.95
Wheel and Treads Kit	1	$14.95	$14.95
Solar Panels	2	$5.69	$11.38
Containment Mechanism for Inside the Rocket	1	$25.00	$25.00
Radio Transceiver	3	$19.95	$59.85
Antenna Connector	3	$0.75	$2.25
Micro Metal Gearmotor	2	$18.95	$37.90
Jumper Wire Kit	1	$14.60	$14.60
Freight Charges	1	$8.00	$8.00
Structures			
5.5" Fiberglass Ogive Nosecone	1	$84.95	$84.95
5.5" Blue Tube (48” Length)	3	$56.95	$170.85
5.5" Blue Tube Couplers	5	$18.95	$94.75
Carbon Fiber Fabric	1	$329.95	$329.95
Epoxy Resin for Carbon Fiber	1	$44.95	$44.95
Epoxy Hardener for Carbon Fiber	1	$21.95	$21.95
1.25" Shrink Tape	2	$39.95	$79.90
Fiberglass Sheet ⅛" x 1 square feet	4	$27.00	$108.00
Large Rail Buttons for 1515 Rail	1	$4.65	$4.65
Center Rings 75mm to 5.36"	2	$13.55	$27.10

5.36" Tube Bulkheads	6	$7.61	$45.66
5.26" Coupler Bulkheads	5	$7.61	$38.05
Freight Charges	1	$134.21	$134.21
Avionics and Recovery			
Blast Caps	4	$15.00	$60.00
GPS	1	$106.00	$106.00
GPS Monthly Fee	4	$25.00	$100.00
Initiators	2	$27.20	$54.40
Shear Pins	2	$3.10	$6.20
Switches	2	$9.93	$19.86
Wire Connector	1	$6.55	$6.55
Freight Charges	1	$12.90	$12.90
Propulsion			
Aerotech L1390 Motor Reload	2	$199.99	$399.98
Aerotech 75mm Forward Seal Disk	2	$35.00	$70.00
		Fullscale Total	**$2,554.31**
Subscale			
Structures			
75 mm Blue Tube	2	$29.95	$59.90
75 mm Blue Tube Coupler	3	$9.95	$29.85
Fiberglass Sheet ⅛" x 1 square feet	2	$27.00	$54.00
Centering Rings 54mm to 75mm	2	$7.30	$14.60
Tube Bulkhead Disk 75mm	5	$3.83	$19.15
Large Rail Button for 1515 Rail	1	$4.65	$4.65
1.25" Shrink Tape	2	$39.95	$79.90

Satin Weave Carbon Fiber Fabric	1	$79.95	$79.95
Epoxy Hardener for Carbon Fiber	1	$21.95	$21.95
Epoxy Resin for Carbon Fiber	1	$104.95	$104.95
Shipping Expenses	1	$56.27	$56.27
Propulsion			
JS80SS 54-2 Grain Motor	1	$79.20	$79.20
		Subscale Total	**$604.37**
Travel			
Expected Hotel Costs - 2 Queen Bed Suites	7	$748.00	$3,740.00
Minivan Car Rentals	4	$508.79	$2,035.16
Fuel Costs - Alabama Trip	5	$140.00	$700.00
Fuel Costs - Fullscale	1	$400.00	$400.00
Fuel Costs - Subscale Launch	1	$160.15	$160.15
		Travel Total	**$6,880.01**
Outreach			
Miscellaneous Supplies	1	$300.00	$300.00
		Outreach Total	**$300.00**
Miscellaneous Supplies and Equipment			
Shop Towels	6	$4.90	$29.40
Electrical Tape	1	$6.73	$6.73
3D Printing Filament	1	$20.00	$20.00

Birch Plywood	1	$12.42	$12.42
Douglas Fir Lumber	1	$14.10	$14.10
Sheet Metal Screw Pan	2	$3.87	$7.74
Hex Nuts	1	$10.67	$10.67
U-bolts	4	$1.14	$4.56
Eye Bolt	4	$1.18	$4.72
Threaded Rod	4	$1.47	$5.88
Lowe's Bucket	1	$3.68	$3.68
Yard Stick	1	$0.98	$0.98
Flex Seal	1	$31.98	$31.98
Multimeter	2	$17.99	$35.98
J-B Weld Original	3	$12.95	$38.85
J-B Weld KwikWeld	1	$15.81	$15.81
Switch Power Supply Driver	1	$25.99	$25.99
Other Unexpected Miscellaneous Costs	1	$200.00	$200.00
Miscellaneous Supplies and Equipment Total			**$469.49**
Overall Total			**$10,507.61**

In Table 43, the expected costs are broken up by fullscale, subscale, travel, outreach, and miscellaneous supplies and equipment. Fullscale and subscale are both broken up by subsystems. Subscale only lists purchased items from structures and propulsion because they are the only subsystems that bought new materials, as payload and avionics and recovery used equipment from previous projects. The subscale cost is finalized since the club has already completed and successfully launched this rocket. Fullscale is a combination between purchased items and expected costs of items. Since the fullscale rocket is still being built, the subtotal for fullscale is not yet finalized. Travel continues to be the most expensive subsection. The estimates are becoming more accurate since the Alabama trip is approaching and this gives the club the opportunity to find specific estimates for the actual dates of the trip. Outreach costs contribute to the club's budget as miscellaneous supplies is necessary to host certain outreach events. Miscellaneous supplies and equipment are expenditures that are common use items in the lab. Most of these items are shared amongst subsystems, so these costs are noted under this header. Table 44 gives an overall outlook on where the club's funds are going for the 2017-2018 school year.

Table 44. Expected Outflow Overview 2017-2018

Budget	**Total Cost**
Fullscale	$2,253.74
Subscale	$604.37
Travel	$6,880.01
Outreach	$300.00
Miscellaneous Supplies and Equipment	$469.49
Total	**$10,507.61**

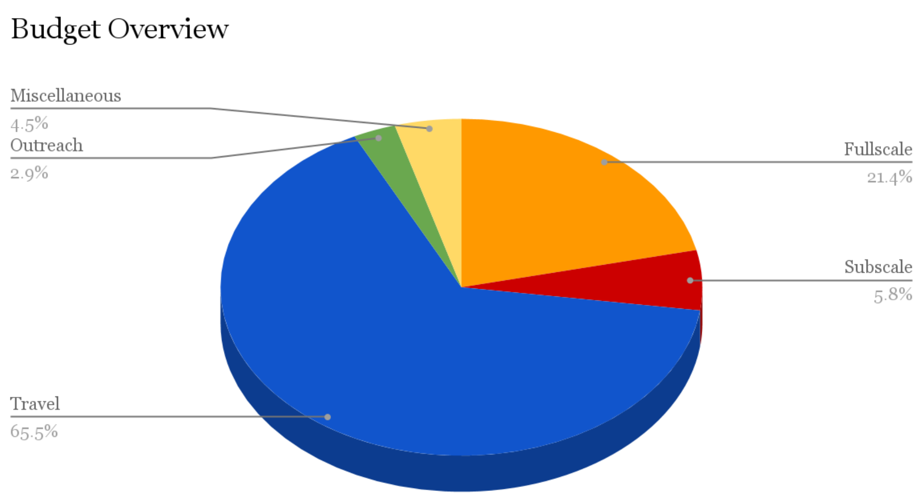


Figure 29. Budget Outflow Overview

Table 44 shows the total cost of each subsection from Table 43. As shown in Figure 29, travel and fullscale continue to be the most expensive costs. Since the club tries to take as many students to Alabama as possible, a large amount of transportation and housing is necessary.

Fullscale is also costly due to the large sized rocket and having proper equipment and materials to ensure the success of the rocket. Table 45 shows the club's current funding plan.

Table 45. Expected Inflow 2017-2018

Donor	**Requested Amount**
Penn State Aerospace Engineering Department	$2,000.00
Penn State Mechanical Engineering Department	$1,000.00
University Park Allocations Committee	$5,000.00
Club Fundraising	$1,105.00
Prior Club Funds	$1,502.59
Total	**$10,607.59**

Comparing Table 44 and Table 45 shows the club does not currently have sufficient funds to do everything it plans to do. The club has reached out to several more possible donors and is still waiting to hear back from them. The College of Engineering, which showed generous support last year, has yet to respond to the club's request for funding, but LTRL is confident the college will continue to support the project. Additionally, LTRL has reached out to companies such as Lockheed Martin, but the club still awaits a response from them as well. The club expects to get $5,000.00 in funding from University Park Allocations Committee (UPAC). UPAC is a university sponsored club that helps other organizations financially. Their help will cover the majority of the travel expenses. Club fundraising accounts for the money the club raised by means other than donations, and is mainly consists of dues. The club has raised $1,105.00 so far by collecting dues. Lastly, the club has leftover money from last year that is being used to help support LTRL while finding other means of funding. Team members will continue to search for more fundraising opportunities as being financially stable is essential to the success of the club. Figure 30 compares the budget the club had at the beginning of the year to the budget that LTRL has now.

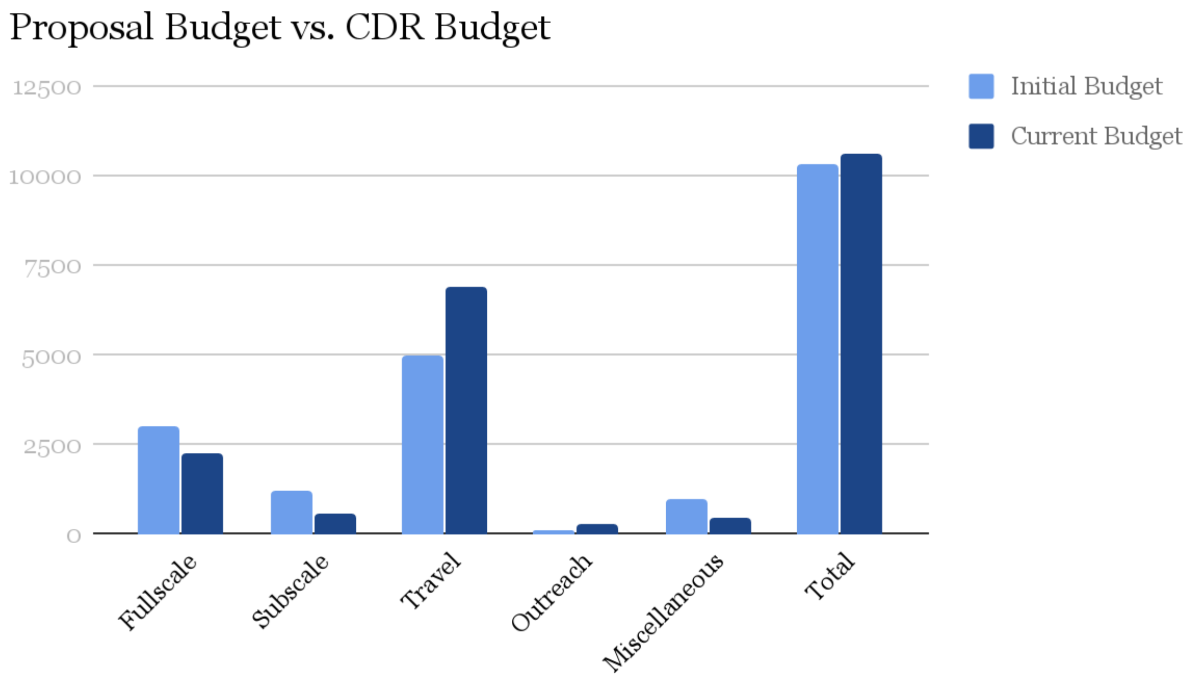


Figure 30. Initial vs. Current Budget Comparison Graph

Figure 30 shows that the club is over its initial budget by about $307. The main reason for this is using carbon fiber wrapped bluetube rather than just bluetube. Carbon fiber will end up costing the club an extra $845.60. Additionally, travel is expected to cost $1,880.01 more than the club thought in the proposal. Fortunately, fullscale, subscale, and miscellaneous supplies and equipment came under budget to help balance the increased expenses for travel. Figure 31 shows the overall look at funding sources.

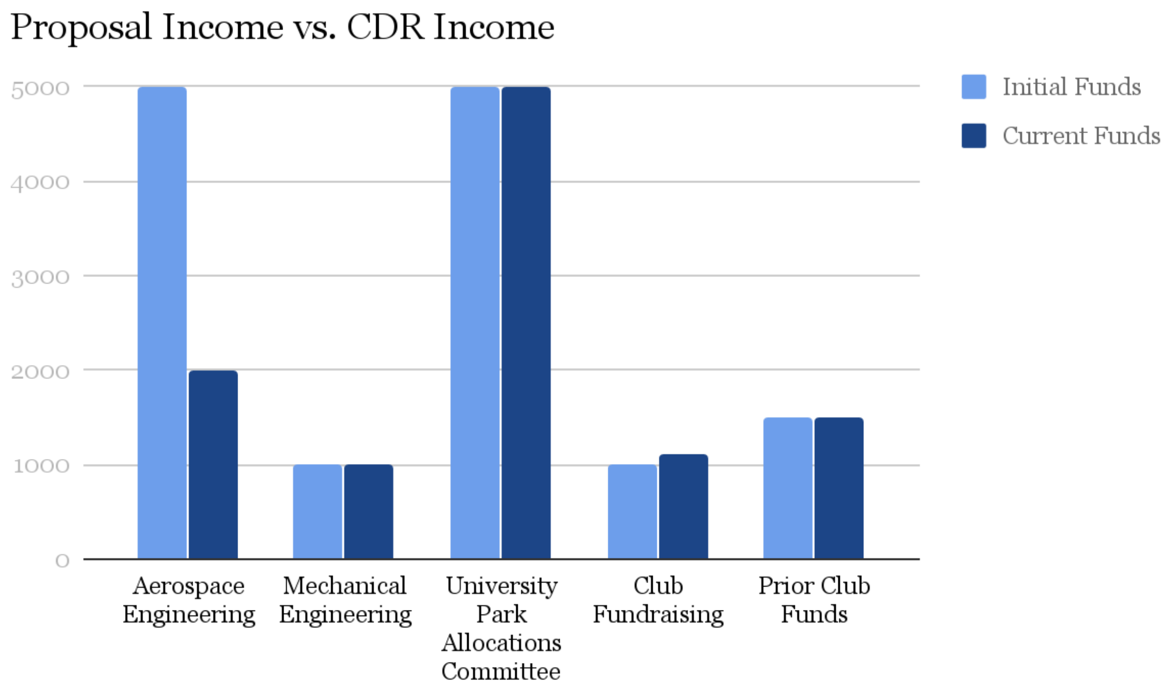


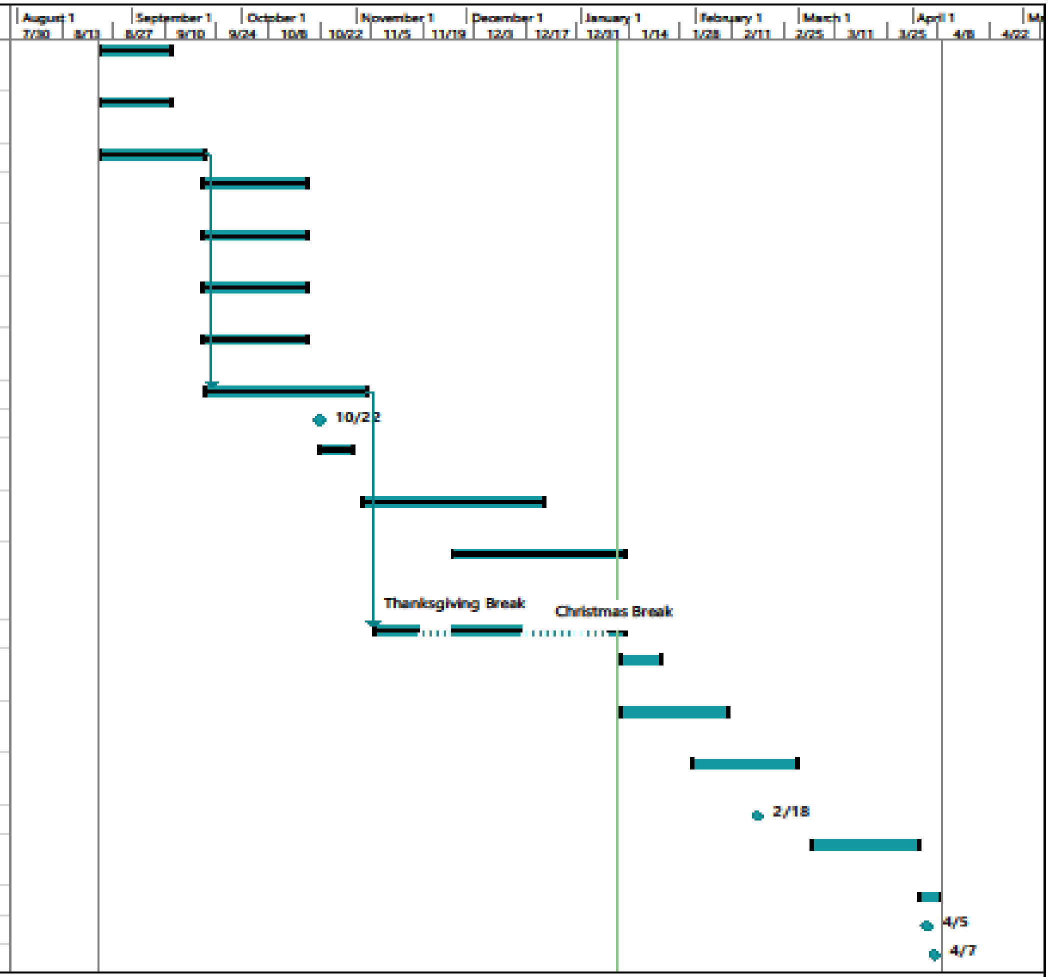
Figure 31. Income Comparison Graph

Figure 31 compares the expected funding from the beginning of the academic year to the expected and current funding now. All the resources' donations remained the same except for the Aerospace Engineering Department and Club Fundraising. LTRL ended up getting $105.00 more than anticipated from the latter. Unfortunately, the club was expecting $3,000.00 more in financial support from the Aerospace Engineering Department based on support in previous years. This reduction in donations has hurt the expected income, so other resources are being contacted, such as the Penn State College of Engineering and Lockheed Martin.

6.4 Timeline

Structures/Propulsion Gantt Chart

ID	Task Name	Duration	Start	Finish	% Complete
1	Preliminary Desgin	14 days	Wed 8/23/17	Mon 9/11/17	100%
2	Material Testing	14 days	Wed 8/23/17	Mon 9/11/17	100%
3	Proposal	21 days	Wed 8/23/17	Wed 9/20/17	100%
4	Subscale Design	21 days	Wed 9/20/17	Wed 10/18/17	100%
5	Subscale Motor Testing	21 days	Wed 9/20/17	Wed 10/18/17	100%
6	Subscale Modeling & Simulations	21 days	Wed 9/20/17	Wed 10/18/17	100%
7	Subscale Construction	21 days	Wed 9/20/17	Wed 10/18/17	100%
8	PDR	32 days	Thu 9/21/17	Fri 11/3/17	100%
9	Subscale Test Flight	0 days	Sun 10/22/17	Sun 10/22/17	100%
10	Subscale Evaluation	7 days	Sun 10/22/17	Mon 10/30/17	100%
11	Finalize Fullscale Design	35 days	Fri 11/3/17	Thu 12/21/17	100%
12	Fullscale Rocket Modeling & Simulations	35 days	Mon 11/27/17	Fri 1/12/18	100%
13	CDR	30 days	Mon 11/6/17	Fri 1/12/18	100%
14	Fullscale Motor Testing	7 days	Fri 1/12/18	Mon 1/22/18	0%
15	Fullscale Construction	21 days	Fri 1/12/18	Fri 2/9/18	0%
16	Fullscale Evaluation	21 days	Wed 1/31/18	Wed 2/28/18	0%
17	Fullscale Test Flight	0 days	Sun 2/18/18	Sun 2/18/18	0%
18	USLI Preparation and Launch	21 days	Mon 3/5/18	Mon 4/2/18	0%
19	USLI Competition	5 days	Tue 4/3/18	Sun 4/8/18	0%
20	LRR	0 days	Thu 4/5/18	Thu 4/5/18	0%
21	Launch Day	0 days	Sat 4/7/18	Sat 4/7/18	0%



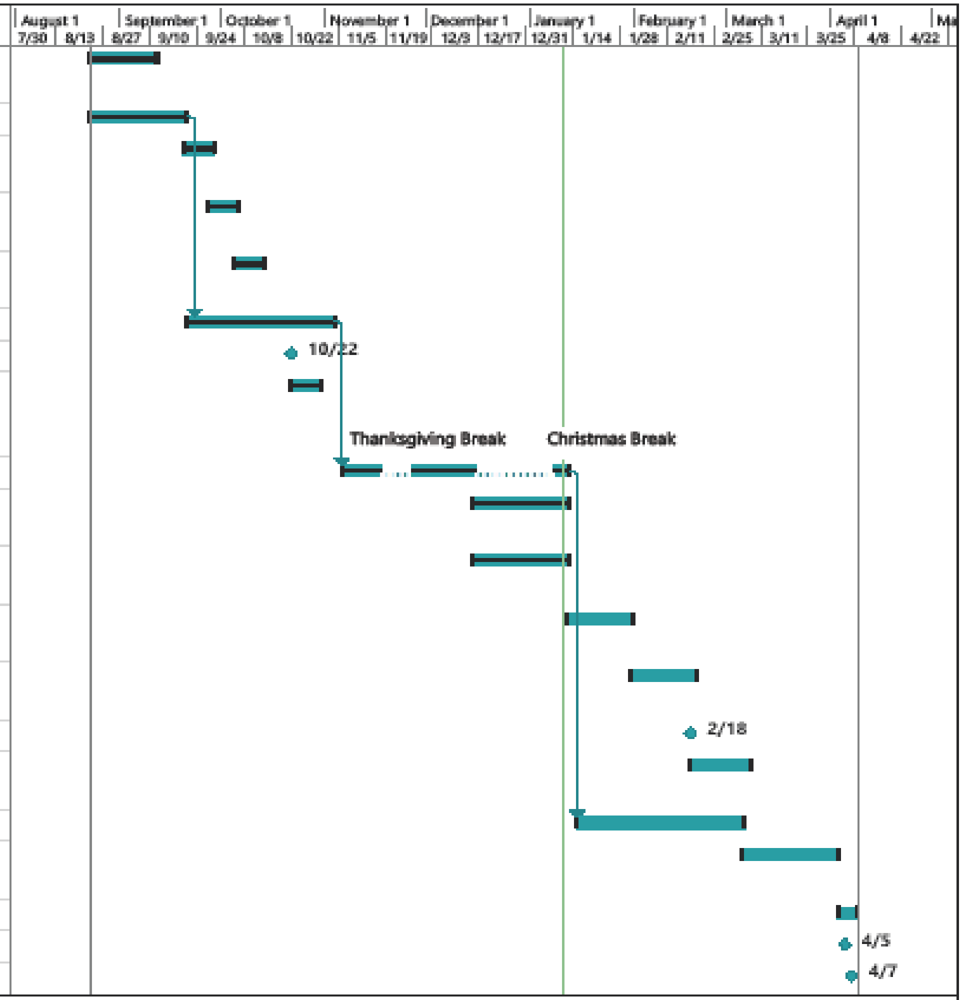
Project: LTRL Structures and Pro
Date: Thu 1/11/18

Task, Split, Milestone, Summary, Project Summary, Inactive Task, Inactive Milestone, Inactive Summary, Manual Task, Duration-only, Manual Summary Rollup, Manual Summary, Start-only, Finish-only, External Tasks, External Milestone, Deadline, Late, Progress, Manual Progress

Page 1

Avionics and Recovery Gantt Chart

ID	Task Name	Duration	Start	Finish	% Complete
1	Preliminary Recovery System Concept	14 days	Wed 8/23/17	Mon 9/11/17	100%
2	Proposal	21 days	Wed 8/23/17	Wed 9/20/17	100%
3	Subscale Recovery System Design	7 days	Wed 9/20/17	Thu 9/28/17	100%
4	Subscale Recovery System Construction	7 days	Wed 9/27/17	Thu 10/5/17	100%
5	Subscale Recovery System Testing	7 days	Thu 10/5/17	Fri 10/13/17	100%
6	PDR	32 days	Thu 9/21/17	Fri 11/3/17	100%
7	Subscale Test Flight	0 days	Sun 10/22/17	Sun 10/22/17	100%
8	Final Subscale Recovery System Verification	7 days	Sun 10/22/17	Mon 10/30/17	100%
9	CDR	30 days	Mon 11/6/17	Fri 1/12/18	100%
10	Fullscale Recovery System Modeling	21 days	Fri 12/15/17	Fri 1/12/18	100%
11	Fullscale Recovery System Design	21 days	Fri 12/15/17	Fri 1/12/18	100%
12	Fullscale Recovery System Construction	14 days	Fri 1/12/18	Wed 1/31/18	0%
13	Fullscale Recovery System Testing	14 days	Wed 1/31/18	Mon 2/19/18	0%
14	Fullscale Test Flight	0 days	Sun 2/18/18	Sun 2/18/18	0%
15	Fullscale Recovery System Verification	14 days	Sun 2/18/18	Wed 3/7/18	0%
16	FRR	36 days	Mon 1/15/18	Mon 3/5/18	0%
17	USLI Preparation and Launch	21 days	Mon 3/5/18	Mon 4/2/18	0%
18	USLI Competition	5 days	Tue 4/3/18	Sun 4/8/18	0%
19	LRR	0 days	Thu 4/5/18	Thu 4/5/18	0%
20	Launch Day	0 days	Sat 4/7/18	Sat 4/7/18	0%



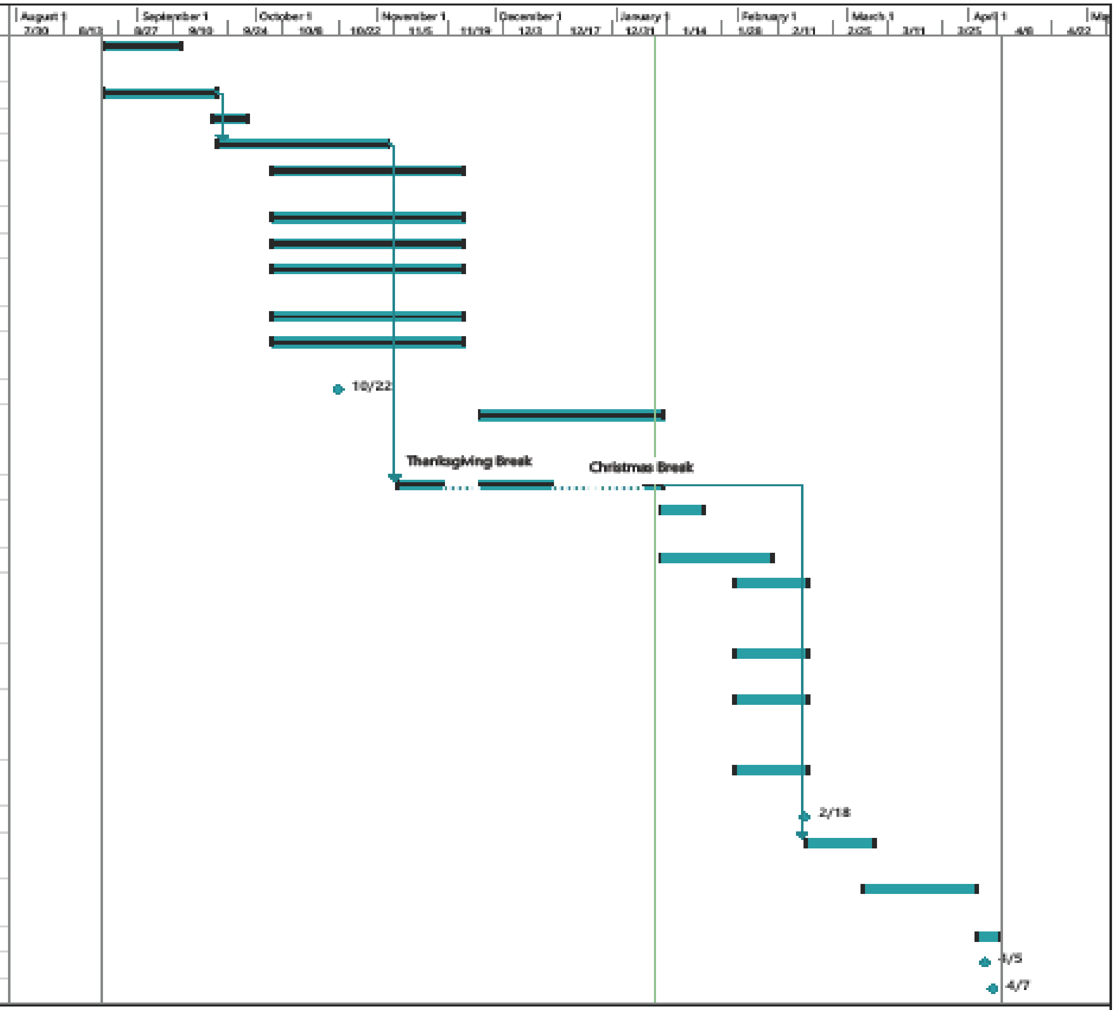
Project: LTRL A&R
Date: Thu 1/11/18

Task		Inactive Task		Manual Summary Rollup		External Milestone	
Split		Inactive Milestone		Manual Summary		Deadline	
Milestone		Inactive Summary		Start-only		Late	
Summary		Manual Task		Finish-only		Progress	
Project Summary		Duration-only		External Tasks		Manual Progress	

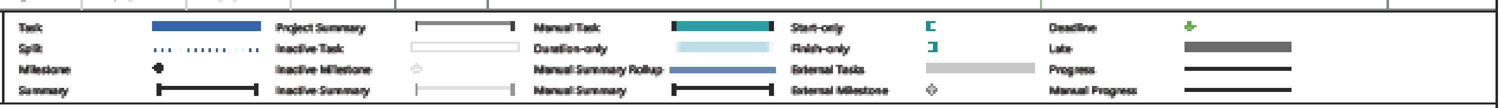
Page 1

Payload Gantt Chart

ID	Task Name	Duration	Start	Finish	% Complete
1	Preliminary Conceptualization	14 days	Wed 8/23/17	Mon 9/11/17	100%
2	**Proposal**	21 days	Wed 8/23/17	Wed 9/20/17	100%
3	Material Selection	7 days	Wed 9/20/17	Thu 9/28/17	100%
4	**PDR**	32 days	Thu 9/21/17	Fri 11/3/17	100%
5	Electronics Container Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
6	Motor Selection	35 days	Thu 10/5/17	Wed 11/22/17	100%
7	Drive Train Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
8	Frame/Suspension Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
9	Wheel Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
10	Solar Panel Deployment Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
11	**Subscale Test Flight**	0 days	Sun 10/22/17	Sun 10/22/17	100%
12	Create Software Flowchart/Identify Modules	35 days	Mon 11/27/17	Fri 1/12/18	100%
13	**CDR**	50 days	Mon 11/6/17	Fri 1/12/18	100%
14	Complete Software Modules	7 days	Fri 1/12/18	Mon 1/22/18	0%
15	Assembly of Rover	21 days	Fri 1/12/18	Fri 2/9/18	0%
16	Test/Review Modules Independently	14 days	Wed 1/31/18	Sun 2/18/18	0%
17	Test Subsystems of Rover	14 days	Wed 1/31/18	Sun 2/18/18	0%
18	Design/Build Containment Chamber	14 days	Wed 1/31/18	Sun 2/18/18	0%
19	Consolodate Modules	14 days	Wed 1/31/18	Sun 2/18/18	0%
20	**Fullscale Test Flight**	0 days	Sun 2/18/18	Sun 2/18/18	0%
21	Test Full Assembly of Rover	14 days	Sun 2/18/18	Wed 3/7/18	0%
22	USLI Preparation and Launch	21 days	Mon 3/5/18	Mon 4/2/18	0%
23	**USLI Competition**	5 days	Tue 4/3/18	Sun 4/8/18	0%
24	**LRR**	0 days	Thu 4/5/18	Thu 4/5/18	0%
25	**Launch Day**	0 days	Sat 4/7/18	Sat 4/7/18	0%



Project: LTRL Payload
Date: Thu 1/11/18



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Appendix A: MSDS Sheets

Epoxy Resin SDS

Fibre Glast
Developments Corporation

GHS SAFETY DATA SHEET (SDS)

SECTION 1 - PRODUCT AND COMPANY IDENTIFICATION

PRODUCT: Part #2000 System 2000 Epoxy Resin

FIBRE GLAST DEVELOPMENTS CORP.
385 CARR DRIVE
BROOKVILLE, OH 45309

TELEPHONE: (937) 833-5200
FAX: (937) 833-6555
FOR CHEMICAL EMERGENCY
CALL (800) 424-9300 24 HRS.

RECOMMENDED USE: Industrial Epoxy Resin supplied exclusively for workplace use.

SECTION 2 – HAZARDS IDENTIFICATION

GHS CLASSIFICATION

Eye Irritation	:	Category 2B
Acute Toxicity (Oral)	:	Category 5
Skin Irritation	:	Category 2
Skin Sensitizer	:	Category 1
Respiratory Irritation	:	STOT SE3

GHS Label Element
Hazard pictogram :

Signal Word : Warning

Hazard statements : H320 Causes eye irritation.
H303 May be harmful if swallowed.
H315 Causes skin irritation.
H317 May cause an allergic skin reaction.

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PDCT-MSDS-00130-04/15-CM

Epoxy Hardener SDS

Fibre Glast
Developments Corporation

GHS SAFETY DATA SHEET (SDS)

SECTION 1 - PRODUCT AND COMPANY IDENTIFICATION

PRODUCT: Part #2060 Epoxy Hardener

FIBRE GLAST DEVELOPMENTS CORP.
385 CARR DRIVE
BROOKVILLE, OH 45309

TELEPHONE: (937) 833-5200
FAX: (937) 833-6555
FOR CHEMICAL EMERGENCY
CALL (800) 424-9300 24 HRS.

RECOMMENDED USE: Industrial Curing Agent supplied exclusively for workplace use.

SECTION 2 – HAZARDS IDENTIFICATION

GHS CLASSIFICATION

Eye Damage : Category 1

Acute Toxicity (Oral and Inhalation) : Category 4

Skin Sensitizer : Category 1

GHS Label Element
Hazard pictograms :

Signal Word : Danger

Hazard statements : H318 Causes serious eye damage.
H302+332 Harmful if swallowed, or if inhaled.
H317 May cause an allergic skin reaction.

Precautionary statements : P202 Do not handle until all safety precautions have been read/understood.
P261 Avoid breathing dust/fume/gas/mist/vapours/spray.
P270 Do not eat, drink or smoke when using this product.
P281 Use personal protective equipment as required.
P285 In case of inadequate ventilation wear respiratory protection.
P273 Avoid release to the environment.

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PDCT-MSDS-00132-04/15-CM

Black Powder SDS

1 **SAFETY DATA SHEET-BLACK POWDER**

Section 1: Identification

Product Identifier: Black Powder (includes all grades)

Manufacturer's Name: GOEX Powder, Inc.

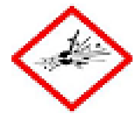
Address: P.O. Box 659
Doyline, LA 71023-0659

Informational Telephone Number: 1-(318) 382-9300

Emerg. Phone Number: 1-(800) 255-3924 (Chem Tel)

Recommended Use: for use in competitive and recreational shooting, muzzleloading hunting and the U.S. Military .

Section 2: Hazard(s) Identification

Hazard category:	Signal Word	Hazard statement	Pictogram
Division 1.1	Danger	Explosive; mass explosion hazard	

Target Organ Warning: Above OSHA levels, chronic exposure may cause skin irritation and damage to the respiratory system, and acute exposure can cause skin, eye, and respiratory irritation.

Section 3: Composition/information on ingredients

Component	CAS-Number	Weight %
Charcoal	16291-96-6	8-18%
Sulfur	7704-34-9	9-20%
Potassium Nitrate	7757-79-1	70-76%
Graphite (note: not contained in all grades of black powder)	7782-42-5	<1%

Section 4: First-aid measures

Ingestion: * Not a likely route of exposure. If ingested, dilute by giving two glasses of water and induce vomiting. Avoid, when possible and contact a Poison control center for advice on treatment, if unsure.

Eye Contact: * Not a likely route of exposure. Flush eyes with water.

Inhalation: * Remove patient from area to fresh air. If not breathing, give artificial respiration, preferably by mouth to mouth. If breathing is difficult, give oxygen. Seek prompt medical attention. Avoid when possible.

Skin Contact: * wash the affected area with copious amounts of water. Some persons may be sensitive to product.

Injury from detonation: * Seek prompt medical attention immediately.

Note to Physician: * Treat symptomatically.

Section 5: Fire-fighting measures

Extinguishing media: * Water may be used as the extinguishing method. DO NOT FIGHT EXPLOSIVES FIRES. Evacuate the area according to Emergency Response Guide 112 guidelines. Isolate the area and guard against any intruders.

Special Procedures: * Black Powder is extremely flammable and may deflagrate. Get away and evacuate the area.

Unusual Hazards: * As with any pyrotechnic, if under confinement or piled in slight confinement, Black Powder can explode. No known toxic fumes are emitted, but good ventilation should still be present.

Flash Point: not applicable.

Auto ignition Temp: Approximate range: 392°-867°F /(200°-464°C)

NFPA Ratings: **Health=1** **Flammability=3** **Reactivity=1**

Advice and PPE for Firefighters: * Fires involving Black Powder should not be fought unless extinguishing media can be applied from a well protected and distant location from the point of fire. Self-contained breathing apparatus (SCBA) and protective clothing must be worn. Follow Emergency Response Guide 112. Wash all clothes prior to reuse.

Carbon Fiber Fabric Wrap SDS

SAFETY DATA SHEET

structural TECHNOLOGIES

SDS IDENTIFICATION NAME: V-Wrap Carbon Fiber Fabric	**PAGE:** 1 OF 4
Product Group: V-Wrap C200H & V-Wrap C400H	**DATE:** 10/08/2015

SECTION I: MATERIAL AND MANUFACTURER IDENTIFICATION

MANUFACTURER:
STRUCTURAL TECHNOLOGIES, LLC
10150 Old Columbia Road
Columbia, MD 21046

EMERGENCY TELEPHONE NUMBER:
800-424-9300
INFORMATION TELEPHONE NUMBER:
410-859-6539

CHEMICAL FAMILY: Carbon Fiber

SECTION II: HAZARD(S) IDENTIFICATION

EMERGENCY OVERVIEW: No unusual conditions are expected from this product.

APPEARANCE AND ODOR: Resin-coated black carbon fibers woven into fabric of varying weight and thickness, depending on the style, with no distinctive odor.

STATEMENTS OF HAZARD:
CARBON MATERIAL IS ELECTRICALLY CONDUCTIVE. ELECTRICAL SYSTEMS SHOULD BE PROTECTED FROM EXPOSURE TO AIRBORNE FIBER.
DUST PARTICLES ASSOCIATED WITH THIS PRODUCT MAY CAUSE IRRITATION OF THE SKIN, EYES, OR UPPER RESPIRATORY TRACT.

PRIMARY ROUTES OF EXPOSURE:
EYES--YES SKIN CONTACT--YES INHALATION--NO INGESTION--NO

HMIS RATING:

CARBON:	HEALTH--1	FLAMMABILITY--0	REACTIVITY--0	SPECIAL—NONE
GLASS:	HEALTH--2	FLAMMABILITY--1	REACTIVITY--0	SPECIAL—NONE
SIZING:	HEALTH--1	FLAMMABILITY--1	REACTIVITY--0	SPECIAL—NONE

POTENTIAL HEALTH EFFECTS:
EYES: Low hazard. May cause temporary irritation.
SKIN: Low hazard for usual industrial or commercial production. No effects expected under normal use.
INHALATION: In some cases – see Section VII. No effects expected under normal use.
INGESTION: Ingestion unlikely under normal use. May cause gastrointestinal irritation.

SIGNS AND SYMPTOMS OF EXPOSURE: Possible Rash.

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE: None known

SECTION III: COMPOSITION/INFORMATION ON INGREDIENTS

This document is prepared pursuant to the OSHA Hazard Communication Standard (29 CFR 1910.1200).

MATERIAL OR COMPONENT	CAS NUMBER	% BY WEIGHT	OSHA(PEL)	ACGIH(TLV)
CARBON FIBER	7440-44-0	92-96	15 mg/m^3 (Total) 5 mg/m^3 (Respirable)	15 mg/m^3 (Total) 3 mg/m^3 (Respirable)
EPOXY SIZING	25068-38-6	2-4	Not Determined	Not Determined

Fiberglass SDS

Fiberglass Safety Data Sheet

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1 Product identifier

- Fiberglass

1.2 Relevant identified uses of the substance or mixture and uses advised against

- Structural reinforcement for thermoset resin products.

1.3 Details of the supplier of the safety data sheet

- NOV Fiber Glass Systems
  17115 San Pedro Avenue, Suite 200
  San Antonio, Texas 78232 USA
  Tel: 1-210-477-7500
  Fax: 1-210-231-5915
  E-mail: Mike.Thayer@nov.com

1.4 Emergency telephone number(s)

- 3E Company, 24-Hour Support (Access Code/Contract Number: 333386)
  - USA, Canada 1-888-298-2344
  - Asia, Pacific 1-760-476-3960
  - Europe, Middle East, Africa 1-760-476-3961
  - Americas 1-760-476-3962

SECTION 2: Hazards identification

2.1 Classification of the substance or mixture

Physical

- Not classified

Health

- Skin irritation, Category 2
- Eye irritation – Category 2
- Specific target organ systemic toxicity – single exposure, Category 3 (respiratory tract irritation)

Environmental

- Not classified

Isopropyl Alcohol SDS

SAFETY DATA SHEET

1. Identification

Product identifier: Isopropyl Alcohol

Other means of identification
Product No.: 9088, 5892, 9095, 9084, 9083, 9082, 9079, 9078, 9059, 9055, 9045, 5986, 5978, 5977, 5967, 5873, 5863, 9827, 5373, 9334

Recommended use and restriction on use
Recommended use: For use in the PortaCount® Respirator Fit Tester
Restrictions on use: Not known.

Manufacturer/Importer/Supplier/Distributor information
Manufacturer

Company Name:	TSI Incorporated
Address:	500 Cardigan Road Shoreview, MN 55126
Telephone:	Customer Service: 800-874-2811
Fax:	
Contact Person:	
e-mail:	answers@tsi.com

Emergency telephone number:
24 Hour Emergency: 908-859-2151

Chemtrec: 800-424-9300

2. Hazard(s) identification

Hazard classification

Physical hazards

Flammable liquids	Category 2

Health hazards

Serious eye damage/eye irritation	Category 2A
Specific target organ toxicity - single exposure	Category 3

Label elements
Hazard symbol:

Signal word: Danger

Hazard statement: Highly flammable liquid and vapor.
Causes serious eye irritation. May cause respiratory irritation.
May cause drowsiness or dizziness.

JB Kwik SDS

MATERIAL SAFETY DATA SHEET

1. Product and Company Identification

Product Name	J-B Kwik
Synonym(s)	Resin and Hardener
CAS #	Mixture
Product use	Bonds and repairs
Manufacturer	J-B Weld Company P.O. Box 483 Sulphur Springs, TX 75482 US Phone: 903-885-7696

2. Hazards Identification

Emergency overview	CAUTION MAY CAUSE EYE IRRITATION. MAY CAUSE SKIN IRRITATION. MAY CAUSE ALLERGIC SKIN REACTION.
Potential short term health effects	
Routes of exposure	Eye, Skin contact, Ingestion.
Eyes	May cause irritation.
Skin	Contact with skin can cause irritation and allergic reaction (sensitization) in some individuals.
Inhalation	Not a normal route of exposure.
Ingestion	May cause stomach distress, nausea or vomiting.
Target organs	Eyes. Skin.
Chronic effects	Prolonged or repeated exposure can cause drying, defatting and dermatitis.
Signs and symptoms	Symptoms may include redness, edema, drying, defatting and cracking of the skin. Symptoms of overexposure may be headache, dizziness, tiredness, nausea and vomiting.
OSHA Regulatory Status	This product is a "Hazardous Chemical" as defined by the OSHA Hazard Communication Standard, 29 CFR 1910.1200.
Potential environmental effects	See section 12.

3. Composition / Information on Ingredients

Ingredient(s)	CAS #	Percent
Iron	7439-89-6	5 - 10
Limestone	1317-65-3	10 - 30
Oxirane, 2,2-[(1-methylethylidene)bis(4,1-phenyleneoxymethylene)]bis, homopolymer	25085-99-8	10 - 30
Phenol, 2,4,6-tris[(dimethylamino)methyl]-	90-72-2	1 - 5
Phenol, polymer with formaldehyde, glycidyl ether	28064-14-4	1 - 5
Carbon black	1333-86-4	0.1 - 1
Titanium oxide	13463-67-7	0.1 - 1

4. First Aid Measures

First aid procedures	
Eye contact	Flush with cool water. Remove contact lenses, if applicable, and continue flushing. Obtain medical attention if irritation persists.
Skin contact	Flush with cool water. Wash with soap and water. Obtain medical attention if irritation persists.
Inhalation	Not a normal route of exposure.
Ingestion	Do not induce vomiting. Never give anything by mouth if victim is unconscious, or is convulsing. Obtain medical attention.

JB Weld SDS

SAFETY DATA SHEET

Issuing Date 11-Nov- 2014 **Revision Date** 11-Nov-2014 **Revision Number** 1

1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

Product identifier

Product SDS Name **Steel Reinforced Epoxy Resin – Twin Tubes - Part A**

J-B Weld FG SKU Part Numbers Covered

8265, 8265F, 8276, 8276F, 8265S, 8265A, 8265H, 8272, 8272F, 8280, 8280F, 8281, 80165, 7265S, 7280, 8276A, 8273H, 8270, 8270F, 8271, 80176, 7276, 7270

J-B Weld Product Names Covered

J-B Weld™ (all Twin Tubes), KwikWeld™ (all Twin Tubes), MarineWeld™ (Twin Tubes Only)

J-B Weld Product Type

Steel Reinforced Epoxy

Recommended use of the chemical and restrictions on use

Recommended Use	General Purpose Adhesive
Uses advised against	No information available

Details of the supplier of the safety data sheet

Supplier Name	J-B WELD COMPANY,LLC
Supplier Address	1130 COMO ST SULPHUR SPRINGS, TX 75482 USA
Emergency Telephone Numbers	Transportation Emergencies: Chemtrec (24 hour transportation emergency response info): 800-424-9300 or 703-527-3887 Poison/Medical Emergencies: Poison Control Centers (24 hour emergency poison / medical response info): 800-222-1222
Supplier Email	info@jbweld.com
Supplier Phone Number	903-885-7696

2. HAZARDS IDENTIFICATION

OSHA/HCS status	This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).
Classification of the substance or mixture	SKIN CORROSION/IRRITATION - Category 2 SERIOUS EYE DAMAGE/ EYE IRRITATION - Category 2B SKIN SENSITIZATION - Category 1
GHS label elements	
Hazard pictograms	
Signal word	Warning!
Hazard statements	Causes skin and eye irritation. May cause an allergic skin reaction.

Mystik Hi-Temp Grease SDS

SAFETY DATA SHEET

Mystik® JT-6® Synthetic Hi-Temp Grease, No. 2, ISO 220

Section 1. Identification

GHS product identifier	: Mystik® JT-6® Synthetic Hi-Temp Grease, No. 2, ISO 220
Synonyms	: Lubricating grease; CITGO® Material Code: 665077002
Code	: 665077002
MSDS #	: 665077002
Supplier's details	: CITGO Petroleum Corporation P.O. Box 4689 Houston, TX 77210 sdsvend@citgo.com
Emergency telephone number	: Technical Contact: (800) 248-4684 Medical Emergency: (832) 486-4700 CHEMTREC Emergency: (800) 424-9300 (United States Only)

Section 2. Hazards identification

OSHA/HCS status	: While this material is not considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200), this SDS contains valuable information critical to the safe handling and proper use of the product. This SDS should be retained and available for employees and other users of this product.
Classification of the substance or mixture	: Not classified.

GHS label elements

Signal word	: Warning
Hazard statements	: Injection under the skin can cause severe injury. Most damage occurs in the first few hours. Initial symptoms may be minimal.

Precautionary statements

General	: Avoid contact with eyes, skin and clothing.. IF IN EYES: Rinse cautiously with water for several minutes. IF SWALLOWED: Do NOT induce vomiting. After handling, always wash hands thoroughly with soap and water. If you feel unwell, seek medical attention and show the label when possible. Keep out of reach of children.
Prevention	: Not applicable.
Response	: Not applicable.
Storage	: Store in a dry place and/or in closed container. Store in accordance with all local, regional, national and international regulations.
Disposal	: Dispose of contents and container in accordance with all local, regional, national and international regulations.
Hazards not otherwise classified	: Injection of petroleum hydrocarbons requires immediate medical attention

Section 3. Composition/information on ingredients

Substance/mixture	: Mixture
Other means of identification	: Lubricating grease; CITGO® Material Code: 665077002

CAS number/other identifiers

CAS number	: Not applicable.

Spray Paint SDS

SAFETY DATA SHEET

51601

Section 1. Identification

Product name	:	KRYLON® ColorMaster™ with Covermax™ Technology Paint + Primer Gloss Black
Product code	:	51601
Other means of identification	:	Not available.
Product type	:	Aerosol.

Relevant identified uses of the substance or mixture and uses advised against

Not applicable.

Manufacturer	:	Krylon Products Group 101 W. Prospect Avenue Cleveland, OH 44115
Emergency telephone number of the company	:	US / Canada: (216) 566-2917 Mexico: SETIQ 01-800-00-214-00 / (52) 55-5559-1588 24 hours / 365 days a year
Product Information Telephone Number	:	US / Canada: (800) 457-9566 Mexico: Not Available
Regulatory Information Telephone Number	:	US / Canada: (216) 566-2902 Mexico: Not Available
Transportation Emergency Telephone Number	:	US / Canada: (216) 566-2917 Mexico: SETIQ 01-800-00-214-00 / (52) 55-5559-1588 24 hours / 365 days a year

Section 2. Hazards identification

OSHA/HCS status	:	This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).
Classification of the substance or mixture	:	FLAMMABLE AEROSOLS - Category 1 GASES UNDER PRESSURE - Compressed gas SKIN CORROSION/IRRITATION - Category 2 SERIOUS EYE DAMAGE/ EYE IRRITATION - Category 2A CARCINOGENICITY - Category 2 TOXIC TO REPRODUCTION (Fertility) - Category 2 TOXIC TO REPRODUCTION (Unborn child) - Category 2 SPECIFIC TARGET ORGAN TOXICITY (SINGLE EXPOSURE) (Respiratory tract irritation) - Category 3 SPECIFIC TARGET ORGAN TOXICITY (SINGLE EXPOSURE) (Narcotic effects) - Category 3 SPECIFIC TARGET ORGAN TOXICITY (REPEATED EXPOSURE) - Category 2 ASPIRATION HAZARD - Category 1 Percentage of the mixture consisting of ingredient(s) of unknown oral toxicity: 39.3% Percentage of the mixture consisting of ingredient(s) of unknown dermal toxicity: 70.8% Percentage of the mixture consisting of ingredient(s) of unknown inhalation toxicity: 72.2%

GHS label elements

Talcum Powder SDS

MINERALS TECHNOLOGIES

TALC

Safety Data Sheet

according to Federal Register / Vol. 77, No. 58 / Monday, March 26, 2012 / Rules and Regulations

Date of issue: 09/11/2012 Revision date: 05/09/2016 Supersedes: 02/06/2015 Version: 2.1

SECTION 1: Identification

1.1. Identification

Product form	:	Mixture
Product name	:	TALC
Product code	:	C-MS-AT-2042STDTALC
Other means of identification	:	A-0005 FILLER, ABT® 1000, ABT® 2500, ABT® 2501, CERCRON® MB 2900, CERCRON® MB 3900, CERCRON® MB 50-60, CERCRON® MB 93-37, CERCRON® MB 96-67, CERCRON® MB 96-68, CERCRON® MB 99-01, CERCRON® MP 97-30, CERCRON® MP 98-25, CERCRON® MP 99-48, MICROTALC® BP-210, MICROTALC® DM 12-50, MICROTALC® MP 10-52, MICROTALC® MP 11-51, MICROTALC ®MP 12-50, 399 TALC, MICROTALC® MPD 12-50, MICROTALC® MP 12-52, MICROTALC® MP 15-38, MICROTALC® MP 20-40, MICROTALC® MP 25-38, MICROTALC® MP 30-36, MICROTALC® MP 50-26, MICROTALC® MP 70-22, MICROTALC® MP 98-28BC, MICROTALC® MP 45-26 BC, MICROTALC® MPD 2500, MICROTALC® MPD 2501, MICROTALC MPD1250UC, MICROTALC MP210, MICROTUFF® 111, MICROTUFF® 191, PC 2000, TALCRON® MP 10-52, TALCRON® MP 12-50, TALCRON® MP 15-38, TALCRON® MP 25-38, TALCRON® MP 30-36, TALCRON® MP 40-27, TALCRON® MP 44-26, TALCRON® 45-26, ULTRATALC® 609, ULTRATALC® 609D, 9910 Talc, TALCRON 25 LOA, TALCRON 35 LOA, TALCRON 40 LOA, TALCRON 45 LOA, TALCRON 30 LOA, FLEXTALC 405D, FORTI-TALC™ 609LC TALC, FORTI-TALC™ 609HC TALC, FORTI-TALC™ MP1250LC TALC, FORTI-TALC™ MP1250HC TALC, FORTI-TALC™ MP1250UC TALC, FORTI-TALC™ MP1538LC TALC, FORTI-TALC™ MP1538HC TALC, TALCRON MP2040, PC 2000, ICMP 4426, FORTI-TALC™ AG111 LC TALC, FORTI-TALC™ AG111 HC TALC

1.2. Relevant identified uses of the substance or mixture and uses advised against

Use of the substance/mixture	:	Mineral Additive

1.3. Details of the supplier of the safety data sheet

Barretts Minerals Inc.
8625 Highway 91 South
Dillon,. MT 59725
USA

Tel. 406-683-3323

1.4. Emergency telephone number

Emergency number	:	+1 760 476 3962 3E Global Emergency Response Services. Access code: 333336 (if you mention SDS name and company name-you don't need the access code)

SECTION 2: Hazard(s) identification

2.1. Classification of the substance or mixture

GHS-US classification

Carcinogenicity Category 1A H350

Full text of H statements : see section 16

2.2. Label elements

GHS-US labeling

Hazard pictograms (GHS-US) :

GHS08

Signal word (GHS-US)	:	Danger
Hazard statements (GHS-US)	:	H350 - May cause cancer (Inhalation)
Precautionary statements (GHS-US)	:	P201 - Obtain special instructions before use P202 - Do not handle until all safety precautions have been read and understood P260 - Do not breathe dust P280 - Wear protective gloves, protective clothing, eye protection, face protection

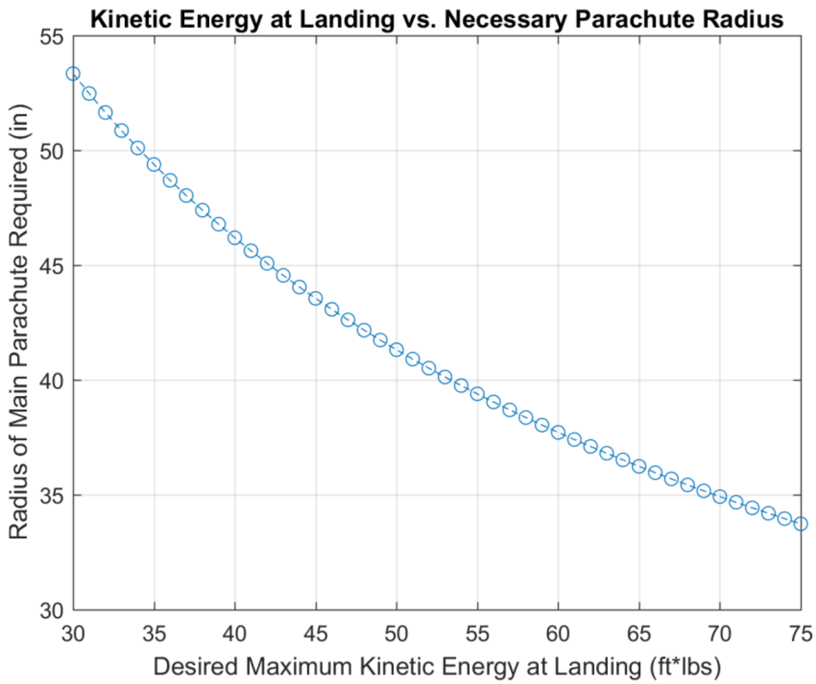
Appendix B: Recovery Decent Profile Calculator

```
% RECOVERY DESCENT PROFILE CALCULATOR (RDPC)
% WRITTEN BY EVAN KERR
% PENN STATE LION TECH ROCKET LABS
% AVIONICS AND RECOVERY LEAD
% LATEST UPDATE: 4/20/2017
```

Calculate necessary area of Parachute to meet certain KE on landing

```
clc, clear, close all
%Gravitational acceleration, units: m/s^2
g = 9.81;
%Density in kg/m^3
rho = 1.225;
%Kinetic Energy Limit in ft-lbs
keMax = 75;

%%%%%%%%%%%%%%%%%%%%%%%%%%% Input Begin %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Coefficient of drag of drogue, main, and tumbling rocket respectively
Cdd = 1.5;
Cdm = 2.2;
Cdr = 1.0;

%These should be in kg
mass(1) = 4.030; %For the fore
mass(2) = 3.478; %For the avionics bay (model minus chord, chutes, and copter)
mass(3) = 4.660; %For the booster
mass(4) = 0.953; %Main parachute
mass(5) = 0.502; %Drogue parachute
%%%%%%%%%%%%%%%%%%%%%%%%%%%% Input End %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

maxMass = max(mass);
totMass = sum(mass);

radiusMainM = ones(1,10);
keMatFtLbs = (30:1:75);
keMatJoule = keMatFtLbs*1.3358;

for i = 1:length(keMatJoule)
    radiusMainM(i) = sqrt((maxMass*totMass*g)/(Cdm*keMatJoule(i)*rho*pi));
end

radiusMainFt = 3.281*radiusMainM;
radiusMainIn = radiusMainFt * 12;
```

```
figure(1);
plot(keMatFtLbs,radiusMainIn,'--o')
title('Kinetic Energy at Landing vs. Necessary Parachute Radius');
xlabel('Desired Maximum Kinetic Energy at Landing (ft*lbs)');
ylabel('Radius of Main Parachute Required (in)');
grid on;
```



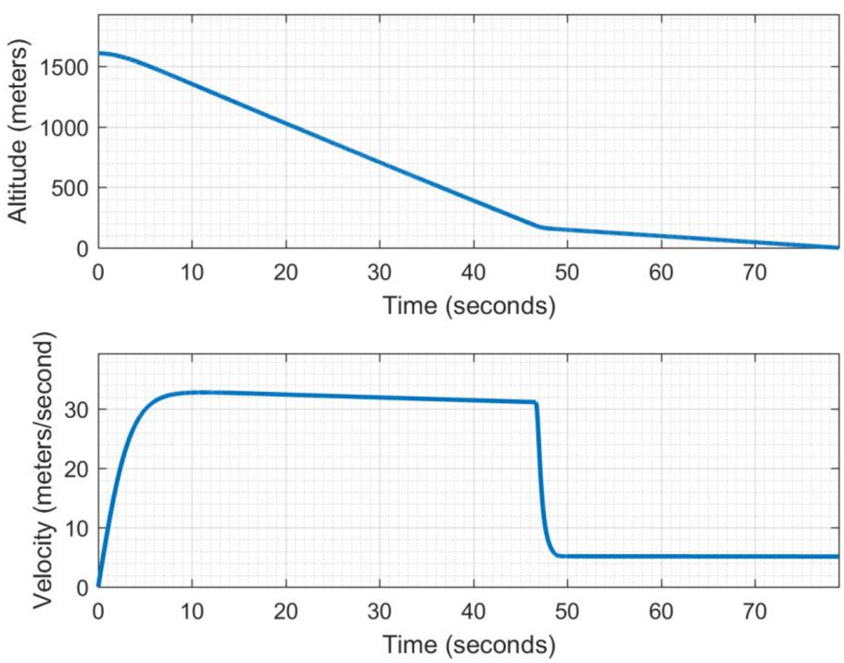
Calculating Force based results

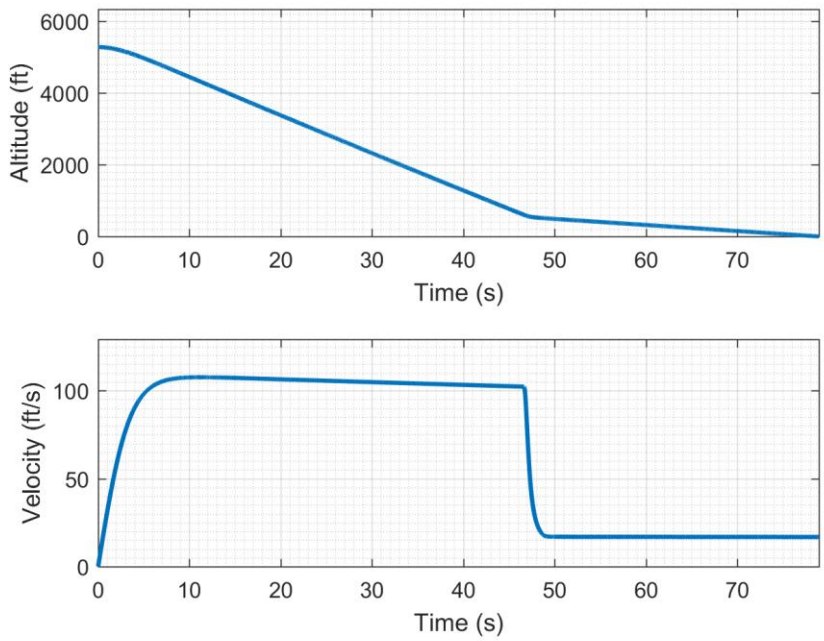
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Input Begin %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Rd_in = 6; %radius of drogue[in]
Rm_in = 42; %radius of main[in]
Rr_in = 7.5; %simulated radius of "tumbling" rocket parachute[in]

apogeeft = 5280; %apogee altitude above ground level [ft]
altDrogueft = apogeeft-1; %altitude above ground level of drogue deployment[ft]
altMainft = 600; %altitude above ground level of main parachute deployment[ft]

altLaunchSite = 183; % Altitiude above sea level of the launch site in meters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Input End %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Rd = 0.0254*Rd_in; %radius of drogue[m]
Rm = 0.0254*Rm_in; %radius of main[m]
Rr = 0.0254*Rr_in; %simulated radius of "tumbling" rocket parachute[m]

apogee = 0.3048*apogeeft;
```

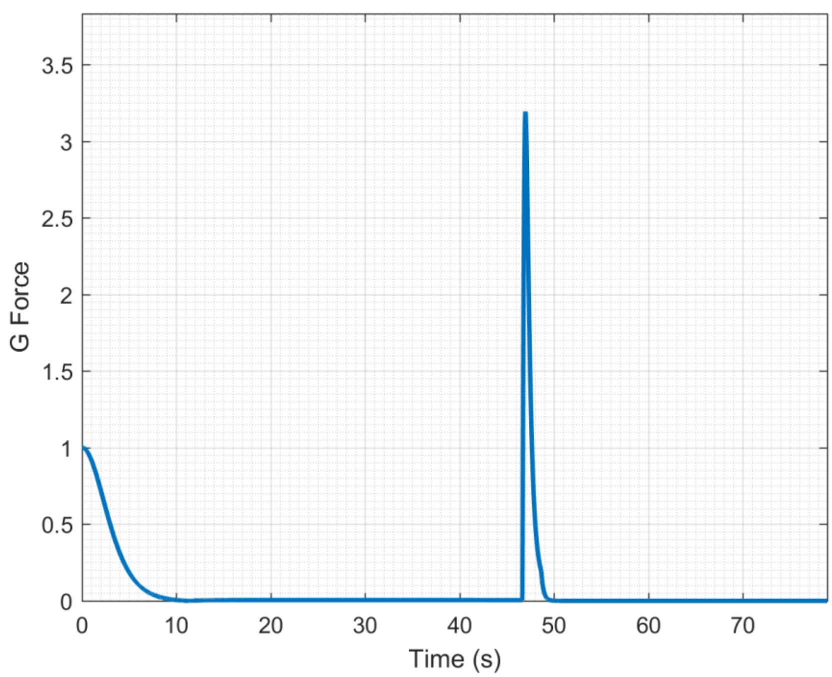
```
altDrogue = 0.3048*altDrogueft;
altMain = 0.3048*altMainft;

% Declare Constants
h = apogee+altLaunchSite; % Initial altitude of the rocket above sea level
h_matrix(1) = h;
time(1) = 0;
dt = 0.01;
v(1) = 0;
a(1) = g;
i = 1; % Counter variable
Temp = 2; % Temperature in Celcius at ground level.
Weight = totMass*g;

% Deployment time and counter initialization for the main and drogue
% parachutes
Kd_dep = 0; % Drogue deployment factor, or how many iterations have run since the drogue was deployed.
Td_dep = 0.25; % Drogue deployment time (how long it takes) in seconds
Td_dep_elapsed = 0;  % Time elapsed since drogue deployment
Km_dep = 0; % Main deployment factor, or how many iterations have run since the main was deployed
Tm_dep = 2;
Tm_dep_elapsed = 0;

%Drag Calculation
while(h >= altLaunchSite) % Although we are integrating over time, the check is whether the height is still above ground level.
    rho_new = rhocalcestSI(h,Temp); % Calculate the density at the given altitude and temperature
    Dragr(i) = .5*Cdr*rho_new*v(i)^2*pi*Rr^2; % Drag of the rocket body
    Dragd(i) = .5*Cdd*rho_new*v(i)^2*pi*Rd^2; % Drag of the drogue parachute
    Dragm(i) = .5*Cdm*rho_new*v(i)^2*pi*Rm^2; % Drag of the main parachute

        if h > (altDrogue + altLaunchSite)% Determines which state of descent the rocket is in and adjusts accordingly by adding the drags
            Drag = Dragr(i); % If the drogue has yet to deploy, the drag of the rocket is the only factor
        elseif h > (altMain + altLaunchSite)
            Kd_dep = Kd_dep + 1; % Increment drogue deployment factor
            Td_dep_elapsed = Kd_dep*dt; % Use the drogue deployment factor to calculate time since drogue deployed
            Drag = Dragr(i) + Dragd(i); % Calculate drage when drogue fully deployed

            % This loop only runs right after chute deployment and models
            % the chute as opening in a linear matter
            if Td_dep_elapsed < Td_dep
                Drag = Dragr(i) + (Td_dep_elapsed/Td_dep)*Dragd(i);
            end
        else
            Km_dep = Km_dep + 1;
            Tm_dep_elapsed = Km_dep*dt;
            Drag = Dragr(i) + Dragd(i) + Dragm(i);
```

```
            if Tm_dep_elapsed < Tm_dep
                Drag = Dragr(i) + Dragd(i) + (Tm_dep_elapsed/Tm_dep)*Dragm(i);
            end
        end
    i = i + 1; % Increment i, the current index value
    a(i) = (-Drag+Weight)/totMass;
    v(i) = v(i-1)+a(i)*dt;
    delh(i) = v(i)*dt;
    h = h-delh(i);
    h_matrix(i) = h;

    time(i) = time(i-1) + dt;
end

figure(2);
ax11 = subplot(2,1,1);
title('Descent Profile In SI Units');

plot(time,h_matrix-altLaunchSite,'LineWidth',2)
ylabel('Altitude (meters)');
xlabel('Time (seconds)');
grid on;
grid minor;
axis([0 max(time) 0 max(h_matrix-altLaunchSite)*1.2]);

ax21 = subplot(2,1,2);
plot(time,v,'LineWidth',2);
ylabel('Velocity (meters/second)');
xlabel('Time (seconds)');
grid on;
grid minor;
axis([0 max(time) 0 max(v)*1.2]);
linkaxes([ax11 ax21],'x');

figure(3)
ax12 = subplot(2,1,1);
title('Descent Profile in English Units');

plot(time,(h_matrix-altLaunchSite)*3.281,'LineWidth',2);
ylabel('Altitude (ft)');
xlabel('Time (s)');
grid on;
grid minor;
axis([0 max(time) 0 max(h_matrix-altLaunchSite)*3.281*1.2]);
```

```
ax22 = subplot(2,1,2);
plot(time,v*3.281,'LineWidth',2);
ylabel('Velocity (ft/s)');
xlabel('Time (s)');
grid on;
grid minor;
axis([0 max(time) 0 max(v)*3.281*1.2]);
linkaxes([ax12 ax22],'x');

figure(4)
title('G Forces vs Time');
plot(time,abs(a/g),'LineWidth',2);
ylabel('G Force');
xlabel('Time (s)');
grid on;
grid minor;
axis([0 max(time) 0 max(abs(a/g))*1.2]);
```





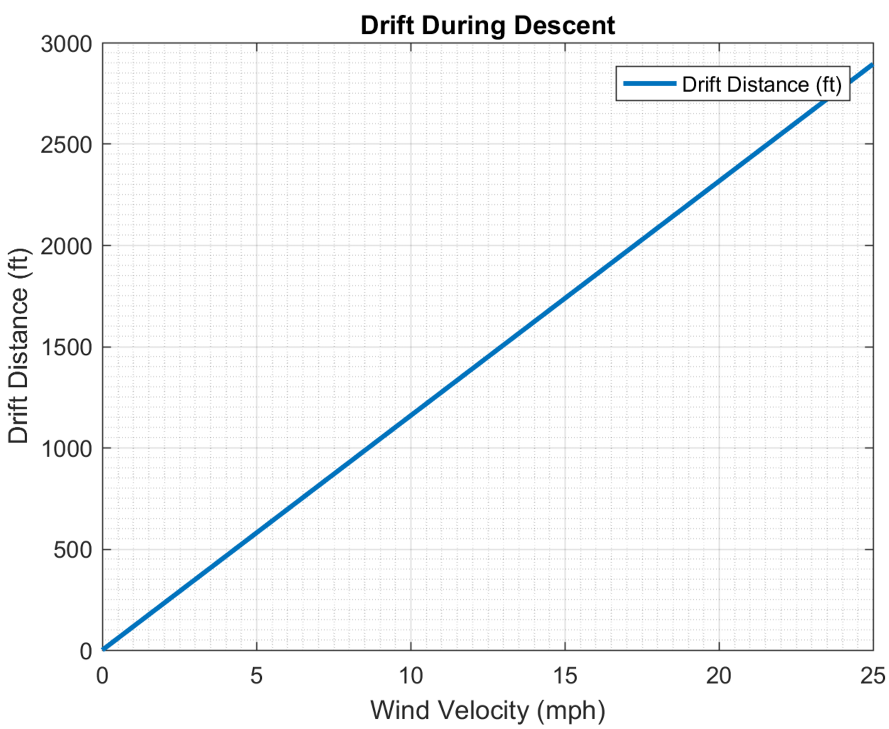


Calculate Drift Distance

```
Windmph = 0:1:25; % Velocity of wind[mph]
Windfps = 1.467*Windmph;
Windmps = Windfps*0.3048;

% Calculate drift distance in metric and standard
descentTime = max(time);
```

```
driftDistM = Windmps*descentTime;
driftDistFt = Windfps*descentTime;

% Plot drift distance
figure(5)
plot(Windmph,driftDistFt,'LineWidth', 2);
ylabel('Drift Distance (ft)');
xlabel('Wind Velocity (mph)');
grid on;
grid minor;
title('Drift During Descent');
legend('Drift Distance (ft)');

% Output max drift distance
fprintf('The drift distance at a wind velocity of 25 mph is %6.1f ft\n\n', max(driftDistFt));
```

The drift distance at a wind velocity of 25 mph is 2894.0 ft



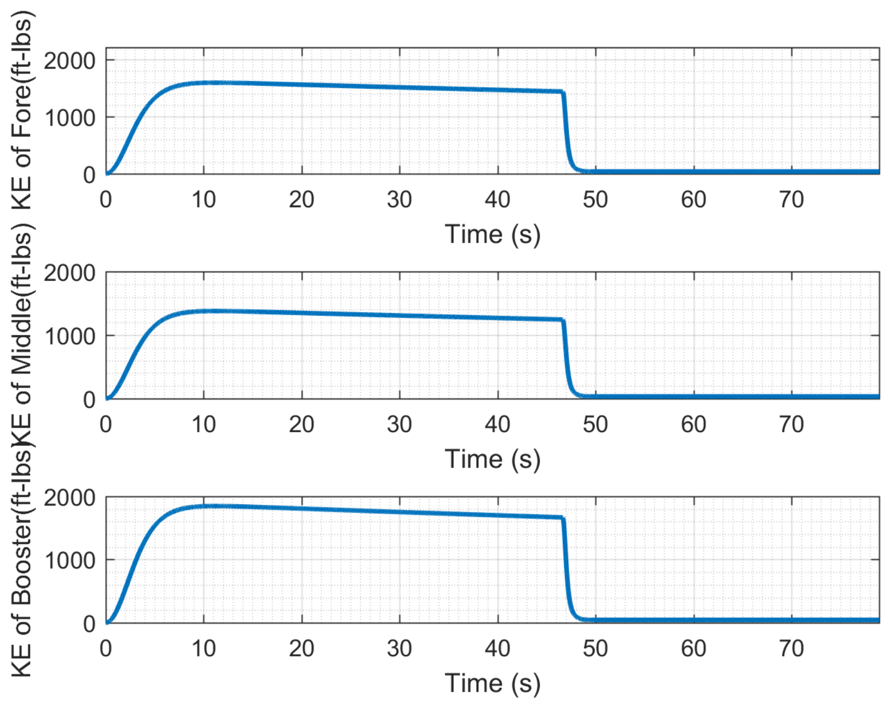
Calculate KE History of each component

```
KEforeSI_mat = (1/2)*v.^2*mass(1);
KEavSI_mat = (1/2)*v.^2*mass(2);
KEboostSI_mat = (1/2)*v.^2*mass(3);

maxKE_SI = max([max(KEforeSI_mat),max(KEavSI_mat),max(KEboostSI_mat)]);
```

```
KEforeST_mat = KEforeSI_mat*0.7376;
KEavST_mat = KEavSI_mat*0.7376;
KEboostST_mat = KEboostSI_mat*0.7376;

maxKE_ST = max([max(KEforeST_mat),max(KEavST_mat),max(KEboostST_mat)]);

% Calculate the KE of each component in Joules at landing
KEforeSI = KEforeSI_mat(end);
KEavSI = KEavSI_mat(end);
KEboostSI = KEboostSI_mat(end);

maxLandingKE_SI = max([KEforeSI,KEavSI,KEboostSI]);

% Calculate the KE of each component in Ft-lbs at landing
KEforeST = KEforeST_mat(end);
KEavST = KEavST_mat(end);
KEboostST = KEboostST_mat(end);

maxLandingKE_ST = max([KEforeST,KEavST,KEboostST]);

figure(6)
ax13 = subplot(3,1,1);
title('Kinetic Energy of Each Component vs. Altitude');

plot(time,KEforeST_mat,'LineWidth',2);
ylabel('KE of Fore(ft-lbs)');
xlabel('Time (s)');
grid on;
grid minor;
axis([0 max(time) 0 maxKE_ST*1.2]);

ax23 = subplot(3,1,2);
plot(time,KEavST_mat,'LineWidth',2);
ylabel('KE of Middle(ft-lbs)');
xlabel('Time (s)');
grid on;
grid minor;
linkaxes([ax13 ax23],'x');

ax33 = subplot(3,1,3);
plot(time,KEboostST_mat,'LineWidth',2);
ylabel('KE of Booster(ft-lbs)');
xlabel('Time (s)');
grid on;
grid minor;
linkaxes([ax23 ax33],'x');
```

```
vf = v(end); %Find final landing velocity

% Print Results
fprintf('The kinetic energy of the nosecone section is %4.2f ft*lbs\n', KEforeST);
fprintf('The kinetic energy of the avionics bay section is %4.2f ft*lbs\n', KEavST);
fprintf('The kinetic energy of the booster section is %4.2f ft*lbs\n\n', KEboostST);

fprintf('The velocity at landing is %4.2f m/s or %4.2f ft/s \n', v(end),v(end) * 3.281);
```

```
The kinetic energy of the nosecone section is 38.96 ft*lbs
The kinetic energy of the avionics bay section is 33.63 ft*lbs
The kinetic energy of the booster section is 45.05 ft*lbs

The velocity at landing is 5.12 m/s or 16.80 ft/s
```



Published with MATLAB® R2016a

Appendix C: Verification of OpenRocket Flight Calculations

```
clc
clear

%CONSTANTS --------------------------------

%Center of Pressure
Ln  = 0.5499;     %length of nosecone [m]
Cnn = 2;          %coeficient of drag for nosecone
Xb  = 2.616;      %length from tip to fin root chord [m]
Xr  = 0.127;      %length from fin root leading edge to fin tip leading edge [m]
Cr  = 0.2032;     %fin root chord length [m]
Ct  = 0.102;      %fin tip chord length [m]
S   = 0.1778;     %fin semispan [m]
N   = 3;          %number of fins
Lf  = 0.19356;    %length of the fin mid-chord line [m]

%Center of Gravity
dn  = 0.4258;     %distance of the nose CG to nose tip [m]
mn  = 1.607;      %mass of the nose [kg]
dp  = 0.8766;     %distance of the payload CG to nose tip [m]
mpayload  = 2.379;  %mass of payload [kg]
dm  = 1.5316;     %distance of the main CG to nose tip [m]
mm  = 4.848;      %mass of main [kg]
dd  = 1.9379;     %distance of the drogue CG to the nose top [m]
md  = 0.907;      %mass of drogue [kg]
db  = 2.563;      %distance of the booster CG to nose tip [m]
mb  = 6.065;      %mass of the booster (with motor) [kg]
M   = mn + mpayload + mm + md + mb;   %mass of the rocket (with motor) [kg]

%Apogee
mr  = 11.964;     %mass of rocket (no motor) [kg]
me  = 3.5635;     %mass of motor [kg]
mprop  = 1.582;   %mass of propellant [kg]
rho = 1.225;      %density of air [kg/m^3]
Cd  = 0.55;       %drag coefficient
D   = 0.1397;     %diameter of body tube [m]
R   = D/2;        %radius of body tube [m]
g   = 9.81;       %gravity constant [m/s^2]
T   = 1405;       %average thrust of motor [N]
t   = 3.63;       %motor burnout time [s]

%CALCULATIONS ------------------------------------
```

```
%Center of Pressure
Xn  = 0.466 * Ln;   %CP location for fins, from tip [m]
Xf  = Xb + ((Xr*(Cr + 2*Ct))/(3*(Cr + Ct))) + (1/6)*((Cr + Ct) - ((Cr*Ct)/(Cr+Ct)));    %CP location of fins, from tip [m]
Cnf = (1+R/(S+R))*(4*N*(S/D)^2/(1+sqrt(1+(2*Lf/(Cr+Ct))^2)));   %CP of fins, from tip [m]
X   = ((Cnn*Xn + Cnf*Xf)/(Cnn+Cnf));    %CP location of rocket from tip [m]

%Center of Gravity
cg = (dn*mn + dp*mpayload + dm*mm + dd*md + db*mb)/M; %CG location of rocket from tip [m]

%Static Stability Calculation
stab = (X - cg) / D;    %static stability margin [calibers]

%Apogee

%Burn Calculations
ma  = mr + me - (mprop/2); %(average) burn mass [kg]
A   = pi*(R^2);         %cross-sectional area of rocket [m^2]
k   = (1/2)*rho*Cd*A;   %aerodynamic drag coefficient [kg/m]
q1  = sqrt((T - (ma*g))/k); %burnout velocity coefficient [m/s]
x1  = (2*k*q1)/ma;      %burnout velocity decay coefficient [1/s]
v1  = q1*((1-exp(-x1*t))/(1+exp(-x1*t)));   %burnout velocity [m/s]
y1  = (-ma/(2*k))*log((T - (ma*g) - (k*v1*v1))/(T-ma*g));   %burnout altitude [m]

%Coast Calculation
mc  = mr + me - mprop;     %coast mass [kg]
qc  = sqrt((T-mc*g)/k); %coast velocity coefficient [m/s]
xc  = ((2*k*qc)/mc);    %coast velocity decay coefficient [1/s]
vc  = qc*((1-exp(-xc*t))/(1+exp(-xc*t)));   %coast velocity [m/s]
yc  = (mc/(2*k))*log((mc*g + k*(vc^2))/(T-mc*g));  %coast distance [m]

%Total Calculation
PA  = y1 + abs(yc);     %apogee [m]

%PRINT VALUES

fprintf('Center of Pressure: %2.4f inches \n', X*39.37);    %print CP [in]
fprintf('Center of Gravity: %2.4f inches \n', cg*39.37);    %print CG [in]
fprintf('Static Stability Margin: %2.4f calibers \n', stab);   %print static stability margin [calibers]
fprintf('Apogee: %2.4f feet \n', PA*3.281);               %print aprogee [ft]
```

```
Attempt to execute SCRIPT fullscale_simulations as a function:
C:\Users\Evan\Downloads\fullscale_simulations.m
```

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Appendix D: Flight Vehicle Assembly Instructions

Nosecone

To assemble the nose cone, insert the shoulder coupler that was included with the nose cone into the open end of the nose cone. Using a 9/64'' drill bit, drill four (4) holes equally separated around the circumference and halfway the depth that the shoulder coupler fits into the nose cone. Screw in a #6 screw into each hole. Measure halfway between the open end of the shoulder coupler and the bottom of the nose cone. Record this value. It will be needed for future steps. The nose cone is complete.

Payload Section

To assemble the payload section, center one (1) large bulkhead (5.375-inch diameter, 0.25-inch-thick) with one (1) small bulkhead (5.235-inch diameter, 0.25 inch thick). Permanently join the two bulkheads with a two-part epoxy. Center the two-layered bulkhead with a coupler (5.36-inch outer diameter, 12-inch length) and permanently join them with a two-part epoxy. Measure and mark six (6) inches from the open end of the coupler. Insert the bulkhead attached end of the coupler into the payload section body tube (5.36-inch inner diameter, 24-inch length) until the end of the body tube aligns with the mark. Using a 9/64'' drill bit, drill four (4) holes equidistant around the circumference three (3) inches from the end of the body tube through the body tube and the coupler. This is the aft end coupler of the payload section. Screw in a #6 screw into each of the holes.

On the opposite end of the payload section body tube, measure and mark the distance from the open end of the body tube. Insert the nose cone shoulder coupler into the open end of the body tube. Mark eight (8) equidistant points around the body tube at the distance previously marked, being sure that none of the marks align with the four (4) screws already installed into the nose cone. Using a 1/16'' drill bit, drill eight (8) holes at the places marked. These will be where the shear pins will be installed on flight day. Before separating the nose cone from the payload section body tube, make a single alignment mark. The payload section is complete.

Main Section

To assemble the main section, slide the main body tube (5.36-inch inner diameter, 18-inch length) onto the coupler of the payload section. Measure three (3) inches from the forward end of the main body tube and mark five (5) equidistant points around the circumference, being sure that none of the points are aligned with the screws on the aft end of the payload body tube. Using a 1/16'' drill bit, drill through both the main section body tube and the coupler inside it. These holes will be where shear pins will be installed on flight day. Make a double alignment mark.

Measure and mark the halfway point on a coupler (5.36-inch outer diameter, 12-inch length). Insert the coupler into the aft end of the main section body tube. This is the A&R coupler. Mark four (4) points equidistant around the circumference three inches forward from the aft end of the main section body tube. Using a 9/64'' drill bit, drill through the body tube and coupler at each of the points marked. Screw in a #6 screw into each of those holes. The main section is complete.

Drogue Section

To assemble the drogue section, slide the drogue body tube (5.36-inch inner diameter, 14 inch length) onto the A&R coupler attached at the aft end of the main section body tube. Mark four (4) equidistant points around the circumference three (3) inches from the forward end of the drogue section body tube edge. Be sure that the points are rotated 45 degrees from where the screws on the aft end of the main section are. Using a 9/64’’ drill bit, drill through the body tube and coupler at each of the points marked. Screw in a #6 screw into each of the holes. With the drogue section and the main section rigidly connected via the A&R coupler, drill a ½’’ hole centered on the separation line. Be sure that the hole is not aligned with any of the surrounding screws. This hole is the atmospheric pressure port. The drogue section is complete.

Booster Section

To assemble the booster section, center one (1) large bulkhead (5.375-inch diameter, 0.25-inch-thick) with one (1) small bulkhead (5.235-inch diameter, 0.25 inch thick). Permanently join the two bulkheads with a two-part epoxy. Center the two-layered bulkhead with a coupler (5.36-inch outer diameter, 12-inch length) and permanently join them with a two-part epoxy. Measure and mark six (6) inches from the open end of the coupler. Insert the bulkhead attached end of the coupler into the booster section body tube (5.36-inch inner diameter, 24-inch length) until the end of the body tube aligns with the mark. Using a 9/64’’ drill bit, drill four (4) holes equidistant around the circumference three (3) inches from the end of the booster section body tube through the body tube and the coupler. This is the forward end coupler of the payload section. Screw in a #6 screw into each of the holes.

Slide the forward end coupler of the payload section into the aft end of the drogue body tube. Three (3) inches forward of the aft end of the drogue section body tube, mark three (3) equidistant points being sure that none of the points are aligned with any of the screws in the forward end of the booster. Using a 1/16’’ drill bit, drill through the drogue section body tube and the coupler inside at each of the three (3) marks. These holes will be where shear pins will be installed on flight day. Make a triple alignment mark.

Mark three (3) equidistant points around the aft end of the booster section body tube. At each of these points, mark a line nine (9) inches long parallel with the center axis of the body tube. Be sure that the end of these lines is aligned with the aft edge of the booster section body tube. Using these lines as a guide, cut three (3) slits nine (9) inches long and 0.45 inch wide. These slots are where the fin brackets will fit.

Center and with two-part epoxy, permanently attach one large bulkhead (5.375-inch diameter, 0.25-inch-thick) to the motor tube (3.031-inch outer diameter, 2.953 inner diameter, 22-inch length). From the open end, measure and mark the distance of 17 inches, 9 inches, and 1 inch. With a two-part epoxy permanently, attach a centering ring (5.36-inch outer diameter, 3.031-inch inner diameter, 0.25-inch thickness) at each of the marked distances. Mark three (3) equidistant points on the outer diameter of the aft most centering ring. Cut a slot (2 inches wide, 0.25-inch-deep) centered at each of these points. With a two-part epoxy, permanently attach the male end of the motor retainer to the open end of the motor tube.

With a two-part epoxy, slide the motor tube into the aft end of the booster section body tube and permanently join them. Be sure that the open end of the motor tube is towards the aft end of the body tube. Be sure that the slits cut into the aft most centering ring are centered with the fin bracket slots. Slide the fin retainment brackets into the fin bracket slits. Using a 9/64'' drill bit, drill eight (8) holes that align with the holes in each of the fin brackets. Screw in a #6 screw into each of the holes. Twenty-four (24) screws should be used in total.

Slide a fin into each of the fin brackets. With the fin bracket as a guide, using a 9/64'' drill bit, drill holes into each of the three (3) holes present in the brackets. Screw in a #6 screw into each of the holes. Nine (9) screws should be used in total. The booster section is complete.

Recovery System

Checked and initialed by two Recovery subsystem members and the Safety Officer after completion

Avionics Bay Assembly (1 day before launch)

- Fresh batteries installed in avionics board slot
- 9V battery clip attached to batteries
- Electrical tape installed over battery holder for retention assurance
    - If this is not done, then there is a risk that the batteries may not stay connected
- Altimeters screwed into altimeter sockets
- 9V battery clip leads wired to altimeter power ports
- Key switch leads wired to altimeter switch ports
    - If this is not done, then the altimeters will not be able to be turned on
- Wire six initiators to male sides of quick snap connector to account for four needed plus two spare
- Blue connector wires are wired to the female side of a quick snap connector and threaded through central feed through hole on drogue side bulkhead
- Green connector wires are wired to the female side of a quick snap connector and threaded through central feed through hole on drogue side bulkhead
- Green connector wires connected to drogue ports of altimeter 1
    - Note: it is crucial that these colored wires are done correctly in order to ensure that the appropriate charges are ignited
- Blue connector wires connected to drogue ports of altimeter 2
- White connector wires are wired to the female side of a quick snap connector and threaded through central feed through hole on main side bulkhead
- Yellow connector wires are wired to the female side of a quick snap connector and threaded through central feed through hole on main side bulkhead
- White connector wires connected to main ports of altimeter 1
- Yellow connector wires connected to main ports of altimeter 2
- Threaded rod installation
    - Threads must be secure so that the coupler is structurally sound
    - Threaded rod with single nut on end inserted through hole 1 in main bulkhead and through the corresponding hole on the avionics board until the nut is flush with the bulkhead

    - Insert a small nut on the opposite side of the threaded rod and screw nut onto threaded rod until nut is flush and tight against avionics board
    - Repeat steps for remaining hole in bulkhead
- Bolts added to all threaded rods and screwed down until bolt is tightly flush on main bulkhead
    - The bolts must be fastened correctly so that the avionics coupler can withstand the forces applied by the shock cords during parachute ejection
- Slide the avionics board into the avionics bay structure
- Seal the avionics bay coupler by screwing on the door

Avionics & Recovery Launch Day Preparation

- Ensure the key switches are in the OFF position
    - Prevents premature lighting of the initiators that can be potentially dangerous to those installing them
- Snap connector wired initiators to the other side of the connector wired altimeters
- Place other ends of each of the four initiators into blast caps and secure each to the exterior of blast cap with tape
    - If this is not done, then there is a risk that the initiators are dislodged and do not ignite the ejection charge
- Main Charge Setup
    - Safety glasses and latex/nitrile gloves are required when handling black powder
    - Measure 2.0g of black powder for each of the two main blast caps
        - The proper amount of black powder must be measured to ensure deployment of parachutes
    - Pour them each into their respective caps
    - Pack the remaining space in blast cap tightly with wadding
        - If this is not done, then the black powder will not ignite
    - Tape over blast cap opening with painter's tape
        - If this is not done, then the ejection charges will fall out of the blast caps and will not ignite
- Repeat last set of instructions for Drogue Charge Setup with 1.5g of black powder
- Use quicklink to connect shock cord designated for use between main parachute and main bulkhead
    - All quicklinks must be installed properly to ensure that every part of the rocket stays connected to each other and that parachutes during descent and lands under the kinetic energy limit
- Use quicklink to connect shock cord designated for use between drogue bulkhead and drogue parachute
- Pull main side shock cord through main body tube section
- Secure main body tube section to avionics bay with shortened screws
- Repeat last two steps for drogue side shock cord and drogue body tube
- Pack main parachute
    - Fold parachute in approved pattern and ensure cords aren't tangled for proper and full opening of chute
        - Tangled cords may cause the parachute to not fully open and improper folding may cause tangling of the cords

- Attach parachute and protective blanket to the shock cord from the avionics bay via quicklink, this placement of the blanket prevents it from sliding up the parachute cords which prevents chute from opening
  - The nomex blanket prevents damage from the ejection charges and attaching it to the quicklink ensures that it does not cause partial opening of the parachute
- Wrap the parachute in its protective nomex blanket
- Take the slack of the shock cord between the parachute and the avionics body tube and fold it, accordion style, back and forth over itself in approximately 8-inch increments. Place it loosely into the avionics body tube
- Place the folded, wrapped parachute in the avionics body tube on top of the shock cord with the blanket facing the charge to optimally shield parachute from the potentially damaging ignition
- Connect designated shock cord between the U-bolt on the booster section and the quicklink of the main parachute
- Fold the shock cord between the parachute and the booster section in the same manner that the other shock cord was and place on top of the parachute

- Repeat parachute packing steps on drogue parachute on the nose cone side on the avionics bay
- Finish remaining assembly of rocket
- Set up rocket on launch rail and ensure launch rail is in a vertical position
- Turn on each key switch and listen for each of the two altimeter's triple beeps that signify that they are ready for launch
  - Altimeters must have continuity beeps to ensure that they will function properly during flight

Recovery Subsystem Members	Safety Officer
______________________________	______________________________

To assemble the avionics bay in preparation for flight, all necessary materials and tools relevant to the assembly of the avionics bay and the recovery system are gathered and inspected for defects. Any faulty materials are removed and replaced with backup supplies. Install the altimeters in the avionics board with screws. Place fresh batteries into the avionics board and wire them to the altimeters with 9V battery clips. Tape must be placed over the batteries to ensure that they will stay connected throughout the flight. Screw the altimeters into the avionics bay. Wire the key switches into the altimeters and install in the body tube. Connect six initiators to the male sides of the connectors so that there are two extra initiators for launch. Wire the blue wires and green wires to the female sides of the quick snap connectors and thread them through the central feed through hole on the drogue side bulkhead. Connect the green wires to the drogue ports of altimeter 1 and the blue wires to the drogue ports of altimeter 2. The avionics bay is then held to drogue bulkhead with the batteries facing the bulkhead with two numbered holes on board corresponding to two numbered holes on the bulkhead. Then, insert the partially constructed avionics bay into structural coupler until the bulkhead is flush with internal bay coupler such that the altimeters are facing the up arrow on the structural coupler. Ensure the numbered holes are aligned with their corresponding labels on the structural coupler. Next, the yellow and white connector wires are wired to the female side of a quick snap connector and threaded through central feed through hole on main side bulkhead. Then, connect the white connector wires to main ports of altimeter 1 and the yellow connector wires connected to main ports of altimeter 2. It is crucial that these colored wires are done correctly in order to ensure that the appropriate charges are ignited. Now, with the avionics board held to the drogue bulkhead and with the batteries facing the bulkhead, align the three numbered holes on the board with the three numbered holes on the bulkhead. Take a threaded rod with a single nut on the end and insert it through hole 1 in the main bulkhead and then through the corresponding hole on the avionics board until the nut is flush with the bulkhead. Insert a small nut on the opposite side of the threaded rod and screw it onto the threaded rod until it is flush and tight against the avionics board. Repeat these steps for the remaining threaded rod and hole in the bulkhead. Ensure that the numbered holes are aligned with their corresponding labels on the structural coupler. The threads must be secure so that the avionics coupler is structurally sound. Now, install the main side bulkhead into the structural coupler with the holes, numbered 1 and 2, aligned with correspondingly numbered threads. Finally, add the bolts to all threaded rods and screw each bolt down until it is tightly flush on the main bulkhead. The bolts must be fastened correctly so that the avionics coupler can withstand the forces applied by the shock cords during parachute ejection. Slide the avionics bay into the coupler and screw the door onto the body of the rocket.

Assembling the recovery harness begins by first ensuring that the key switches are in the OFF position. This is important because it prevents premature lighting of the initiator that can be potentially dangerous to those installing them. Then the initiators are snapped to the other side of the connector wired altimeters. Then place the other ends of each of the four initiators into blast caps and secure each to the exterior of blast cap with tape. If this is not done, then there is a risk that the initiator is displaced and do not ignite the ejection charge. Before setting up the charges, safety glasses and latex or nitrile gloves are required when handling black powder. For the main charges, measure 2.0g of black powder for each of the two main blast caps and pour them each into their respective caps. The proper amount of black powder must be measured to ensure deployment of parachutes. Pack the remaining space in blast cap tightly with wadding and tape over blast cap opening with painter's tape. If this is not done, then the ejection charges will fall out of the blast caps and will not ignite. Repeat these for the drogue charges, but with only 1.5g of black powder. Now, use a ¼" quicklink to connect the shock cord designated for use between main parachute and main bulkhead to the U-bolt on the main bulkhead. Use another quicklink to connect the shock cord designated for use between drogue bulkhead and drogue parachute to the U-bolt on the drogue bulkhead. Pull main side shock cord through main body tube section and secure the main body tube section to the avionics bay with shortened screws. Do the same for drogue side shock cord and the drogue body tube. All quicklinks must be installed properly to ensure that every part of the rocket stays connected to each other and that parachutes during descent and lands under the kinetic energy limit. Now to pack the main parachute, begin by folding the parachute in the approved pattern and ensuring the cords aren't tangled for proper and full opening of chute. Tangled cords may cause the parachute to not fully open and improper folding may cause tangling of the cords. Attach the parachute and protective blanket to the shock cord from the avionics bay via quicklink, this placement of the blanket prevents it from sliding up the parachute cords in a way that prevents the parachute from opening. The nomex blanket prevents damage from the ejection charges and attaching it to the quicklink ensures that it does not cause partial opening of the parachute. Wrap the parachute in its protective blanket. Take the slack of the shock cord between the parachute and the avionics body tube and fold it, accordion style, back and forth over itself in approximately 8-inch increments. Place it loosely into the avionics body tube. Now, place the folded, wrapped parachute in the avionics body tube on top of the shock cord with the blanket facing the charge to optimally shield parachute from the potentially damaging ignition. Connect the designated shock cord between the U-bolt on the booster section and the quicklink of the main parachute. Fold the shock cord between the parachute and the booster section in the same manner that the other shock cord was and again place loosely on top of the parachute. Repeat these parachute packing steps on drogue parachute on the nose cone side on the avionics bay. Finish remaining assembly of rocket and set it up on the launch rail. At the launch rail, turn on each key switch and listen for each of the two altimeter's triple beeps that signify that they are ready for launch. Altimeters must have continuity beeps to ensure that they will function properly during flight.

Post Flight Procedures

Recovery Harness:

- At the landing site, detach some of the shock cords from the quicklinks to ease transportation
- At the launch preparation site, detach all of the shock cords from the bulkheads
- Wrap and tie the shock cords for storage
- Remove the quicklinks from the bulkheads
- Detach the parachutes from the quicklinks
- Lay the parachutes out and inspect them for damage
- Fold the parachutes for storage
- Place all supplies in their respective places for storage

Avionics Bay and AV Bay Coupler:

- Detach the colored wires from the bulkheads
- Remove one of the bulkheads from the coupler
- Detach the key switch wires from the altimeters
- Remove the avionics board from the coupler
- Remove the other bulkhead and threaded rods
- Take the avionics bay to the RSO for the apogee check (bring a wire for the switch)
- Unscrew the key switches
- Disconnect the green, blue, white, and yellow wires from the altimeters
- Disconnect the power supply from the altimeters
- Unscrew the altimeters from the avionics bay
- Remove the batteries from the avionics bay
- Place all supplies in their respective places for storage

Data:

- Plug the altimeters into a computer to extract data
- Compare the data to the estimated flight data
- Adjust the code if necessary
- Place records of the data in a folder to be accessed in the future

After landing, approach the rocket with caution because there might be parts scattered and possibly hot from the ejection charges. Firstly, disconnect some of the shock cords to move the rocket from the field to a safe area, most likely the launch preparation area. Once at a safe area, disassemble the recovery harness. This involves detaching all of the quicklinks from the bulkheads, parachutes, and shock cords. Then, wrap the shock cords to be stored. Then, lay out the parachutes and inspect them for any damage. Damaged parachutes do not work as well and need to be replaced. After inspection, fold and wrap the parachutes for storage. Place every recovery harness component in their respective place to be stored or transferred to the lab and then stored.

For the avionics bay and coupler, start by detaching the blue, green, yellow, and white wires from the bulkhead. Then, remove one of the bulkheads from the coupler. Detach the key switch wires from the altimeters. Now, the avionic bay should be free to slide out of the couplers. Remove the avionics bay and the other bulkhead from the coupler. The altimeter should then be taken to the RSO to inform them of the altitude of apogee. Since the switch is no longer attached, bring a wire to serve as a switch for the official altimeter. Then, continue disassembling the avionics coupler. Unscrew the key switches from the coupler and carefully remove them. Being too forceful with the switch may break it. Next, detach the blue, green, yellow, and white wires from the altimeters. Detach the power supply wires from the altimeter as well. The altimeters should now not have any wires connected so they can be unscrewed from the avionics bay. Lastly for the avionics bay, remove the batteries. Place every avionics bay and coupler component in their respective place to be stored or transferred to the lab and then stored.

Once at a computer, plug the altimeters in and extract the data. Compare the actual flight data to the estimated data from computer simulations. If there are any discrepancies, the data must be looked over and fixed. The flight data should be stored on the computer for future reference.

Appendix E: Testing Procedures

Carbon Fiber Airframe Testing Procedure

Abstract:
The current design is similar to previous models that LionTech Rocket Labs has used in the past. The only failure that previous designs have experienced was zippering of the body tube. Two testing procedures are to be done to ensure the rocket is capable of withstanding any and all forces seen during takeoff, flight, parachute ejection, and landing.

The first procedure is a tensile test. The objective of a tensile test is to exert tensile forces on a test piece that is structurally identical to the material used in the final design. These forces are to be increased until the test piece fails. In the case of this procedure, failure is when the material initially begins to permanently deform. Once the material fails, the force needed to cause this outcome is recorded and compared to the maximum force that the rocket is expected to experience during operation. If the expected maximum force is less than the force recorded with the test, then the current design is sufficient enough to be used. If the expected maximum force is greater than the test result, then a new design must be created and tested. This process is to be continued until the test results exceed the estimated maximum values.

Objective:
Determine the tensile load that can be applied to the wrapped tube before failure for blue tube wrapped in 1 layer, 2 layers, and 3 layers of carbon fiber wrapping. Using these results and predicted loads experience during flight, a safety factor can be obtained to validate the design choice.

Necessary Equipment:

- Sample of 3, 3-inch diameter tubes wrapped with 1 layer, 2 layers, and 3 layers of carbon fiber
- 2 Aluminum blocks machined to fit the interior of each body tube and contains 4 threaded holes for machined screws
- 2 Aluminum rods machined to fit through the blocks. These rods are used as attachment points for the tensile equipment
- Minimum of 8 machine screws
- Tensile loading equipment (to be determined by equipment faculty/provider)
- Carbon Fiber Airframe Testing Procedure Document

Assembly
For reliable results, proper assembly of testing equipment is imperative. The assembly procedure shall go as follows:

1. Prepare each tube section for testing; this includes cutting the tube to necessary length (as required by testing equipment or faculty), drilling 4 holes on each end of the tube and ensure alignment of those holes with the aluminum block
2. Align one end of the tube with an aluminum block and secure it using 4 machined screws.

3. **(Important)** Check that the aluminum is aligned perpendicularly to the tube. *Misalignment will disturb testing results as the load will no longer be purely tensile.
4. Feed aluminum rod through the aluminum block with the stop on the interior of the tube; clamp the block once fed through so it cannot fall into the tube.
5. Feed second aluminum rod into second aluminum rod, again with the stop on the side of the block to the interior of the tube. Again, clamp the rod so it won't slide out of the block.
6. Align the other end of the tube with the second block-and-rod assembly.
7. **(Important)** Check that the aluminum is aligned perpendicularly to the tube. *Misalignment will disturb testing results as the load will no longer be purely tensile.
8. If alignment is true, this assembly is ready to load into the testing equipment. Load the assembly into the testing equipment by attaching each end of the rod to the testing grips (or similar mechanism depending on tensile equipment).
9. Run the experiment
10. Record the load at failure in the table below.
11. Repeat steps 1-10 for the remaining configurations

Provide sample images of each of the completed steps here for future use

Results:

Configuration	**Load at failure**
1 layer of wrapped carbon fiber	
2 layers of wrapped carbon fiber	
3 layers of wrapped carbon fiber	

Success of results:

The test can be deemed successful if all the following are true:

a) Results are realistic
b) A trend can be examined (i.e. load at failure for 2 layers is higher than 1 layer and strength of 3 layers is greater than 2 and 1 layer)
c) Failure is at the screw holes as expected

Validation of design

Using the data recorded, scale the strength of the carbon fiber wrapped tube up to the diameter of full scale. Determine the safety factor of full scale design using the scaled failure strength and expected maximum load experienced during flight.

Motor Testing and Checkout Procedures

Local Environmental Conditions
Temperature:
Humidity:
Air pressure:

Hardware Installation

1. Assemble load cell fixture as follows:
    a. Fasten the load cell to the load cell mount with screws on the inner set of holes.
    b. Fasten a threaded rod to the top of the load cell and secure the connection with a nut and washer.
    c. Place bolts and washers through the outer set of holes on the load cell mount, with the bolt head facing upward.
2. Screw the threaded rod upwards through the cantilever beam of the reaction fixture, securing the connection with a nut and washer on top of the cantilever beam.
3. Refer to and follow *Motor Preparation Procedures* to prepare the motor for this test.
4. Install the prepared motor as follows:
    a. Insert loaded motor into motor mount tube.
    b. Position the motor retainment tabs on the aft end of the motor mount tube underneath the motor and tighten their screws to secure them in that position.
5. Locate ignition Power Supply a safe distance from the test stand.
6. Locate miscellaneous hardware and tools a safe distance from the stand.

Instrumentation Installation

1. Take the wires from the load cell and wire them into the Data Acquisition System (DAQ) as follows in Table XXXX.

Ch	1	2	3
GND	Vin(+)	Vin(-)	Vout
Bl	W	G	R

2. Locate the DAQ a safe distance from the test stand and opposite the plume direction. Secure wiring to the test fixture where appropriate to prevent damage to the wires.
3. Set InstruNET sample rate to 1000Hz.
4. Set number of channels to 3.
5. Verify all channels are enabled for digitizing.
6. Configure InstruNET network and sensor settings per Tables XXXX through XXXX.

	Network	Device	Module	Channel
Load Cell	1	1 i100	1 #100	Ch1 Vin+

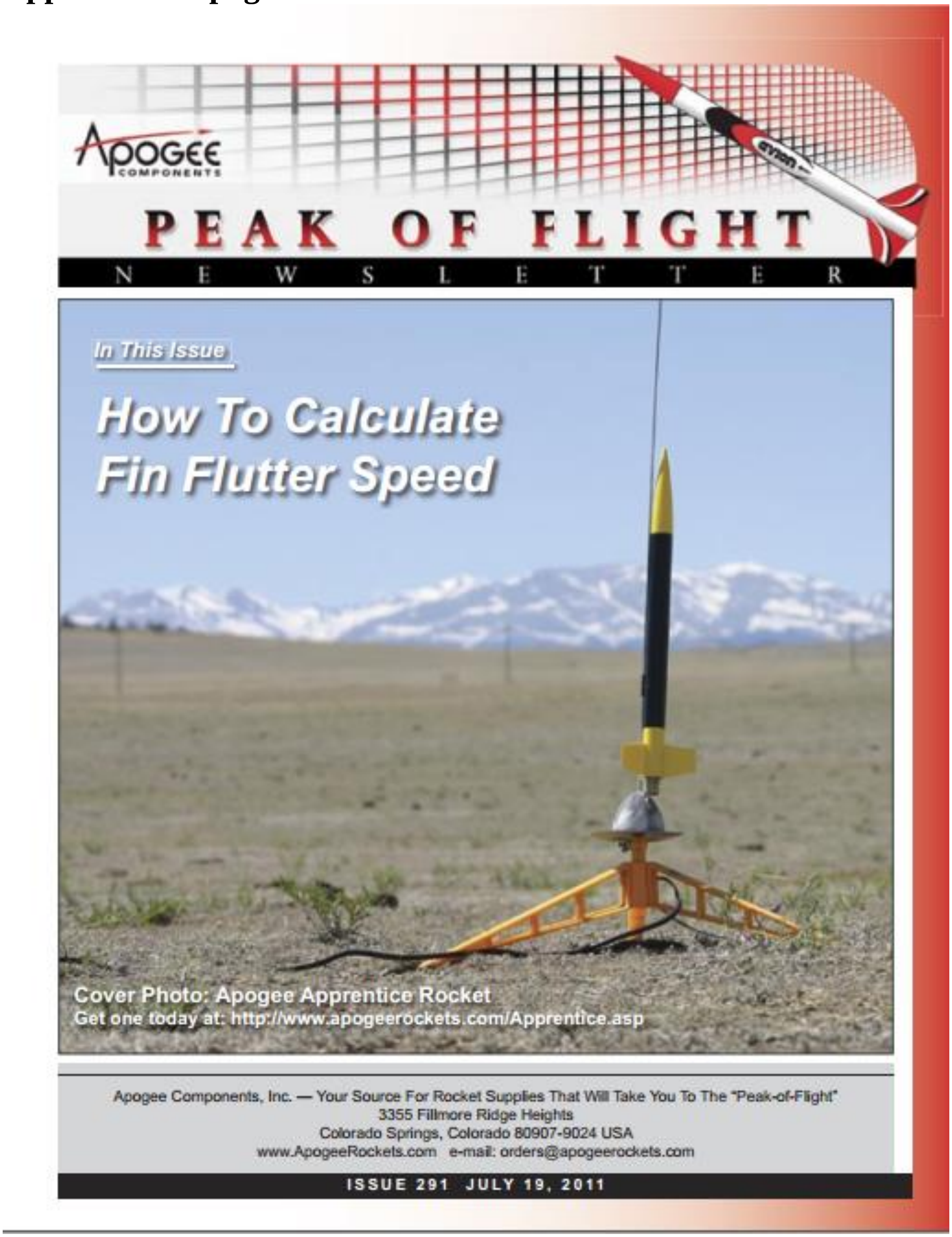
Sensor	Units	Range (Low, High)	Mex Force (lbf)	Manf. Rec. Voltage (V)	Sensitivity (mV/V)	Resistance (Ohms)	Excitation Voltage (V)	Low-Pass Filter (Hz)	# Ch.
Load Cell	lbs	(0, 500)	500	10	2.00654	352.60	1.3	4000	1

1. Verify that sensors are outputting correct nominal readings and units.
2. Save InstruNET sensor settings.
3. Position and test digital video cameras a safe distance from the test stand.

Testing Preparation
Test Date:
Test Number:

1. Refer to and follow *Initiator Installation Procedures* to install the initiator for this test.
2. Move all personnel and remaining equipment a safe distance away from the test stand.
3. When test director is ready and all personnel are in a safe area, they will vocally announce the impending test.
4. The test director then provides power to the initiator.

Appendix F: Apogee Rockets Fin Flutter



PEAK OF FLIGHT

How To Calculate Fin Flutter Speed

By Zachary Howard

After construction completed on July 1, 1940, the Tacoma Narrows Bridge was the third largest suspension bridge in the entire world, behind the Golden Gate Bridge and the George Washington Bridge. Its infamy lies not with historic length but in its nickname, Galloping Gertie. The nickname arose from the bridge's easily excitable bending mode. Drivers would watch the oncoming cars rise and fall with the violent motion of the bridge. During a particularly strong forty-mile per hour gust the newly excited torsion mode of the bridge caused a violent twisting along the centerline of the bridge. Figure 1 below shows the bending and torsional modes of the bridge. Despite being made from carbon steel and concrete on, November 7, 1940 the growing torsional oscillations overwhelmed the natural damping of the bridge and Gertie plunged 300 ft into the ocean below. After months of research NACA engineers diagnosed the cause of the vibrations as aeroelastic flutter.

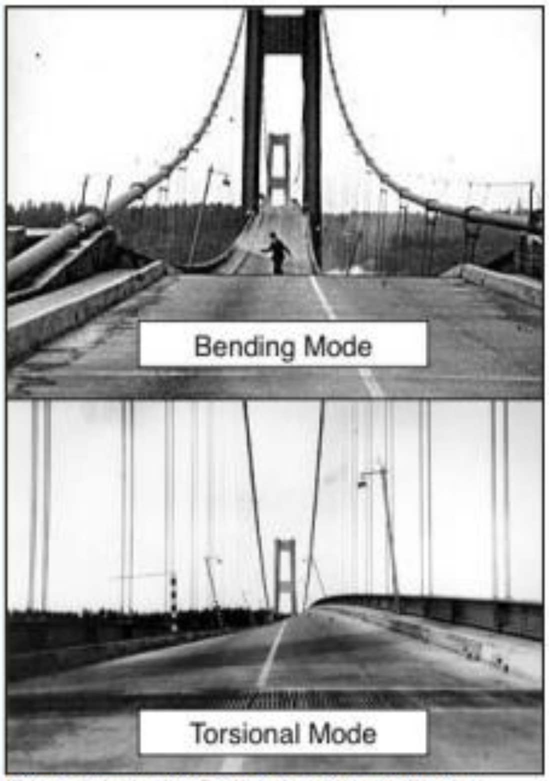


Figure 1. Galloping Gertie's Bending and Torsion Modes

Background

In textbooks aeroelastic flutter is defined as "a dynamic instability associated with the interaction of aerodynamic, elastic and inertial forces." The essence of this definition involves understanding the interaction between an object and the surrounding air. Let's start with the simple aerodynamic concept of lift. In the case of Galloping Gertie, the bridge construction did not allow air to pass through the bridge; rather it was diverted above and below. This diversion of air creates lift and a pitching moment around the aerodynamic center. Due to the coupling between an increase in pitching moment and an increase in lift, a positive feedback loop is created. This means that the increase of one variable drives the increase of the other in an infinite loop. If not damped, the positive feedback loop leads to uncontrolled aeroelastic flutter and ultimate failure of the structure. In

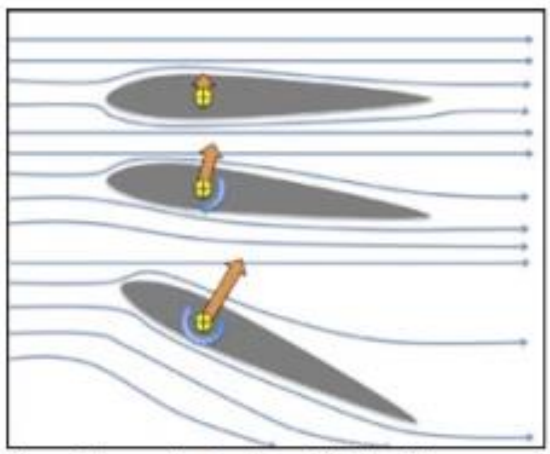


Figure 2. Increasing Torsion on Pitching Wing

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How To Calculate Fin Flutter Speed

Figure 2 notice how an increase in the lifting force (orange arrow) creates a clockwise rotation of the wing and an increased torsional moment (blue arrow).

Unlike the Tacoma Narrow bridge, a fin attached to a rocket does not have large mechanical dampers. Instead, rockets need to rely on thoughtful construction and air to damp out any vibrational energy in the fins. Air is very efficient at reducing the amplitude of the vibration while the rocket remains under the flutter velocity. However, once the flutter velocity is exceeded the air will exponentially amplify the oscillations and rapidly increase the energy in the fin to the point of destruction. Figure 3 shows the exponential damping and amplification of vibrational energy in a rocket fin below and above the flutter speed. For the remainder of this article we will establish an equation for predicting the flutter boundary and discuss all variables involved.

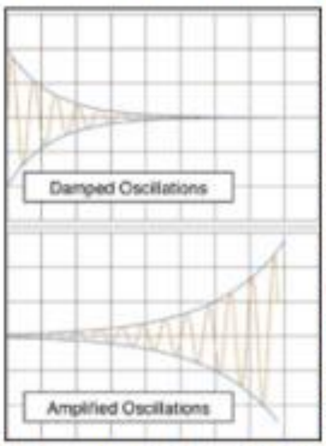

Figure 3. Damped and Amplified Oscillations

Flutter Boundary Equation

The Flutter Boundary Equation is based on an earlier calculation published in NACA Technical Paper 4197. If you are familiar with that paper you will notice that Equation 1 listed below is slightly different than the one presented in the technical paper. The most significant mathematical change is the use of a more accurate term for torsional modulus. This accuracy was gained by the inclusion of plate theory. Due to the complex nature of the flutter boundary equation we will focus our efforts on learning to understand the variables rather than trudging though the derivation.

$$V_f = a\sqrt{\frac{G}{\frac{1.337AR^3P(\lambda+1)}{2(AR+2)(\frac{t}{c})^3}}}$$

Equation 1. Flutter Boundary Equation

To begin our dissection of the Flutter Boundary Equation we will analyze the sole material property included in this equation, the Shear Modulus. Identified by the letter (G) it has units of pounds per square inch or PSI, and is the representation of the amount of deformation associated with a particular amount of force. Simply, the higher the Shear Modulus the more force it can handle.

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How To Calculate Fin Flutter Speed

For the purposes of this equation the materials are assumed to be isotropic, which means that the mechanical properties of the material are the same in all coordinate directions. This assumption is very accurate for metals because they are manufactured in a relatively uniform way, but for wood and hand laid composites isotropy cannot be assumed. In wood, shear stresses are unique to each axis, making the material orthotropic. You have probably noticed how it is easier to split wood along the grain rather than trying to cut it perpendicularly.

Additionally, there is no guarantee that two pieces of wood, even from the same tree, will have the same material properties. The same is true for all hand laid composites as well, because of the variability in cloth fibers and epoxy application. Therefore, when using published shear data on orthotropic materials, add an additional safety factor.

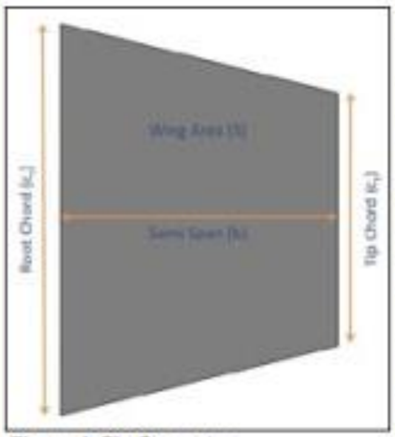

Figure 4. Fin Geometry

From Equation 1, the variables under the square root describing the geometry of the wing are the thickness of the wing (t), root chord (c), Aspect Ratio (AR) and the Taper Ratio (l). The equations for these variables are listed below, along with a wing geometry guide shown in Figure 4. All units should be in inches.

In a recent optimization study done by the Air Force they found that semi-span had the most impact in flutter speed calculations. Logically this makes sense, because a stubbier fin will be stiffer and more able to resist torsion as compared to a longer, more flexible fin. However, there is a trade off here with the minimum effective area needed to keep your rocket going straight. Through multiple design iterations using the RockSim software (www.ApogeeRockets.com/rocksim.asp), you should be able to come up with the right mixture of all desired values.

$$S = \frac{1}{2}(c_r + c_t)b$$

$$AR = \frac{b^2}{S}$$

$$\lambda = \frac{c_t}{c_r}$$

Equations 2. Geometric Equations

Next we come to Air Pressure (P). Using static atmo-

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How To Calculate Fin Flutter Speed

spheric models you will find that in the Troposphere, which is below 36152 ft, temperature and pressure vary linearly with altitude according to those listed in Equations 3. There are more equations that model temperature and pressure changes in the Upper and Lower Stratosphere, which you can find at http://www.grc.nasa.gov/WWW/K-12/airplane/atmos.html. The answers to the pressure calculations need to be converted into pounds per square inch in order to make sure that all the units under the square root cancel out.

$$T(°F) = 59 - .00356h$$

$$P(lbs/ft^2) = 2116 \times \left(\frac{T + 459.7}{518.6}\right)^{5.256}$$

Equations 3. Temperature and Pressure Variations

The last variable of the Flutter Boundary Equation is speed of sound (a). Dependent only on the temperature of the medium, the equation for the speed of sound is given in Equation 4.

$$a = \sqrt{1.4 \times 1716.59 \times (T(°F) + 460)}$$

Equation 4. Speed of Sound

This equation already has the Ideal Gas Law constants associated with air inserted, making the temperature calculated through Equations 3 the only variable. The unit on this calculation is feet per second, which due to cancellation among all other units makes the Flutter Boundary Equation in terms of feet per second.

Equation Verification and Safety Factor

In order to verify this equation, I have tested the Flutter Boundary Equation with data published in an article called *"Fin Flutter"* at http://www.info-central.org/?article=138 by Duncan McDonald. Although his attempt at calculating fin flutter was wrong (He forgot to add in the pressure terms and to keep consistent units. Also, some of the constants in the equation are deceiving because they are actually a combination of a bunch of constant terms), he had valuable test data from contributor Jeff Taylor who flew accelerometers in his rockets and recorded their maximum speed.

Based on the article's data, my Flutter Boundary Equation successfully predicted the two instances of flutter and the three safe flights of Jeff's rocket. That is a 100% success rate in five test cases. Without more significant testing the true accuracy of this equation will not be known, but preliminary calculations suggest that a comfortable safety margin is anything 20% below the flutter velocity speed. However, there have been instances of accuracy to within 5%.

The one major prediction problem is that the flutter velocity changes with altitude; therefore, to accurately predict flutter speed the altitude at which maximum velocity is achieved must be known. Usually this is not known, so keeping the rockets velocity under the maximum allowable at sea level is advised.

Root Chord (c_r)	9.75 in
Tip Chord (c_t)	3.75 in
Thickness (t)	.125 in
Semi-Span (b)	4.75 in
Shear Modulus (psi)	380000psi

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How To Calculate Fin Flutter Speed

Example

To truly cement your understanding of the Flutter Boundary Equation this following example will walk you through all equations necessary, with real numbers from an actual rocket. We're going to assume the rocket is at 3000ft.

Step 1: Preliminary Calculations

$$S = \frac{(9.75 \times 3.75)4.75}{2} = 32.06 in^2$$

$$AR = \frac{4.75^2}{32.06} = .70$$

$$\lambda = \frac{3.75}{9.75} = .38$$

$$T = 59 - .00356(3000) = 48.32°F$$

$$P = \frac{2116}{144} \times \left(\frac{48.32 + 459.7}{518.6}\right)^{5.256} = 13.19 \frac{lb}{in^2}$$

$$a = \sqrt{1.4 \times 1716.59 \times (48.32 + 460)} = 1105.26 \frac{ft}{sec}$$

Step 2: Plug into Flutter Boundary Equation

$$V_f = a \sqrt{\frac{G}{\frac{1.337 AR^3 P(\lambda + 1)}{2(AR + 2)(\frac{t}{c})^3}}}$$

$$V_f = 1105.26 \sqrt{\frac{380000}{\frac{1.337 \times .70^3 \times 13.19 \times (.38 + 1)}{2(.70 + 2)(\frac{.125}{9.75})^3}}}$$

$$V_f = 788.6 \frac{ft}{sec} \cong 537.67 mph$$

The maximum velocity was measured at 449 mph, which is below the flutter speed. In another test with the same rocket, the maximum velocity was clocked at 631 mph. On that test the fins broke, as predicted by the equation.

Authors Note

Firstly, I would like show my appreciation to Tim Van Milligan for publishing my article in the fantastic Peak of Flight Newsletter. Having been a subscriber for a long time now, I have always appreciated the constant stream of knowledge presented in these newsletters.

About the Author

Zachary Howard is a recent graduate from Georgia Tech in Aerospace Engineering. From local launches to competing in the Team America Rocketry Challenge, his lifelong passion for rocketry has not wavered. After a recent failed Level 1 attempt, Zachary revisited his old textbooks and begun deciphering the phenomena of fin flutter that claimed his rocket.