University of Notre Dame

2016 - 2017

Notre Dame Rocketry Team

Proposal for NASA Student Launch Competition

Fragile Materials Protection and Roll Control Experiments

Submitted September 30, 2015

365 Fitzpatrick Hall of Engineering

Notre Dame, IN 46556

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1 Team Information

1.1 General Information

Student Launch Option:	Task 1: Design of 2 payload experiments Aerodynamic Analysis and Communications Payload
Team Name:	Notre Dame Rocketry Team 365 Fitzpatrick Hall of Engineering Notre Dame, IN 46556
Faculty Advisor:	Dr. Aleksandar Jemcov, Professor Department of Aerospace and Mechanical Engineering ajemcov@nd.edu
Team Leader:	Jonathan Spraul jspraul@nd.edu
Safety & Reliability Officer:	George Porter gporter2@nd.edu
NAR Mentor:	Dave Brunsting, NAR/TAR Level 2 dacsmema@gmail.com
NAR/TRA Section:	TRA #12340, Michiana Rocketry

1.2 Team Organization

The Notre Dame Rocketry Team consists of 39 members coming from all class years and STEM majors. There are 18 returning members and 21 new members. As shown in Figure 1, the team has been broken down into four groups with the Team Captain overseeing these groups. The four groups are: 1) Vehicle Design; 2) Recovery Systems; 3) Fragile Object Protection Payload; and 4) Roll Control Payload.

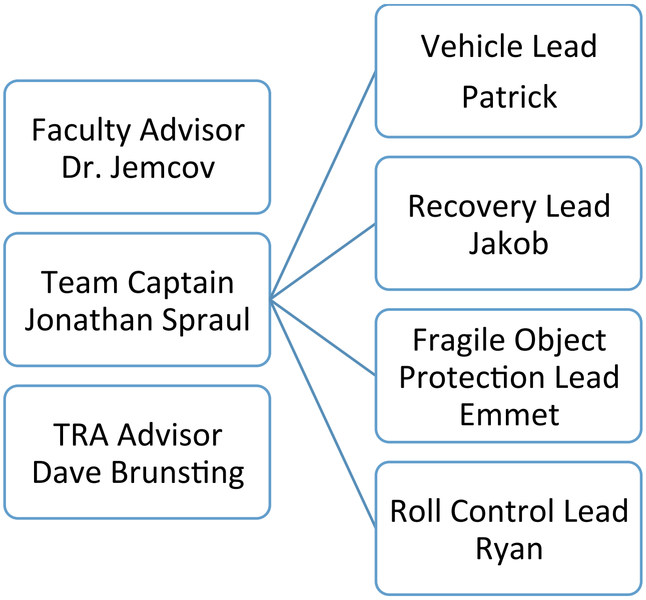


Figure 1. Team organization chart

1.3 Key Member Information

Jonathan – Team Captain

Jonathan is a senior aerospace engineering major. He thinks he wants to have a career in propulsion after thoroughly enjoying his first class on the subject this semester. This is his second year on the team. He was previously recovery lead during his first year on the team. He got his start in rocketry by flying Estes kit rockets with his dad and has enjoyed it ever since. He is also currently working on his private pilot's and is getting close to his first solo flight. He also really enjoys playing Kerbal Space Program and recreating historic rockets in the game.

George – Safety and Reliability Officer

George is a junior studying Aerospace Engineering, and a second year member of the rocketry team. Last year, he worked on the vehicle's design and construction. George wants to draw on the knowledge that he gathered last year in order to be an effective safety officer, while also helping with the vehicle's development. He has had a passion for rocketry and spaceflight since he was very young, and is excited to contribute more to the team in the coming year. In addition to the Rocketry Team, George is the treasurer of the American Institute of Aeronautics and Astronautics chapter of Notre Dame, a member of the Engineering Leadership Council, and a member of the lacrosse club.

Patrick – Vehicle Design Lead

Patrick is a senior, studying Aerospace Engineering and French Language and Literature. He is from Maryland and enjoys taking in the natural diversity of the state, from beaches to mountains. He previously served as NDRT's Co-Lead and is excited to see how the team will respond to the changes and challenges it will face this year. At large, he is interested in the development of massive astronautical projects in the context of international co-operation.

Jakob – Recovery Lead
Jakob is a junior Mechanical Engineering major. After a full year of experience on the recovery squad, he is excited to apply everything he has learned to further improve the system. Jakob is intrigued by all things engineering, and is eager to explore diverse industries such as biotechnology, automotive, and aerospace of course. Outside of school and the rocket team, he enjoys playing ping pong, playing soccer, and travelling.

Emmet – Fragile Material Protection Lead
Emmet is a Senior Aerospace Engineering student from Long Island, NY. This is his second year on the Notre Dame Rocketry Team and he is very excited to be leading the Fragile Object Protection Payload. Emmet dreams of pushing the boundaries of human understanding through pioneering space exploration missions. Outside of the rocketry team, Emmet is interested in photography, running and now that he lives off campus, he has also become a rollerblading fanatic.

Ryan – Roll Control Lead
Ryan is a junior Aerospace Engineering major with a secondary major in Philosophy, Science, and Mathematics. This is his second year on the Rocket Team, and he is very enthusiastic about leading a squad for the Roll Induction experimental payload. He previously worked on the aerobraking experimental payload, and was able to gain a lot of experience in payload design and implementation. He hopes to use the knowledge gained from this team to eventually work on a commercial space program.

Madison – Educational Outreach Committee Chair
Maddie is a junior aerospace engineering major from St. Louis, Missouri. This is her second year on the Notre Dame Rocketry team, and she is excited to be a veteran member of the vehicle squad and the educational outreach lead this year. After graduation, Maddie hopes to work in the space industry, hopefully in the design and testing of space launch vehicles. Outside of rocketry, she is the vice president of her dorm, works as a teaching assistant, does undergraduate research, and is involved in Campus Ministry and SWE. She also enjoys running, hiking, and cooking.

Alex – Corporate Sponsorship Committee Co-Chair
Alex is a junior studying aerospace engineering. This is her second year with the Notre Dame rocket and is Co-lead of the corporate sponsorship committee and a member of the Roll control squad. She first found her love for rocketry through Team America Rocketry Challenge in high school. Outside of school Alex competes across the country for Irish Dance.

Monica – Corporate Sponsorship Committee Co-Chair
Monica is a junior aerospace engineering student from southern California. This is her second year on the team and she is a returning member on the Vehicle Design team. She is looking forward to gaining more experience this year as well as help new members integrate into the team. She is co-lead of the Corporate Sponsorship Committee, which focuses on raising team funds in order to purchase higher quality materials and take as many members as possible to the competition in April. On campus, she is also part of the STEM Leadership Committee, Hispanic Engineers and Scientists, and conducts research in the Microfluidics Laboratory. Monica hopes to attend graduate school after college and become part of the mission to Mars.

2 Facilities/Equipment

2.1 Facilities Overview

2.1.1 Stinson-Remick Hall of Engineering

Stinson-Remick Hall is the main work location for the Notre Dame Rocketry Team. In this building the rocket team will have its weekly meetings and have access to various multi-purpose rooms that have computers projectors and a white board. The team has 24hr access to Stinson-Remick and an available workspace in room 213. This room serves as one of the main locations for the construction of the launch vehicle. There is also a large storage closet available with a dedicated file cabinet to the team.

Further, available in Stinson-Remick is a standard fully equipped machine shop. This shop has various pieces of equipment that will be useful to the construction of the vehicle. The equipment includes a laser cutter, CNC routers, band saws, belt sander, dremel, circular saw, drills, hammers and various other construction necessities. This equipment is available during the machine shop office hours. During office hours there are trained people available to ensure the safety and quality of the work performed. There also additive manufacturing machines available for use.

2.1.2 Fitzpatrick Hall of Engineering

Fitzpatrick Hall of Engineering has uniaxial testing machines. These machines would serve to evaluate the stress and strain of the materials under consideration for the launch vehicle. The test specimen would be held between two wedge grips and a uniaxial tension or compression test would be performed. Doing this as well as using rosettes and stress and strain gages could give the stress and strain profiles of the material in consideration. This information would serve to indicate the stress and strain that the proposed body material is able to withstand and thus a more informed decision on construction can be taken.

2.1.3 Hessert Laboratory

Hessert Laboratory has the main lab and also smaller labs with wind tunnels available that can be used to test the aerodynamic forces on the vehicle. These wind tunnels can also serve to test the roll control functions of the selected payload without having to physically launch the vehicle. The lab houses three open-return wind tunnels, an Environmental Wind tunnel, three tri-sonic wind tunnels an anechoic open jet wind tunnel. These wind tunnels all have different flow velocity capabilities as well as different test section sizes. Depending on the side or speed requirements for the launch vehicle these test sections can be used to analyze the flight characteristics of the launch vehicle.

2.1.4 Innovation Park

Innovation Park is a facility founded by Notre Dame which has various pieces of equipment and facilities. There is a 3D printer available for use here which will be used in the event that a larger part needs to be printed or if the printers available at the University are unavailable. There are also various technicians available at Innovation Park who can be used as resources for advice on a specific phase of construction or on methods of construction.

2.2 Computer Equipment

2.2.1 3-D Modeling

PTC Creo Parametric 3.0 will be used in order to create accurate models of the physical rocket. It is a valuable tool for determining the size, structure, and integration of all parts of the rocket.

2.2.2 Flight Simulation

OpenRocket and RockSim will be used to simulate the rocket launch. This will estimate the apogee, drift distance, and velocities at different points during the launch. We will use both programs in order to verify each estimate throughout the design process.

2.2.3 Structural and Flow Simulation

Ansys Fluent will be used in order to simulate the flow around the rocket during flight. This will give vital data, such as the flow over the fins, drag coefficients, and reactions when roll induction is activated.

ADINA and ABIQUS will be used in order to calculate the structural loads on the rocket. This will give crucial information on structural integrity, and help to indicate any weaknesses in the design of the rocket.

2.2.4 Miscellaneous Programs and Resources

MATLAB will be used for a variety of purposes, including some simulation, calculations, and the display of data. Microsoft Office will be used for document and presentation creation.

Additionally, all students have access to Notre Dame’s high speed wired and wireless networks. Combined with campus email, students are able to use their personal computers to complement the available campus resources.

Conference rooms are available on campus for use in video conferences. These rooms are equipped with Windows computers, (including presentation software), broadband internet connection, speakerphones, and webcams.

The Notre Dame Rocketry Team will implement the Architectural and Transportation Barriers Compliance Board's Electronic and Information Technology Accessibility Standards (36 CFR 1194).

2.3 Web Presence

The team will post all documents on its web page whose link is: http://ndrocketteam.com/. The team will update its followers on the Community Engagement opportunities in which it was able to participate. It will also update its followers on the status of design and dates of test launches.

In addition, the team is present on Facebook @ndrocket and on Twitter @NDRocketry. The team updates its followers through both media the status of the launch vehicle's design as well as general news within the aeronautical industry.

3 Safety

3.1 Team Safety Protocols

3.1.1 Materials Safety

General instructions will be provided to the entire team for the safe handling of dangerous materials and avoidance of potential dangers. Proper training and supervision will be required before any team member handles hazardous or dangerous material. Material Safety Data Sheets (outlined in Table 1) will be posted in the construction lab. All policies regarding material safety will be enforced by the safety officer.

Table 1. Material Safety Data Sheet Outline

Material	Prevalence	Dangers	Corrective Response
Ammonium Perchlorate	Common (found in motors)	Risk of fire, burns	Keep flame away, treat burns normally
Black Powder	Common (found in engine charge)	Risk of fire, burns	Keep flame away, treat burns normally
Epoxy Hardener	Common (adhesive)	Skin Irritation	Flush area with water
Epoxy Resin	Common (adhesive)	Skin Irritation	Flush area with water
Fiberglass	Common (body of rocket)	Skin Lacerations, Dust Inhalation	Use mask and gloves while cutting, treat injuries with bandages or stitches if necessary
Carbon Fiber	Common (body of rocket)	Skin Irritation, Dust Inhalation	Flush area with warm water, Wash mouth out immediately under clean, fresh air

3.1.2 Facilities Safety

Successful completion of a safety course and a signed University safety agreement are the prerequisites for any team member to work in the machine shop. All team members working the machine shop must be accompanied by the safety officer or other University appointed machine-shop supervisor.

3.1.3 Safety Officer

The Notre Dame Rocketry Team has chosen George Porter as the Safety Officer for the 2016-2017 year. This is George’s second year on the team, and he has both rocketry construction and machine-shop experience. He is employed by the University as a Teaching Assistant for the machine shop certification course, and thus is trained in the use of the facilities and safety protocols. George will be in charge of ensuring the team carries out the proper safety procedures and will perform risk and mitigation analysis along with contingency planning for all safety aspects of the project.

The safety officer will ensure that MSDS and other safety documents are up to date and readily available to all team members. The safety officer will be present throughout the construction process and whenever a potential hazard exists for any personnel if the safety officer cannot be present, then he will appoint a capable representative to take his place.

3.1.4 Project Risk and Assurance

Given the year-long schedule of the project, it is crucial to identify potential risks to a successful mission. These risks, as well as steps to mitigate problems, are summarized below in Table 2.

Table 2. Project Risks and Mitigation

Risk	Probability	Effect	Mitigation
Project Falls Behind Timeline	High	Rushed delivery or project failure.	Continually track progress; anticipate potential scheduling problems. Additional launch days designated.
Initial Design Unfeasible	Moderate	Significant design changes; failure to follow timeline.	Analyze design for feasibility and performance. Continually update mass estimates and simulation.
Design cannot meet budget constraints	Moderate	Design must be changed to less expensive option.	Continually update budget projections, use cost-effective materials.
Failure during test flight	Low	Potential loss of rocket, or end of project.	Test components individually before full scale flight; prepare backup materials.

3.2 NAR/TRA Personnel and Responsibilities

The Notre Dame Rocket team will be advised by David Brunsting of Michiana Rocketry (TRA #12340). He currently has a high powered rocketry Level 2 certification, allowing him to purchase and work with L class impulse motors, which will be used for the team rocket. As a past prefect of Michiana Rocketry, David has several years of experience in high powered rocketry, and will help ensure that all NAR high powered safety code requirements (Appendix A) are met.

During the design and construction process, David will provide advice and work with the team to ensure a high level of quality and safety. He will be responsible for purchasing, storing, transporting, and handling the rocket motors and detonation charges. Also, He will be present for all rocket launches, supervising preparation and recovery activities.

3.3 Hazard Recognition, Accident Avoidance, and Pre-launch Briefings

Prior to construction, a safety meeting will be conducted detailing appropriate procedures. This meeting will include presentations of potential dangers, as well as actions to mitigate risks. Additionally, all applicable laws and regulations will be emphasized. Before launches, a separate safety meeting will be held. At these meetings, the safety officer will emphasize launch specific details and operations (including NAR high powered safety code). The NAR/TRA mentor and faculty advisor will be present at all meetings to provide additional input.

3.4 Inclusion of Caution Statements in Plans, Procedures, and Other Working Documents

Representatives have been chosen from each sub-team and will serve as liaisons for the safety committee to their respective teams. These individuals will be trained and have knowledge of materials and facilities safety procedures, as well as hazard recognition and accident avoidance. Each representative will be responsible for including caution statements in their sub-team’s plans, procedures, and working documents. There will also be safety briefings before each step in the design and construction processes in order to ensure caution when working with potentially dangerous materials.

3.5 Federal, State, and Local Regulations

The Federal Aviation Administration (FAA) [www.faa.gov] has specific laws governing the use of airspace. A demonstration of the understanding and intent to abide by the applicable federal laws (especially as related to the use of airspace at the launch sites and the use of combustible/ flammable material), safety codes, guidelines, and procedures for building, testing, and flying large model rockets is crucial. The procedures and safety regulations of the NAR [http://www.nar.org/safety.html] shall be used for flight design and operations.

The Notre Dame Rocketry Team is cognizant of all local, state, and federal laws concerning the use of airspace, as well as the use of combustible and flammable material. As the perfect of a TRA section, the team mentor is particularly familiar with local regulations. Especially relevant sections and regulations are:

- Federal Aviation Regulations 14 CFR, Subchapter F, Part 101, Subpart C (governing usage of airspace)
- Code of Federal Regulation 27 Part 55: Commerce in Explosives (handling and use of low explosives)
- NFPA 1127 “Code for High Power Rocket Motors” (fire prevention)

3.6 Purchase, Storage, Transport, and Use of Motors and Energetic Devices

The Notre Dame Rocketry Team understands that high-power rocket motors must be purchased and stored by certified users 18 years of age and older. The rocket motors used will be handled only by team members with appropriate NAR/TRA Level 2 certification. Since there are no current team members with this certification, the team’s mentor Dave will be responsible for purchasing and storing the full-scale motors prior to use. The team will use only properly NAR/TAR certified motors.

Motors will be purchased locally and stored in a secure, fireproof cabinet, in close proximity to a fire extinguisher and appropriate emergency contact information. The motors will be stored without the igniter installed. Only the NAR/TRA certified mentor will have access to the cabinet, and he will ensure that the proper safety precautions are taken leading up to and during launch. Neither the team members nor the mentor will alter or tamper with the motors in any way. The subscale vehicle's motors do not require prior certification to handle, but as an extra safety measure Dave will purchase and store these motors as well.

Current plans call for the motor to be transported by car to the launch site. The NAR/TRA certified mentor will oversee transport and, in conjunction with the team Safety Officer, will conform to all local, state, and federal regulations. If it becomes necessary to ship the motor to the launch site, it will be properly declared as hazardous material in conformance with federal law.

The NAR/TRA certified mentor will assemble all reusable motors prior to use. He will also accompany the vehicle to the launch pad to ensure that it is prepared properly for launch.

3.7 Safety Agreement

All members of the Notre Dame Rocketry Team have agreed to follow the safety procedures outlined above. The team will also submit to range safety inspections, recognizing that the Range Safety Officer has the final say on all safety issues. A signed safety agreement will be kept on record (Appendix B). Failure to comply with the safety requirements may result in the team being prohibited from launch. All team members are required to sign this agreement.

4 Technical Design

4.1 Mission Requirements

Design, construct, and launch a rocket to an altitude of exactly 5,280 ft above ground level while carrying at least 1 scientific payload. The vehicle will deploy both a drogue and main parachute for recovery purposes. Vehicle and its payloads must be reusable on the same day as launch without repairs or modifications.

4.1.1 Vehicle Requirements

- Vehicle must deliver payload(s) to an apogee of 5,280 ft above ground level
- Vehicle must contain at least 1 commercially barometric altimeter
- All recovery electronics must be powered by commercially available batteries
- Rocket and payload must be able to be launched again on the same day, without repairs or modifications
- Vehicle must have 4 or less independent sections
- Vehicle is limited to a single stage

- Vehicle must be capable of being prepared for flight within 4 hours
- Vehicle must be capable of remaining in launch ready configuration on pad for at least 1 hour without failure of critical component
- Vehicle must be capable of being launched by standard 12 volt direct current firing system without external circuitry or special ground equipment
- Vehicle must use commercially available solid motor propulsion system using APCP
- Minimum static stability margin of 2.0
- Minimum off rail velocity of 52 ft/s
- Successfully launch and recover sub-scale model prior to CDR
- Successfully launch and recover full-scale model prior to FRR
- Vehicle ballast must not exceed 10% of total weight of rocket
- Vehicles must not
    - Utilize forward canards
    - Utilize forward firing motors
    - Utilize friction fitting for motors
    - Exceed Mach 1 at any point

4.1.2 Recovery Requirements

- The launch vehicle must stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee and a main parachute is deployed at a lower altitude
- Each team must perform a successful ground ejection test for both drogue and main parachute prior to subscale and full scale launches
- Independent sections of vehicle must have a kinetic energy of 75 ft-lbf or less at landing
- Recovery system electrical circuits must be independent of any payload electrical circuits
- Recovery system must contain redundant commercially available altimeters
- Motor ejection is not a permissible form of primary or secondary deployment
- Each altimeter shall be armed by a dedicated armed switch accessible from the exterior of the rocket in launch configuration
- Each altimeter must have a dedicated power supply
- Each arming switch must be capable of being locked in the ON position
- Removable shear pins must be used for both the main and drogue parachute compartments
- An electronic tracking device must be installed in the launch vehicle and must transmit the position of the tethered vehicle or independent section to a ground receiver
- The recovery system electronics shall not be adversely affected by any other on-board electronic devices during flight

4.1.3 Roll Control System Requirements

- Teams must design a system capable of controlling launch vehicle roll post motor burnout
- System must first induce at least 2 rotations around roll axis of vehicle
- After two rotations, it must induce a counter rolling moment to halt rolling motion for remainder of launch vehicle ascent
- Teams must provide proof of controller roll and successful counter roll
- Team must not intentionally design a launch vehicle with fixed geometry that can create a passive roll effect
- Teams shall only use mechanical devices for rolling procedures
- Additional fins must be aft of the post-motor burnout center of gravity

4.1.4 Fragile Object Protection

- Teams must design a container capable of protecting an object of unknown material, size and shape
- May be multiples, exact replicas of the object
- Object(s) shall survive throughout the entirety of the flight
- Teams shall be given the object(s) at team check in table on launch day
- Teams may not add supplemental material to the protection system after receiving object(s)
- Object(s) must be sealed in payload until after launch
- The provided object can be any size and shape, but will be able to fit inside a cylinder 3.5” in diameter and 6” in height
- The object(s) shall have a maximum combined weight of approximately 4 ounces

4.2 Vehicle Design

4.2.1 Vehicle Description

The projected vehicle dimensions are shown below, in Table 3. The diameter was chosen based on the amount of space needed for the fragile materials payload. This large diameter will also allow for more space inside the rocket. The rocket design, shown in Figures 2 and 3 was developed from the preliminary estimates from the payload sub-teams about the potential mass. A general CAD representation is shown in Appendix C.

4.2.1.1 Vehicle Dimensions

Table 3. Projected Vehicle Dimensions and Characteristics

Property	**Dimension**
Length of Rocket (in)	94.75
Diameter of Rocket (in)	5.5
Number of Fins (Main / Payload)	4 / 4
Root Chord (in) (Main / Payload)	7 / 3
Tip Chord (in) (Main / Payload)	7 / 3
Sweep Angle (°) (Main / Payload)	32 / 32
Fin Height (in) (Main / Payload)	6.2 / 2
CG Position from Nose Cone (with motor) (in)	60.638
Position of Payload Fins from Nose Cone (in)	65
Weight without Motor (lbs)	418
Weight with Motor (lbs)	550
Estimated Stability Margin without Motor	3.84
Estimated Stability Margin with Motor	2.44

4.2.1.2 Vehicle Layout

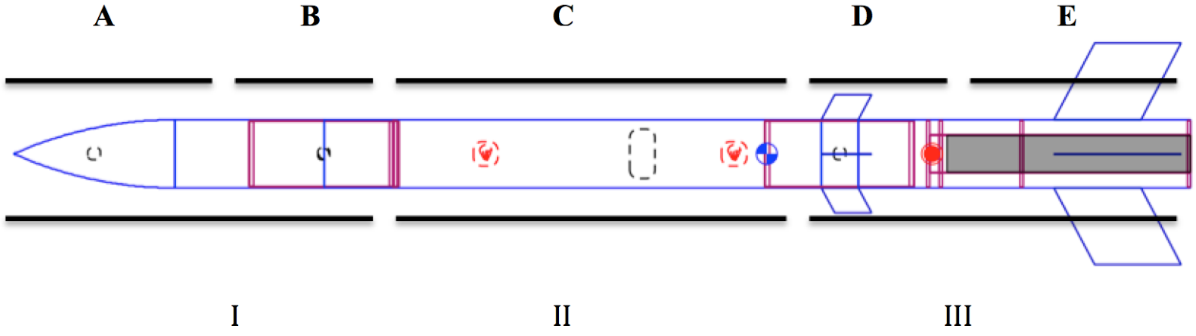


Figure 2. Vehicle Design Layout (LH Shown, RH Opposite)

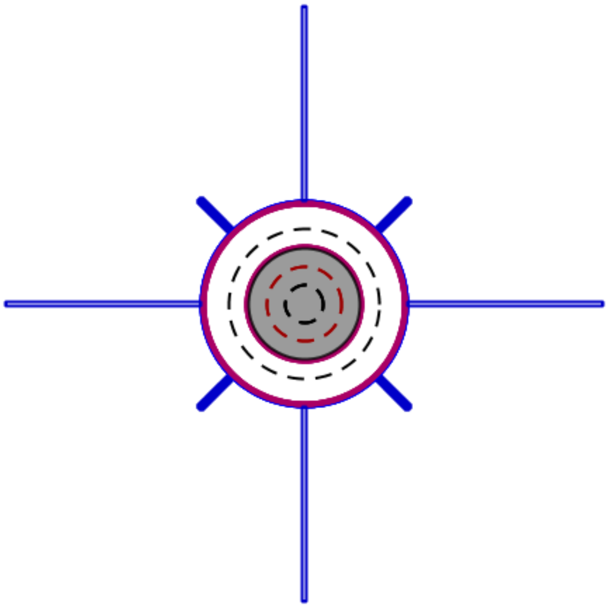


Figure 3. Vehicle Design Layout (Bottom View Shown)

Table 4. Design Layout

Section	Sub-Section	Label	Composed of	Description
I	Nose Cone	A	Hollow nose cone, 13 inches in height and 5.5” in diameter, made of fiberglass	Connected to the fragile materials payload bay below
	Fragile Materials Payload Bay	B	12” of carbon fiber tubing body tube, and 12 inches of carbon fiber coupler	Holds fragile materials protection payload
II	Parachute Bay	C	40” carbon fiber body tube	Holds CRAM (Compact Removable Avionics Module), as well as a main and drogue parachute.

III	Roll Control Payload Bay	D	12” Fiberglass coupler with carbon fiber body tubing	Holds second set of fins for controlling roll during flight and electronics to read and compute proper spin
	Fin Can and Motor Mount	E	26.75” Carbon Fiber tube and carbon fiber fins.	Hold motor and motor mount and carbon fiber fins.

4.2.1.3 Fins

In order to maintain flight in the vertical direction, fins were chosen that maximize stability and minimize drag thereby also maximizing apogee. A parallelogram fin shape was chosen because it is highly effective at low Reynolds Numbers. Conveniently, this fin shape is easy to make and replicate and because all of the fins have the same airfoil shape, there is no drag that would arise from asymmetrical fin shapes. These fins provide the best stability for the launch vehicle at the speeds it will operate. A two-dimensional view is shown in Figure 4.

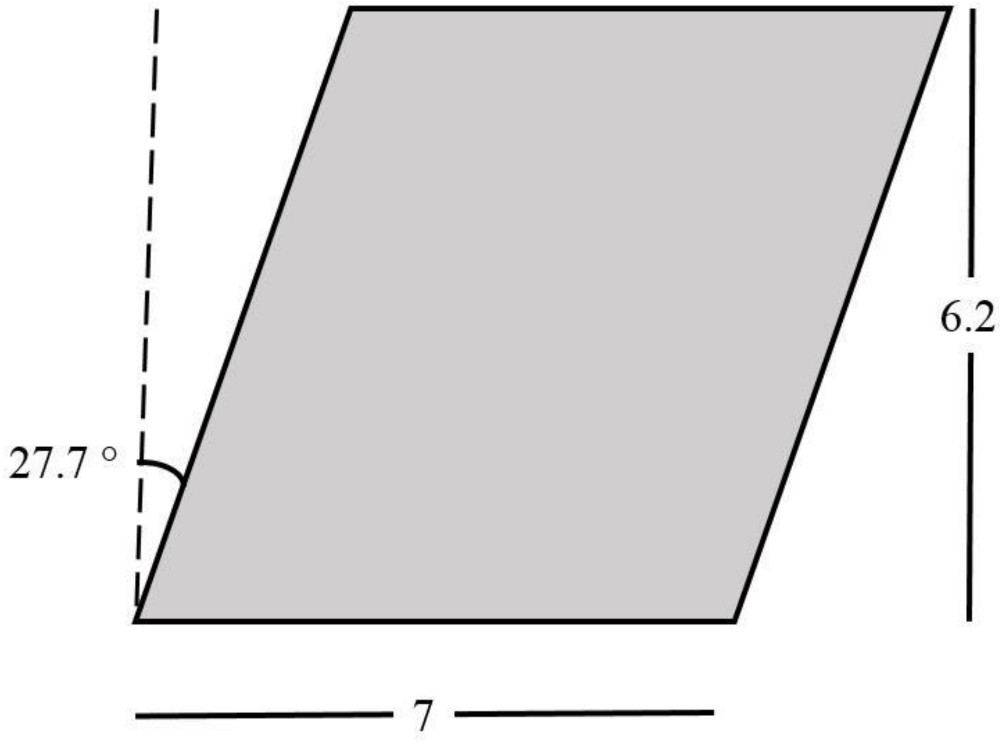


Figure 4. Proposed full scale fin sketch and dimensions (inches)

4.2.2 Applicable Physics

4.2.2.1 Stability

The stability will also be estimated using an in-house function in Python which can be seen in Appendix 5.2.1. The function takes into effect the dimensions of the launch vehicle including fin sizes, radii and proceeds to calculate the moment coefficients and returns a stability margin.

4.2.2.2 Projected Altitude

Using the current motor models detailed in Section 2.2.5, the team has made some simulations for the altitude of the launch vehicle using OpenRocket. The currently predicted altitudes are 5525 ft for the Loki L840CT motor and 5612 ft for the Loki L1482 motor. These altitudes are satisfactory.

They give the team ample room with which to work while it develops the roll control payload. The rolling motion is expected to increase the coefficient of drag of the launch vehicle as it disrupts the flow. This means that the launch vehicle is sure to achieve a lower altitude than currently predicted.

As the team continues with the design, it will perform more sophisticated analysis of the coefficient of drag using CFD methods and/or the campus wind tunnel. This will depend on the exact understanding of the amount of rolling achieved by the launch vehicle, an understanding that will grow as the team works through its design.

Additionally, the team has started developing a program which will estimate the altitude in order to verify the simulations in OpenRocket. This program, whose rudiments are shown in Appendix D, will be more flexible than OpenRocket since we can split up the flight path in many parts representing the real flight instead of one homogeneous flight path that OpenRocket simulates. This will be useful to implement the roll and counter-roll stage of flight that cannot be implemented in OpenRocket or RockSim.

4.2.3 Material Selection

4.2.3.1 Nosecone and Body Tube

Carbon fiber was selected as the primary material for the body tube and nose cone primarily because of its excellent strength to weight ratio. The other option considered for the primary material was phenolic; however, in a pound for pound comparison the carbon fiber is much stronger. While the density of carbon fiber is higher than that of phenolic, the strength is so much greater that less material can be used, having the overall effect of decreasing the weight. Because of the decreased weight of the rocket, the payloads will be able to use more weight, allowing for improved designs that are more effective. Carbon fiber works very well with other materials, should the need for a specific part be built from a different material.

Table 5. Material Properties for Body Structure

Material	Carbon Fiber
Component Use	Nose cone, body tube
Tensile Strength (ksi)	373
Tensile Modulus (msi)	19.9
Shear Modulus (msi)	0.6
Compressive Strength (ksi)	198
Compressive Modulus (msi)	18.5
Specific Weight (lb/in^3)	0.065

4.2.3.2 Fins

The fins of the rocket will be made of carbon fiber and will be made in-house. The fins will be mounted directly onto the motor mount to provide stability. They will fit into the premade slits on the carbon fiber body tube. This technique will decrease the likelihood of a fin detaching and being damaged during flight and landing. There will be four fins placed 4 in. above the bottom of the fin can. Although the four fins will add weight, they allow for the rocket to maintain stability and to control the center of pressure.

Figure 4 in Section 4.2.1.3 shows the shape of the fins for the full-scale rocket. Research of different shapes and placements of the fins was conducted and the results indicated that this parallelogram design is best for stability of the rocket and minimizes drag for the speeds the rocket will be reaching.

4.2.3.3 Integration Material

The motor mount will be constructed of 76 mm diameter carbon fiber tubing. Three fiberglass centering rings will be used to stabilize the motor mount. Carbon fiber provides an excellent strength to weight ratio and can secure the motor mount in a stable position throughout the entire flight. For extra support, slow cure epoxy adhesive will be applied to hold the pieces in place. Bulkheads will also be made from fiberglass to provide strength, while reducing the weight, compared to previous year's plywood that required ½ in thick bulkheads. Fiberglass is cheaper than carbon fiber. Fiberglass properties are shown in Table 6. Forged eyebolts, rated at 1500 lbs. link the shock cords to each section of the rocket. Similarly, the quick links attached the parachute to the shock cord are rated for 2000 lbs. These specifications have been used successfully in prior years. High quality adhesives are crucial to maintaining structural integrity. Different brands of adhesives are still in consideration, but Great Planes brand 30 Minute Epoxy has been previously used in successful flights and will continue to be used this year. This epoxy has an initial cure time of 30 minutes, a handling time of 6 hours, and a full cure time of 24 hours. The epoxy has a tensile strength of 2000 psi. In addition, Glenmarc brand Rocketpoxy G5000 will be used in areas such as fin attachments, to provide a stronger adhesive. This adhesive has a handling time cure of

4 hours and a full cure time of 24 hours. This Rocketpoxy has a tensile strength of 7,600 psi and is great in working specifically with carbon fiber and fiberglass. JB Weld will also be used in the adhesives ensuring motor retention. JB Weld is a secure adhesive for anything surrounding the motor due to its high temperature tolerance.

Table 6. Fiberglass Material Properties

Material	Component Use	Tensile Strength (ksi)	Compressive Strength (ksi)
Fiberglass (Polyester and Continuous Rovings Laminate 70% E-glass	bulkheads, centering rings	116	50.8

4.2.4 Propulsion

By utilizing the simulation software OpenRocket, a number of motor configuration were simulated with a preliminary model of the launch vehicle. The vehicle design used a liberal estimate of unknown weights. The two motors selected for the current configuration are the Loki Research L840CT and the Loki Research L1482. The L840CT has a total impulse of 874.3 lbf*s with a maximum and average thrust of 263 lbf and 187.5 lbf, respectively. The L1482 has a total impulse of 872.7 lbf*s with a maximum and average thrust of 407.5 lbf and 339.7 lbf, respectively.

Table 7. Loki L840CT and Loki L1482 Motor Properties

Manufacturer	Loki Research	Loki Research
Classification	L840CT	L1482
Diameter	2.95 in	2.99 in
Length	19.61 in	19.57 in
Total Weight	8.26 lb	7.80 lb
Propellant Weight	4.57 lb	4.05 lb
Average Thrust	187.5 lbf	339.7 lbf
Maximum Thrust	263 lbf	407.5 lbf
Total Impulse	874.3 lbf*s	872.7 lbf*s

Burn Time	2.6 s	4.6 s

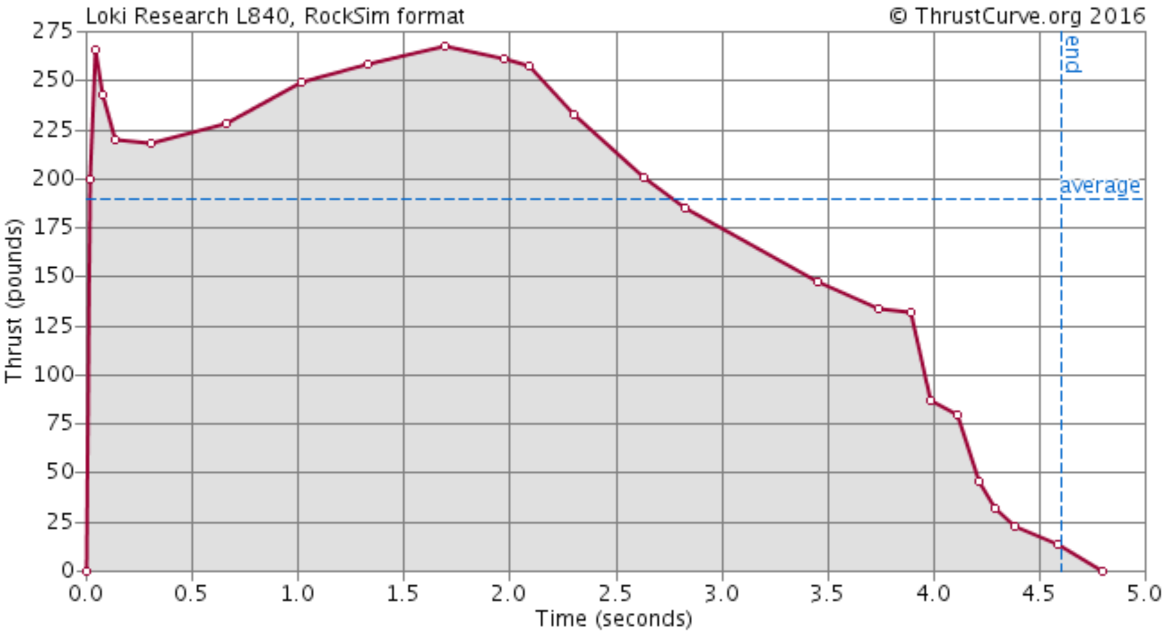


Figure 5. Thrust Curve of Loki Research L840CT

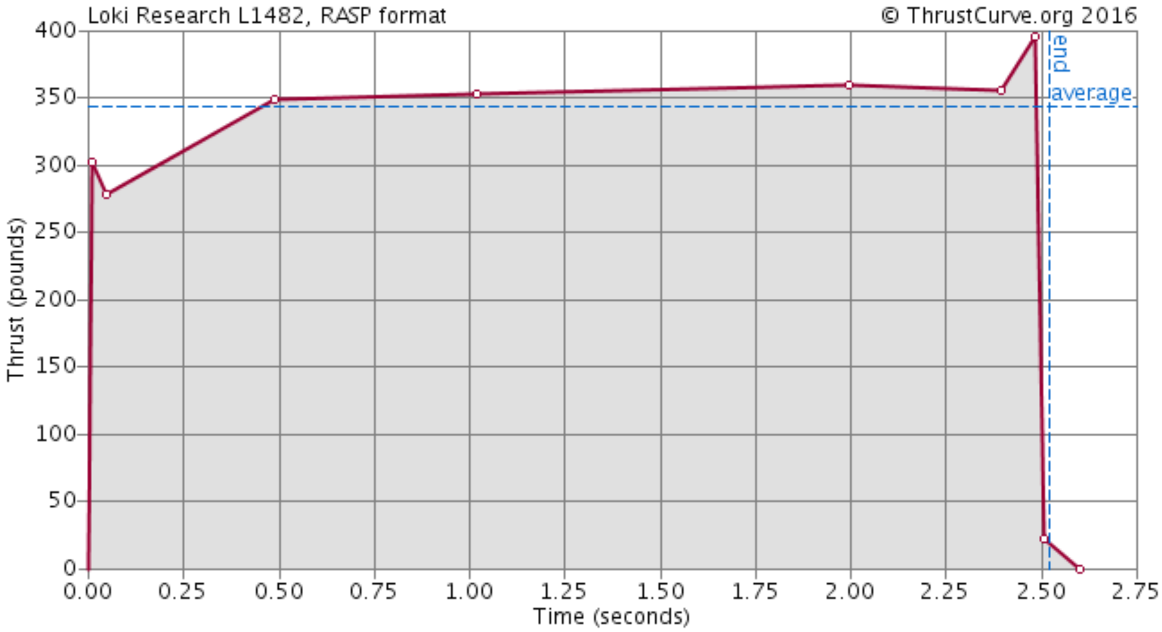


Figure 6. Thrust Curve of Loki Research L1482

This motor selection predicts the launch vehicle will hit apogee at an altitude of 5525 ft for the Loki L840CT and an apogee of 5612 ft for the Loki L1482. Though these altitudes are higher than the target altitude, it is within range that can be accounted for by changes in weight or aerodynamic qualities prior to launch. The most important factor that will decrease the high is the roll induction. Simulations for this will occur shortly after the proposal is finished. The cheaper motors will also allow for cheaper test launches.

4.2.5 Recovery System

4.2.5.1 Recovery System Overview

The recovery system for the proposed launch vehicle will consist of two recovery devices, a drogue parachute to be deployed at apogee and a main parachute to be deployed at 600 ft AGL. Each parachute will be of nylon construction and purchased from commercial suppliers to ensure quality and reliability. The recovery devices will be tethered to the airframe by tubular nylon shock chords and anchored to the avionics bay of the vehicle via steel eyebolts. Deployment of the parachutes will be controlled by a commercial *Raven v3* altimeter which ignites a black powder charge for each parachute, and Nomex cloth will be used to protect the shock cords and parachutes from these charges.

For redundancy this system will be repeated in the vehicle, resulting in two independent *Raven* altimeters, each with its own pyrotechnic charges. The avionics bay will contain both altimeters, providing electromagnetic and physical shielding from the rest of the vehicle components. The avionics bay will have a modular design that was first developed last year by the Notre Dame Rocketry Team and is called the Compact Removable Avionics Module (CRAM). A more detailed explanation of the CRAM is found further in this document. Each of the parachute bays is kept closed during ascent through the use of shear pins, which will shear upon the ignition of the ejection charges.

4.2.5.2 Altimeters

The Featherweight *Raven* will be used as both the primary and redundant controller for ejection charges. The *Raven* allows for up to four deployment events (although only two will be used), and has brownout protection in case of loss of power during flight. The *Raven* uses a pressure sensor at 20 Hz to measure the external barometric pressure, allowing determination of altitude. The altimeter calculates the point of zero velocity of the rocket to determine apogee of the flight. The *Raven* will be programmed to deploy the main drogue parachute at apogee, and the main parachute at 600 feet. Each altimeter is armed by its own switch which will be accessible from the outside of the rocket. The switches will be locked in the “on” position prior to launch. Specifications of the *Raven* altimeter are shown below in Table 8.

Table 8. Specifications of Featherweight Raven 3 Altimeter

Power Source	9V Battery
Maximum Altitude	100,000 ft
Altitude Resolution	0.00004 atm

Sample Rate	20 Hz
Dimensions	0.8" x 1.8" x 0.5"
Weight	6.6 grams
Apogee Detection Method	Zero Vertical Velocity
Drogue Charge (Primary) at:	Apogee
Drogue Charge (Secondary) at:	Apogee + 1 second
Main Charge (Primary) at:	600 feet altitude
Main Charge (Secondary) at:	550 feet altitude

4.2.5.3 Electrical Protection

The two altimeters have separate dedicated batteries, securely fastened in the electronics bay. The altimeter circuits will be independent except for a connection to ground, where each negative pole of the batteries will be connected to, as well as any other electronic components of the rocket. Copper plated shielding components will completing encapsulate the altimeters and will also be grounded to increase the shielding efficiency. A stranded gauge 16 copper wire will run through the tubular shock chords to connect the ground of each section of the vehicle. Extra precautions will be taken when designing components and assembling the vehicle to ensure no electrical shorts can happen by electric components touching another grounded structure.

4.2.5.4 CRAM:

The Compact Removable Avionics Module (CRAM) was first conceived last year as an alternative to the traditional avionics bay constructed out of a coupler tube with bulkheads on each end. The CRAM has the same capabilities as the traditional avionics bay, yet dramatically reduces space needed and weight, as well as increasing the vehicle structural integrity.

The CRAM is essentially a cylinder of the diameter of a coupler tube but only has a length of two inches. The top and bottom of the module have plywood bulkheads similar to those on the ends of the coupler in a traditional design. Ejection charges are mounted on the bulkheads in the same way. Instead of two body tube sections being attached on the ends of the coupler based bay, the CRAM is inserted into one single body tube, which is in turn split into two sections for the two parachute bays. Figure 7 shows a diagram comparing the traditional coupler design and the CRAM concept.

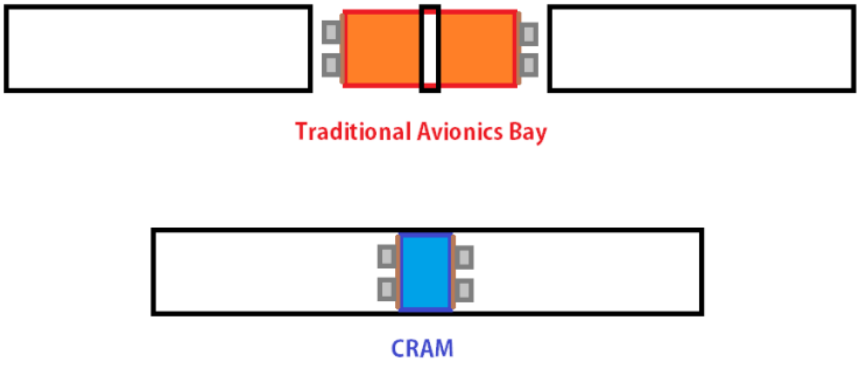


Figure 7. Traditional avionics bay coupler compared to the CRAM

The CRAM is attached to the body tube by screwing into a 3D printed coupling inside, by being first inserted and then spun 90 degrees to a position where the coupling holds it in place, similar to the screw lid of a jar. In addition the module is locked to keep from spinning by a metal screw perpendicular to the body wall. The coupling design allows for the load path of the parachutes to be dissipated onto the airframe body tube. Figure 8 presents this concept by illustrating the diagram of a cut section of the CRAM and the coupling mechanism.

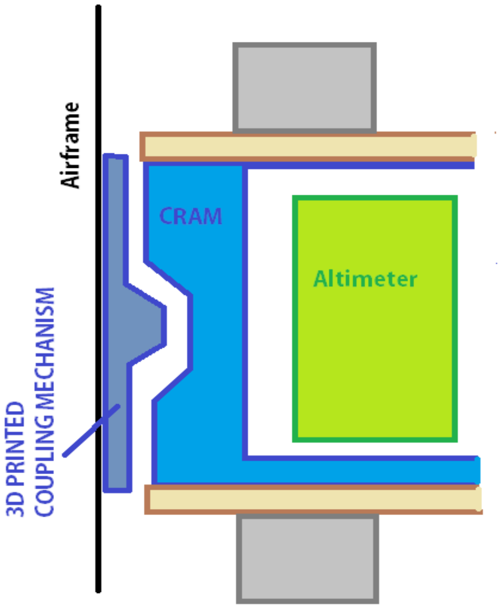


Figure 8. CRAM Cut Section Diagram

The body of the CRAM is 3D printed and thus has dedicated compartments on the inside for each component (altimeters, batteries, etc.) This concept was proved successful with the first and second versions of the CRAM, which were tested in flight over the last two years. Version 3 of the CRAM will improve on the minor shortcomings of the previous two versions by better protecting the core from black powder exposure and refining the geometry to further minimize size without compromising robustness. Figure 9 shows a CAD model of the general form and features of the CRAM.

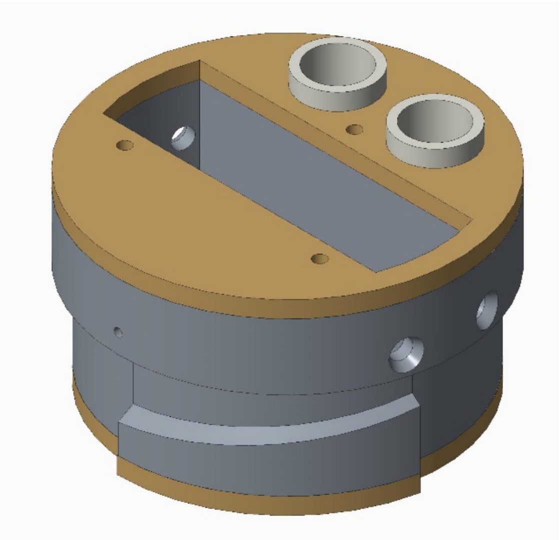


Figure 9. Preliminary CRAM v3 design intent

4.2.5.5 Ejection Charge Testing

Manufacturer data specifies that each 4-40 nylon shear pin will break upon application of 40 pounds of force. As three pins will be used to prevent out-of-sequence separation, at least 120 pounds of force will be needed to separate each rocket section. To provide a factor of safety, 150 lbs of force will be generated.

FFFFg black powder will be used for the ejection charges. Based on the volume of the parachute bay, RocketryTools predicts that 2.3 grams of black powder would provide 150 lbs. of force to eject the main parachute. For the drogue parachute, RocketryTools predicted 1.3 grams of black powder will produce the same amount of force.

Tests of the black powder's effectiveness will take place prior to any subscale or full launches. Representative body tube sections will be connected by shear pins, and charges will be wired in their flight configuration. The charges will then be ignited to ensure that enough force is generated to separate the rocket.

4.2.5.6 Electronics Testing

The *Raven* altimeters have the capability of running full flight simulations, which test the onboard components and the ejection charge outputs. These simulations will be run with light bulbs instead of electronic matches. Ground tests will be run for full electrical circuits of the recovery system.

4.2.5.7 Kinetic Energy at Landing

The statement of work limits the kinetic energy at landing of each independent section to 75 ft-lbs. The size of the main parachute will be selected as a function of the terminal decent velocity of the vehicle and the vehicle's mass. Therefore the use of the appropriate parachute will ensure the kinetic energy at landing of each section is less than 75 ft-lbs.

Two different methods will be used to calculate the descent velocity. The OpenRocket software package will be used as one of them, in which the software will estimate the descent velocity based on the parachute information inputted. The second method, used for redundancy, will take a more direct approach by using the coefficient of drag of the parachute (provided by the manufacturer) to determine the terminal velocity. Such calculations will be carried out by utilizing a custom Matlab Program. The preliminary values for the parachute sizes will be first submitted in the PDR document.

4.2.6 Integration

4.2.6.1 Recovery System Integration

The recovery payload will be located in the recovery section (section 2) of the rocket. Couplers will connect the recovery section to sections 1 and 3 of the rocket. Shear pins will hold the sections together until the ignition of ejection charges in the avionics module causes the desired sections to separate for deployment of the drogue or main parachute. The recovery section will house the drogue and main parachutes in addition to the Compact Removable Avionics Module (CRAM). The CRAM will be located in the middle of the section with the drogue parachute on one side and the main parachute on the other. Both parachutes will be attached via shock cord to a 1500lb-rated eye bolt on either side of the CRAM. The quick links connecting the shock cords to the parachutes are rated for 2000lb. These specifications have been used successfully in past years. The CRAM itself will attach to the rocket by screwing into a 3D printed coupling inside of the recovery section of the rocket. Additionally, the CRAM will be held in place via a screw perpendicular to the rocket body so as to prevent spinning and/or detachment of the CRAM from the airframe. The Recovery System is discussed more in Section 4.2.5 above.

4.2.6.2 Payload Integration

4.2.6.2.1 Roll Control System

The roll induction payload will utilize smaller carbon fins separate from the main fins attached to the bottom of the rocket. These smaller fins will be placed aft of the post-burnout center of gravity, spaced radially around the body of the rocket. They will be attached to the servo motor using steel connecting rods and bevel gears. The payload will be housed in a 12-inch coupler and positioned at the forward end of the fin can. A bulkhead will be placed at the top of the coupler to hold the payload secure. Four steel rods will run through the fin can and payload, parallel to the center axis of the rocket.

Nuts on the steel rods will hold the bulkhead in place, keeping the payload secure. The payload will be separated into multiple compartment bays that encase different components, such as the batteries, arduino, and servo motor. For the compartments, 3D printed ABS plastic will be used. These compartments are non-structural and will only be used to separate payload components. ABS plastic was chosen because it is accessible, inexpensive, and works with the 3D printers that will be used. 3D printing the compartments will help reduce the size and weight of the payload. It will also ease loading, modifying, and unloading the payload.

4.2.6.2.2 Fragile Object Protection System

The fragile materials payload will be located in the first section of the rocket, directly beneath the nose cone. The payload will be able to be moved in and out of the launch vehicle because it will be housed in a coupler. The object provided on launch day will be contained and protected by a concentric cylinder design. The inner cylinder will be just large enough to contain the largest possible object. This cylinder will be suspended in the larger cylinder by a series of springs, which are responsible for reducing most of the impulses imparted to the fragile material payload. In order to hold the object still within the first cylinder, it will be suspended in a viscous fluid that is able to evenly support the mass of the object.

4.2.6.3 Motor Integration

The propulsion system will be held in place by the motor mount, which is located in the fin can of the rocket. The motor retention system is primarily concerned with keeping the motor secure in the body tube during burnout and during descent.

The motor mount will be held securely to the fin can by three centering rings and a bulkhead on the upper end of the motor mount. The motor mount and fin can will be made out of carbon fiber tubing, while the centering rings and bulkhead will be made out of fiberglass, due to cost. The motor mount and centering rings will be attached to one another and to the fin can by epoxy that will the keep the motor and its casing components in place during flight. The centering rings provide extra stability by preventing the motor from gimballing and ensure a straight and stable flight path.

There will also be two screws, offset 180 degrees from each other, screwed into the furthest aft centering ring. Using washers, they will secure the aft lip of the motor so that during descent, the motor casing does not fall out of the motor mount and become a hazard on the launch site. These screws will be secured using JB Weld to ensure that the screws remain stable and can withstand high temperatures experienced during burnout. This method of retention has been used in previous years by the Notre Dame Rocketry Team and there is high confidence in the success of this method.

4.2.7 Construction Methods

Regarding the construction methods, the team will use many of the same methods used as the previous years while trying to improve upon the established system. In order to make these improvements we will discuss the presented construction methods with our Michiana Rocketry advisor. All of the necessary components including body tube materials, fin materials, recovery material and payload materials will be purchased to be used for construction and ensure the material's quality. The followings details what the intended construction methods will be.

The rocket will be constructed in segments and then assembled. This will be done in order to establish a focus on each component of the rocket to ensure that each individual component works without interfering with the other components. This then requires special attention to the assembly of the launch vehicle and to the construction of the rocket body in order to ensure the structural stability of the launch vehicle. Thus the sections of the body tube will be specifically ensured to be the same size and all stationary components of the rocket will be adhered or bolted together and the parts of the rocket that will come apart in decent will be sheer pinned together and dry fitted in order to maintain structural stability during launch and flight.

The rocket materials purchased will be used to construct the body tube, couplers, motor mount, centering rings, bulkheads, fins and motor mount in cases when construction is needed. A quality control for each component will be emplaced to ensure the quality of all constructed components. This quality's basic layout is two have no less than two members work on each part. Have a third member check the work and finally have the construction co-lead check off on the construction of the component. Team members will have access to the machine shop with professional equipment and supervision in order to maintain the safety and quality of the construction.

One important facet of the structural stability of the rocket is the fin configuration. The fins will be robustly built to endure all forces experienced during flight. As such the fins will be securely adhered to the body of the rocket in order to prevent any unwanted movement. Also the wings will be blended slightly into the body with fillets either by layer of rocketpoxy or carbon fiber in order to reduce the shearing forces experienced and the fin body interface. Fin alignment will be ensured by the fin alignment mount that was constructed by the rocket team in previous years. This will ensure the stability of the rocket during flight.

After the construction of the rocket test for forces, aerodynamic capabilities and flight capabilities will be tested. Information from these tests will be used to further refine the construction of the launch vehicle. Potential changes will be discussed and carried out in accordance with attaining flight safety and design goals and discussed in further detail in subsequent documents.

4.2.8 Verification Methods

The Vehicle Sub-team has assembled the requirements aligned in the 2017 NASA Student SL Handbook and compiled the plan of verification for each requirement.

The plan and method of verification is intended to provide the Sub-team a general roadmap and give NASA SL officials an idea of how the Sub-team will proceed. The plan of verification will be expanded as the year goes by and all requirements will be verified by the Flight Readiness Review.

Table 9. Verification Plan and Methods

REQUIREMENTS	PLAN OF VERIFICATION	METHOD OF VERIFICATIONS
The launch vehicle will hit an apogee of 5280 feet	- Calculations using physical principles will be performed to estimate apogee using a coded program - Software simulations will be performed to verify apogee calculations - Full Scale Test will verify that the fully-built vehicle will reach target altitude	OpenRocket RockSim In-house program that utilizes Physics equations Full Scale Test
The launch vehicle shall carry one commercially available, barometric altimeter	- Inspection: the recovery sub-team lead will ensure that an altimeter is on the vehicle	Quality
The launch vehicle shall be recoverable and reusable	- Through the full-scale test, the team will recover the rocket and confirm that it is reusable	Full Scale Test
All recovery electronics shall be powered by commercially available batteries	- By inspection, the recovery lead will ensure that new batteries are provided for each launch	Inspection Full Scale Test
The launch shall be limited to a single stage and four (4) independent sections	- By inspection, the team shall be able to verify that the vehicle is a single-stage. - By the full-scale test launch, the team shall confirm that the vehicle has 3 sections	Inspection Full Scale Test
The launch vehicle shall be capable of being prepared for launch in 4 hours	- The team will prepare the vehicle in 4 hours during the full scale test.	Full Scale Test
The launch vehicle shall be launched using a 12 volt direct firing system	- In the full-scale test launch, the team will use a 12 volt firing system.	Full Scale Test

The launch vehicle shall require no special ground equipment to initiate launch	- By the full-scale test, the team will launch with no special ground equipment.	Full Scale Test
The launch vehicle shall use a commercially available motor	- The team will use either Aerotech or Loki for a motor. This will be demonstrated on the CDR.	Inspection of NAR and TRA approved motors Full Scale Test
The minimum velocity off the rail shall not be below 52 ft/s	- Using OpenRocket and RockSim simulation, the team will confirm that the minimum velocity off the rail will not be below 52 fps. Through the full-scale test, the team will verify that the velocity is not below 52 fps.	OpenRocket and RockSim Full Scale Test
The team shall launch and recover a subscale	- Through the subscale test, the team will launch and recover a subscale prior to the design of the Full Scale.	Subscale Test
The launch vehicle shall have a static stability of at least 2.0 at rail exit	- Verified by simulation - Before the Full Scale or Subscale tests, procedures shall be followed to ensure the center of gravity is where it should be.	OpenRocket and RockSim Full Scale Test Subscale Test
The launch vehicle shall have a sufficient thrust-to-weight ratio to achieve required apogee.	- The team will calculate the thrust-to-weight ratio using predicted weights. - Through the full-scale test, the thrust-to-weight ratio will be measure and the team will verify it is sufficient.	Calculations Full Scale Test

4.2.9 Vehicle Test Plan

Table 10. Vehicle Test Plan

TIME PERIOD OF TEST	TEST	PURPOSE OF TEST
October 2016	FEM Analysis	To analyze load paths and stresses in order to re-inforce effectively
November 20, 2016	Subscale Test	To verify simulations performed in OpenRocket and RockSim and utilize correction factors where applicable
November 2016	Material Stress Test	To verify the strength and stress properties of chosen material
November 2016	CFD analysis	To calculate the coefficient of drag

		To finalize fin design To attain a more refined calculation of altitude
December 2016	Wind Tunnel Analysis	To verify drag estimates during normal flight and during roll. To attain final calculation of apogee.
January 2017	Full Scale Test	To verify simulations performed in OpenRocket and RockSim To verify the requirements in Section 2.2.8.1
February 2017	2nd/Back-up Full Scale Test	To verify the requirements in Section 2.2.8.1 To test features added for safety and efficiency post-CDR

4.3 Payloads

4.3.1 Roll Control Payload

4.3.1.1 Payload Overview

The purpose of the Roll Control Payload is to perform an aerodynamic analysis experiment to control and measure the induced roll and counter-roll of the rocket after burnout and before apogee. The goal is to create axial roll in the rocket after burnout occurs, and after two full rotations are experienced and measured, counter-roll will then be induced to bring the rotation to a halt. This roll will be achieved by fins located fore of the main fins and aft of the post-burnout center of gravity to ensure stability. A servomotor with a bevel gear system will control all four fins, and will have precision position functionality to accurately turn the fins in order to induce the roll. The rotation of the rocket will be measured through an Altitude and Heading Reference System (AHRS) and Inertial Measurement Unit (IMU) sensor. This data, through an Arduino, will be analyzed and then used to control the servomotor.

4.3.1.2 Design Criteria

To ensure the payload will achieve these goals, six key design criteria have been determined.

1. Vehicle Stability: Any actuation (or failure) of the control mechanism must not have a negative effect on the overall stability of the vehicle. This criterion will be forefront in the design process.
2. Vehicle Integrity: The presence of this payload in the rocket must not compromise the structural integrity of the rocket. Adjustments to the body of the rocket must be limited in order to prevent shearing.
3. Speed: The fins must act as fast as possible. A high sampling rate for altitude and acceleration data is necessary, as well as quick actuation of the mechanism. Computational and mechanical delays must be kept to a minimum.
4. Accuracy: The algorithms employed by the onboard processor must be as accurate to minimize error. The control mechanism construction must be precise to ensure consistency in fin actuation.

5. Calibration: Because the controller is not a true closed-loop system, the drag coefficient of the unchanged rocket and the rocket with fins must be accurately calculated.
6. Simplicity: The design will benefit from being simple, both mechanically and computationally. Simplicity reduces opportunities for failure, and increases the chances of successful design and implementation.

4.3.1.3 Physical Implementation

Four small, controllable fins will be equally spaced radially around the body of the rocket. The fins will be located aft of the post-burnout center of gravity and forward of the main fins. The fins will be connected to a central bevel gearbox inside the rocket body, allowing them to be controlled together through the motion of a single, high-torque servo. The servo will allow for a continuous range of motion for the fins. The shafts and gears will be made of steel, the fins will be carbon fiber, and the frame will be 3D-printed PLA or ABS plastic.

4.3.1.4 Electronic Components

An Arduino microcontroller will be used to control the adjustable secondary fins of the rocket, providing the ability for the rocket to roll in either a clockwise or counterclockwise motion. The controller will interface with an accelerometer and altimeter for rotational data and height measurements. Using these readings, the Arduino will do all of the calculations necessary for roll control. A motor connected to the adjustable fins by metal rods will be regulated by the Arduino control algorithm and is the component responsible for physically adjusting the fins.

4.3.1.5 Roll Control Payload Control Algorithm

The control system will activate immediately after burnout, which will be detected by the onboard accelerometer. At this point the control system will begin to induce roll, and the gyroscope will be used to track the number of revolutions completed. Once two full revolutions have been completed, the control system will halt the rocket's roll, again depending on gyroscopic data for verification. As the system's ability to control roll depends on airflow over the fins, control authority will decrease as velocity decreases, so it is critical that the system completes its roll / counter-roll operation as quickly as possible after burnout.

4.3.2 Fragile Object Protection Payload

4.3.2.1 Payload Overview

The purpose of the Fragile Object Protection Payload is to protect an unknown fragile object during all stages of flight – from launch through recovery of the rocket. Nothing is known about the object(s) except for maximum dimensions and weight. The payload will consist of a mostly hollow section of the rocket, filled only with a separate inner cylinder, which is held by springs attached to the inner wall of the coupler that represents the exterior of the payload. The springs will be designed so as to absorb most of the acceleration experienced during takeoff and landing. Inside of the aforementioned inner cylinder will be a viscous fluid, in order to suspend the fragile object uniformly, while still allowing for limited movement at high impulses and ensure its safety during flight. With the combination of the springs and viscous fluid, the fragile object will be kept unbroken and undamaged throughout all stages of the rocket's flight.

4.3.2.2 Design Criteria

To ensure the payload achieves these goals, the following key design criteria have been determined:

1. Versatility: This is the most important design requirement, as the payload must be designed to be able to protect a wide scope of potential fragile objects. To be successful, it must be robust enough to protect any given shape or size within the maximum dimensions.
2. Vehicle Stability: The payload and must be designed in conjunction with the body so that any movement of mass in the Fragile object protection does not cause the rocket to enter a state where the stability margin is not sufficient for stable flow.
3. Simplicity: The more complex a design, the more liable it is to fail when put to the test. Therefore, our design will benefit from staying as simple as a series of springs and an enclosure of viscous fluid.
4. Calibration: It will be essential that proper spring constants are chosen so as to allow for sufficient movement to dissipate the rocket acceleration while not requiring greater displacement than is allowed by the overall dimensions of the payload.
5. Strength: Due to the fact that this payload will purposefully allowing for vibration of its components, it is imperative that the connections of all pertinent spring connections are robust enough to handle all the applied forces caused by normal rocket vibration, as well as the payload vibration.

4.3.2.3 Viscous Fluid Implementation

If versatility in design for a known payload is important, then versatility in design for an unknown payload is indispensable. Unlike a mechanically dependent design, a viscous fluid has the versatility to form a unique mold around any object, so the utilization of a viscous fluid for payload protection allows a greater scope of protectable shapes. There are two types of viscous fluids that will be considered for the fragile object's design: shear thickening fluids or Newtonian fluids. Shear thickening fluids increase their viscosity, sometimes to a quasi-solid state, when exposed to intense forces, such as the acceleration due to takeoff. An example of a shear thickening fluid is "Oobleck," a quicksand-like mixture of cornstarch and water. Conversely, the viscosity Newtonian fluids always remain constant, regardless of the forces applied to it. An example of a Newtonian fluid is corn syrup. In addition to the versatility of a fluid to mold to an object, if a fluid with an appropriate viscosity is chosen, the object can stay suspended in the fluid under constant gravitational acceleration. This ensures that the object does not settle to the bottom of the inner cylinder while on the launch pad before ignition.

4.3.2.4 Spring Implementation

The internal apparatus of the protection mechanism will be held within a rigid casing. This casing will be attached to the fuselage via springs mounted on all sides. The springs on the top and bottom will serve to oppose the displacement of the internal apparatus during vertical acceleration and deceleration such as during takeoff, motor burnout, and main parachute deployment. The springs on the sides of the inner cylinder will serve to balance the horizontal shifting that may occur, most notably during landing. Overall, the springs provide a buffer for the internal apparatus so that high g-forces will not be transmitted to the fragile object. This will reduce the likelihood of the object, from experiencing dangerous levels of acceleration.

5 Educational Engagement

5.1 Educational Projects

The Notre Dame Rocketry team plans to engage the community in multiple events throughout the year and promote interest in science, technology, engineering, and math among local younger students. The team plans to engage in three types of events, including larger science fair events and group presentations, and smaller, more engaging lessons. For the first of these categories, we plan to team up with the St. Joseph County Library, Society of Women Engineers, the Notre Dame College of Engineering, and several other organizations. The latter event category is going to be our main form of educational outreach, as smaller workshops allow for the team members to work one-on-one with students and more successfully engage the students in the material through hands on activities, quiz competitions, and more. For these events, the team is already working the Notre Dame College Mentors for Kids, The Boys and Girls Club of South Bend, the Riley High School TARC team, and a few local schools. The team has an educational outreach lead, who is in charge of organizing these various events throughout the year. In the past, NDRT has had a rather successful educational outreach program, and the team hopes to build upon this success this year through more intensive outreach programs.

5.2 Lesson / Program Plans

For smaller events, we have developed several lesson and activity plans that can be adjusted for various age groups and program lengths. The team hopes to combine some of these events into a series, to better engage the students and create a more meaningful connection with them. Some of the specific programs are explained in more detail below.

Can it fly?

This lesson introduces the students to the history of flight and space flight, focusing specifically on the earliest concepts of rocketry, before walking the students through a modified engineering design process where they can create and test their own rocket design in OpenRocket.

Physics is Phun
This lesson covers some of the fundamental lessons of physics, including Newton's laws, stability, and general aerodynamics and allows students to utilize them in the building and launching of their own paper rockets.

Rocketry 101 Curriculum
This group of 5 lessons cover the basics of rocketry for middle school aged students, ending in the launch of their own group Estes rocket. The first day introduces students to the history of aerospace and the U.S. space program as well as giving them an introduction to rocketry and some of the basic physics principles that we will be using, ending with a fun quiz game over some of the new concepts. The second day uses Newton's third law of motion to describe the concept of stability and include a paper rocket building activity, which focuses heavily on fin design. On this day, each group will also receive an Estes rocket and will begin the process of assembly. The third day focuses on altitude. The students will learn a simplified formula to determine rocket apogee and will create basic altitude measurement devices, which utilize the basics of trigonometry to measure the height of objects in the room. This activity will help them to measure the altitude of their rockets on launch day. The fourth lesson covers the basics of rocket recovery and gives the students the chance to attach parachutes to their team's rocket. The final day of the curriculum is split into two portions. The first half covers rocket launch safety, and the second half includes the rocket launches. After this final day, the groups will regroup to access the success of their rockets and reflect on everything they learned. This full curriculum will hopefully give the students a sense of the design process engineers go through.

What is engineering?
This year, we are lucky to have engineering majors from multiple disciplines on the team. For older students, especially those in high school, we have planned a program to introduce them to engineering and what various types of engineers do. It will include a brief presentation and group activity, followed by a Q&A session. We hope to visit multiple schools with this program.

5.3 Science Alive!

NDRT hopes to partner with the St. Joseph County Library again this year for the Science Alive! Fair. This annual event invites different hobby groups and organizations to show local students aspects of real world science. For the fifth year in a row, Notre Dame will have a table set up to display its rocket and exhibit the exciting world of rocketry. In addition to posters explaining the project, several interactive demonstrations are planned. Students will be able to see the proper way to pack a parachute, as well as the effect of drag on a body. Model rockets will help show the importance of rocket stability. The team will also bring pictures and videos from their first test flights. Last year, attendance at the event topped 1,000 people.

6 Project Plan

6.1 Development Schedule

Following a detailed schedule will be crucial to mission success. To organize tasks and ensure deadlines are met, the timeline shown below in Figure 6 has been created.

September 2015	
30	Proposal Submitted
October 2015	
14	Subscale Construction Completed
31	PDR Submitted
November 2015	
19-20	Subscale Test Flight
2-18	PDR Presentation
December 2015	
2	Roll Control System Finished
7	Full scale Rocket Construction Finished
10	Test Flight 1 – Full Scale Rocket
January 2016	
13	CDR Submitted
17-31	CDR Presentation
21	Test Flight 3 – Full Scale Contest Rocket
February 2016	
TBD	“Science Alive!” (Educational Engagement)
18	Test Flight 4 – Pre-Contest Launch
March 2016	
6	FRR Submitted
8-24	FRR Presentation
April 2016	
5	Travel to Huntsville, AL
5	LRR
6	Safety Briefing
7	Rocket Fair & MSFC Tours
8	Launch day
8	Banquet
8	Backup launch day
24	PLAR Submitted

Figure 10. Key deadlines for project success

6.2 Budget and Funding Plan

Budget

Table 10 analyzes the projected budget for 2015-2016.

Table 11. Projected 2016 - 2017 budget

Structure	$1,783.32
Recovery	$973.00
Roll Control Payload	$700.00
Fragile Object Protection Payload	$400.00
Propulsion	$1005.00
Miscellaneous	$238.00
Rocket Subtotal	$5,098.85
Subscale Rocket Subtotal	$266.00
Outreach	$250.00
Travel	$6,332.00
Total Project Cost	$11,946.85

The cost for the rocket this year can be explained as follows:

- Structure: The structures costs are made up of the construction materials of the main launch vehicle itself
- Recovery: The recovery costs include purchasing new parachutes and altimeters due to damage sustained to prior recovery systems.
- Roll Control Payload: The costs associated with this system include the construction of the payload, an accelerometer, an Arduino, and an electric motor, in addition to electrical equipment necessary to run the system.
- Fragile Object Protection Payload: These costs are directly tied to the construction materials necessary to build the payload.
- Propulsion: The budget for the propulsion section consists of 3 full scale engines to be used in different test flights throughout the year.
- Miscellaneous costs: Miscellaneous costs include building materials such as epoxy, resin, and JB Weld.

Funding

Funding will be drawn from a general account dedicated to aerospace design projects at Notre Dame. Support for this fund comes from a wide variety of sources, including the College of Engineering, the Department of Aerospace and Mechanical Engineering, and generous donors. The fund is replenished each year as necessary.

Additionally, the team is working on securing sponsorships from several different aerospace companies. The Boeing Company has already given a large sponsorship to augment the funding we receive from the University.

6.3 Community Support

Notre Dame has reached out to Michiana Rocketry, the local TRA club, for support and expertise. The club response has been overwhelmingly enthusiastic. Several club members have volunteered time and advice to the team. Helpful suggestions of vendors, supplies, and services have been invaluable to the team. In many ways, members of the club have all been team mentors.

6.4 Sustainability

Several measures are in place in order to ensure that NDRT (Notre Dame Rocketry Team) is successful this season and will continue to do so in subsequent years.

Through Educational Outreach events, the NDRT continues to increase its influence in the local South Bend community. This helps the team gain the community and university support needed for current and future success. In addition, as the team gains more exposure, it becomes easier to recruit and to gain sponsorships. The events referenced here-in are detailed in Section 5.

The team has additionally created the Corporate Sponsorship Committee, whose purpose is to expose the team to possible corporate sponsors. Within less than a year in existence, the team has gained USD 10,000 from a small company in Washington. Growing relationships with sponsors is thus an important aspect of the sustainability.

Furthermore, the team has a Recruiting Committee, whose purpose is to expose the team to the rest of the University. The team has emphasized that anyone, from any college, from any major can join. Indeed, for the year 2016-17 the team has grown its size from 33 members to 45+ members. Not all of these are mechanical engineers or aerospace engineers. Some are Physics majors, electrical engineers and computer scientists.

In order to consolidate the resources for incoming teams, the team has a **Box** account that archives previous designs and reports. Each year’s team has access to this account and can learn from previous mistakes and successes. This ensures that the next year’s team does not have to start from scratch but can have a reference while doing designs.

Appendix A NAR High Power Rocket Safety Code

1. **Certification.** I will only fly high power rockets or possess high power rocket motors that are within the scope of my user certification and required licensing.
2. **Materials.** I will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass, or when necessary ductile metal, for the construction of my rocket.
3. **Motors.** I will use only certified, commercially made rocket motors, and will not tamper with these motors or use them for any purposes except those recommended by the manufacturer. I will not allow smoking, open flames, nor heat sources within 25 feet of these motors.
4. **Ignition System.** I will launch my rockets with an electrical launch system, and with electrical motor igniters that are installed in the motor only after my rocket is at the launch pad or in a designated prepping area. My launch system will have a safety interlock that is in series with the launch switch that is not installed until my rocket is ready for launch, and will use a launch switch that returns to the "off" position when released. The function of onboard energetics and firing circuits will be inhibited except when my rocket is in the launching position.
5. **Misfires.** If my rocket does not launch when I press the button of my electrical launch system, I will remove the launcher's safety interlock or disconnect its battery, and will wait 60 seconds after the last launch attempt before allowing anyone to approach the rocket.
6. **Launch Safety.** I will use a 5-second countdown before launch. I will ensure that a means is available to warn participants and spectators in the event of a problem. I will ensure that no person is closer to the launch pad than allowed by the accompanying Minimum Distance Table. When arming onboard energetics and firing circuits I will ensure that no person is at the pad except safety personnel and those required for arming and disarming operations. I will check the stability of my rocket before flight and will not fly it if it cannot be determined to be stable. When conducting a simultaneous launch of more than one high power rocket I will observe the additional requirements of NFPA 1127.
7. **Launcher.** I will launch my rocket from a stable device that provides rigid guidance until the rocket has attained a speed that ensures a stable flight, and that is pointed to within 20 degrees of vertical. If the wind speed exceeds 5 miles per hour I will use a launcher length that permits the rocket to attain a safe velocity before separation from the launcher. I will use a blast deflector to prevent the motor's exhaust from hitting the ground. I will ensure that dry grass is cleared around each launch pad in accordance with the accompanying Minimum Distance table, and will increase this distance by a factor of 1.5 and clear that area of all combustible material if the rocket motor being launched uses titanium sponge in the propellant.
8. **Size.** My rocket will not contain any combination of motors that total more than 40,960 N-sec (9208 pound-seconds) of total impulse. My rocket will not weigh

more at liftoff than one-third of the certified average thrust of the high power rocket motor(s) intended to be ignited at launch.

9. **Flight Safety.** I will not launch my rocket at targets, into clouds, near airplanes, nor on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site, and will not put any flammable or explosive payload in my rocket. I will not launch my rockets if wind speeds exceed 20 miles per hour. I will comply with Federal Aviation Administration airspace regulations when flying, and will ensure that my rocket will not exceed any applicable altitude limit in effect at that launch site.
10. **Launch Site.** I will launch my rocket outdoors, in an open area where trees, power lines, occupied buildings, and persons not involved in the launch do not present a hazard, and that is at least as large on its smallest dimension as one-half of the maximum altitude to which rockets are allowed to be flown at that site or 1500 feet, whichever is greater, or 1000 feet for rockets with a combined total impulse of less than 160 N-sec, a total liftoff weight of less than 1500 grams, and a maximum expected altitude of less than 610 meters (2000 feet).
11. **Launcher Location.** My launcher will be 1500 feet from any occupied building or from any public highway on which traffic flow exceeds 10 vehicles per hour, not including traffic flow related to the launch. It will also be no closer than the appropriate Minimum Personnel Distance from the accompanying table from any boundary of the launch site.
12. **Recovery System.** I will use a recovery system such as a parachute in my rocket so that all parts of my rocket return safely and undamaged and can be flown again, and I will use only flame-resistant or fireproof recovery system wadding in my rocket.
13. **Recovery Safety.** I will not attempt to recover my rocket from power lines, tall trees, or other dangerous places, fly it under conditions where it is likely to recover in spectator areas or outside the launch site, nor attempt to catch it as it approaches the ground.

MINIMUM DISTANCE TABLE

Installed Total Impulse (Newton-Seconds)	Equivalent High Power Motor Type	Minimum Diameter of Cleared Area (ft.)	Minimum Personnel Distance (ft.)	Minimum Personnel Distance (Complex Rocket) (ft.)
0 -- 320.00	H or smaller	50	100	200
320.01 -- 640.00	I	50	100	200
640.01 -- 1,280.00	J	50	100	200
1,280.01 -- 2,560.00	K	75	200	300

2,560.01 -- 5,120.00	L	100	300	500
5,120.01 -- 10,240.00	M	125	500	1000
10,240.01 -- 20,480.00	N	125	1000	1500
20,480.01 -- 40,960.00	O	125	1500	2000

Note: A Complex rocket is one that is multi-staged or that is propelled by two or more rocket motors

Appendix B Safety Agreement

(The following is the safety agreement that all team members have signed)

By signing below, I agree to abide by all regulations, standards and guidelines set forth by the National Association of Rocketry. I have read and understand the High Powered Rocketry Safety Code and will follow all rules outlined within the code. I am cognizant of all local, state, and federal laws regarding the regulation of airspace and handling of explosive or controlled materials.
I understand that the Huntsville Area Rocketry Association will oversee the contest launch, and I will abide by all club rules at the launch. I acknowledge that the Notre Dame rocket will be subject to range safety inspections before flight, and I will comply with the determination of the safety inspection. The Range Safety Officer has the final say on all rocket safety issues, and failure to comply with safety requirements will prohibit the team from launching its rocket.

I agree to abide by all procedures outlined by the Safety Officer of the Notre Dame Rocket Team, Team Leader, and Team Advisor when working on the NASA Student Launch project. I will use laboratory equipment and tools only when properly trained or under appropriate supervision. I will follow all Material Safety Data Sheets for materials used in design, construction, launch, and conclusion of the project.

I understand that failure to comply with anything in this safety agreement can result in my removal from the Notre Dame Rocketry Team.

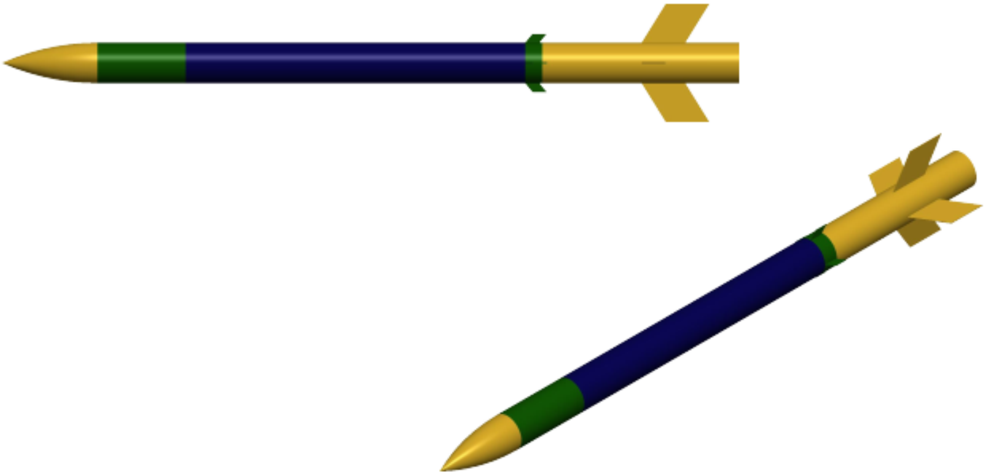
____

(Team Member Name Printed)

____

(Team Member Signature) (Date)

Appendix C Proposed Launch Vehicle



University of Notre Dame Rocket Team			Title: PROPOSAL_ROCKET_DESIGN	
Scale: 0.025	Date: Sep-25-16		Drawn By: Madison Hetlage	

Appendix D Performance Prediction Programs

Stability Program

```
import math

def CP(Ln, d, df, dr, Lt, Xp, Cr, Ct, S, Lf, R, Xr, Xb, N):
  """
      Ln : length of nose
      d  : diameter at base of nose
      df : diameter at front of transition
      dr : diameter at rear of transition
      Lt : length of transition
      Xp : distance from tip of nose to front of transition
      Cr : fin root chord
      Ct : fin tip chord
      S  : fin semispan
      Lf : length of fin mid-chord line
      R  : radius of body at aft end
      Xr : distance between fin root leading edge and fin tip
           leading edge parallel to body
      Xb : distance from nose tip to fin root chord leading edge
      N  : number of fins
  """
  # nose cone terms
  Cn_n = 2
##    Xn = .666*Ln #for cone
##    Xn = .466*Ln #for ogive

  # conical transition terms
  Cn_t = 2 * ((dr/2)**2 - (df/2)**2)
  Xt = Xp + (Lt/3) * (1 + (1-(df/dr)) / (1-(df/dr)**2))

  # fin terms
  Cn_f = (1 + (R/(S+R)) * ((4*N*(S/d)**2) / \
                     (1 + math.sqrt(1 + ((2*Lf)/(Cr+Ct))**2)))
  Xf = Xb + ((Xr*(Cr+2*Ct))/(3*(Cr+Ct))) + \
        (1/6)*((Cr+Ct)-((Cr*Ct)/(Cr+Ct)))

  # center of pressure calculation
  Cn_r = Cn_n + Cn_t + Cn_f #sum of coefficients
  CP = (Cn_n*Xn + Cn_t*Xt + Cn_f*Xf) / Cn_r #CoP d from nose tip

  return CP
```

Altitude Prediction Program

```
    impulse = 874.3
    thrust_duration = 2.6
    Ft = impulse/thrust_duration

    m = 550
    g = 9.81
    Fw = m*g

    p = 0.07835
    A = 0.458
    Cd = 0.550
    Fd = .5*p*A*Cd*v**2

    Fnet = Ft -Fw + Fd

    a = Fnet/m
    t = thrust_duration
    v = (Fnet/m)*t
    #quadratic to solve

    a = v/t
    y = .5*a*t**2

    a_f = -9.81
    a_net = a_f + (a_i-a_f)*e*-t
#integrate twice
```