University of Notre Dame

2017 - 2018

NDRT
NOTRE DAME ROCKETRY TEAM

Notre Dame Rocketry Team

Proposal for the NASA Student Launch Competition

Deployable Rover and Air Braking System Payloads

Submitted September 20, 2017

365 Fitzpatrick Hall of Engineering

Notre Dame, IN 46556

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1 Team Information

1.1 General Information

Chosen Design Experiment:	Option 2 - Deployable Rover Payload
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NAR/TRA Section:	TRA #12340, Michiana Rocketry

1.2 Team Organization

The Notre Dame Rocketry Team consists of 70 members with 25 of those being returning members and the rest being new members. All class years are represented and the grand majority are STEM majors. Because of large recruiting efforts and high interest in the payloads, the Notre Dame Rocketry Team has greatly increased in size, but maintains its goal of having everyone involved in the entire process. In order to establish organization, the team has been broken down into four technical sub-teams with the Team Captain managing these groups. The four technical sub-teams are as follows: 1) Vehicle Design; 2) Recovery Systems; 3) Deployable Rover Payload; and 4) Air Braking System. The team has also appointed three returning members to lead non-technical committees which are as follows: 1) Safety Committee; 2) Educational Engagement Committee; and 3) Corporate Sponsorship Committee. An overall organizational chart is shown in Figure 1.

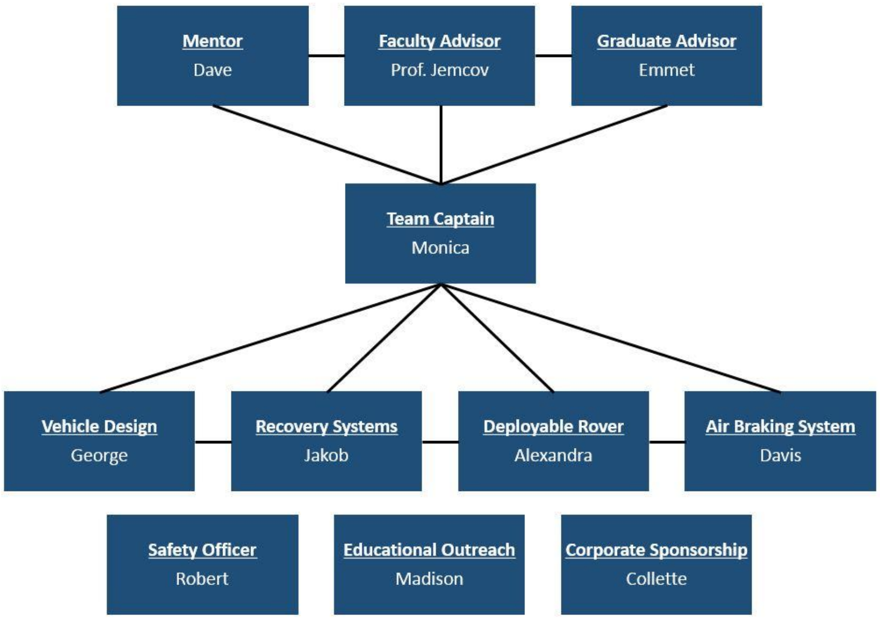


Figure 1. *Team organization chart.*

The Notre Dame Rocketry Team is confident in each lead's abilities and experience to manage a sub-team and committee. We are confident that each group will showcase successes throughout the year.

1.3 Key Member Information

Monica – Team Captain

Monica is a senior Aerospace Engineering major and is a third year member of the team. Previous to being team captain, she was on the Vehicle Design team and assisted with flight simulations while also being co-lead of the Corporate Sponsorship Committee. Due to her internship experience, Monica is intent on pursuing a career in structural analysis of space systems and hopes to receive a Master's degree along the way. She is looking forward to helping the team grow and place in the top 5 teams in this year's competition.

George – Vehicle Design Lead

George is a senior studying Aerospace Engineering, and a third year member of the rocketry team. Last year, he worked on the vehicle's design and construction and was the team's safety officer. He is very excited to lead the vehicle's design squad this year, building on his past experience with the team. George has had a passion for rocketry and spaceflight since he was very young, and dreams of pushing the frontier of space exploration. In his spare time, George enjoys playing on the Club Lacrosse team and cooking.

Jakob – Recovery Systems Lead

Jakob is the Recovery System lead for the Notre Dame Rocket Team. He has thoroughly enjoyed his three years with the team, and he has found the leadership and hands-on engineering experience to be truly invaluable. Jakob has a diverse range of engineering interests but hopes to continue with a career in biotechnology after school. Outside of classes and the rocket team, he enjoys playing soccer, travelling, and chilling with his bros.

Alexandra – Deployable Rover Payload Lead

Alex is a senior Aerospace Engineering major and is in her third year with the team. The last two years she was a member of the experimental payloads and the co-lead of the Corporate Sponsorship Committee. Alex is excited to lead the Deployable Rover Payload and hopes to use her experiences from the past two years as well as the diversity of her team to put forward a robust project. She first found her love for rocketry through Team America Rocketry Challenge in high school. Outside of school Alex competes in Irish Dance competitions across the country.

Davis – Air Braking System Lead

Davis Whitson is a senior Aerospace Engineer from Houston, TX. This is his second year on NDRT. Last year he was a member of the Vehicle Design team, and this year he is lead of the Air Braking System team. In addition to NDRT, he is a teaching assistant for the Mechanisms and Machines course and does undergraduate research for the Hypersonic Gas Dynamics Laboratory. He hopes to work in the field of engineering design of either aircraft or spacecraft. Outside of NDRT and engineering he has many interests including hiking, archery, and running.

Robert – Safety Officer

Robert is a senior physics major who plans to graduate with concentrations in applied physics, advanced physics, and astrophysics. This is his second year on the rocketry team. Last year, he worked on the vehicle's design and construction. Robert 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.

2 Facilities and 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. This is the location where weekly meetings will be held. There are several multi-purpose rooms complete with white boards, projectors and computers. The main workspace will be in room 213, which is reserved specifically for the team every Sunday. The team also has a locker to store smaller items. There is also a large storage closet in which the team will have the ability to store all major vehicle components and presentation materials.

Also available in Stinson-Remick is a standard fully equipped machine shop. This shop has various pieces of equipment useful for construction such as a laser cutter, CNC routers, band saws, a belt sander, a Dremel with several blades, a circular saw, drills, hammers, additive manufacturing machines and various other construction necessities. Trained students hold office hours every day in the workshop, which allows the team to use the equipment during those hours. The Notre Dame Rocketry Team holds safety to the highest regard and is dedicated to making sure that any team member has safe practices while performing quality work in the shop.

Stinson-Remick conveniently allows 24 hour access for all Notre Dame engineering students.

2.1.2 Fitzpatrick Hall of Engineering

Fitzpatrick Hall of Engineering houses university staff that aids the team in administrative and financial matters. Aside from that, the Hall of Engineering has several laboratories with uniaxial testing machines that will be used 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 would provide the stress and strain profiles of the materials in consideration. By performing these tests, team members will be able to make more informed decisions of what materials to use for each system.

2.1.3 Hessert Laboratory

Hessert Laboratory has the main aerodynamics lab with different size wind tunnels available for use in testing aerodynamic forces on the launch vehicle. The lab houses three open-return wind tunnels, an Environmental Wind tunnel, three tri-sonic wind tunnels and an anechoic open jet wind tunnel. These wind tunnels all have different flow velocity capabilities as well as different test section sizes. The Notre Dame Rocketry Team plans to take full advantage of said wind tunnels to analyze the flight characteristics of the launch vehicle. They will also serve to test the effect of the air braking system on the vehicle while in flight.

2.1.4 Innovation Park

Innovation Park is a facility founded by Notre Dame less than a mile away from campus. It is primarily a technology and entrepreneurship facility with different pieces of equipment. There is a 3D printer available for use that has the option to print larger parts in carbon fiber, plastic and other materials. There are various technicians onsite who can be used as resources for advice on a specific phase of construction or material choices.

2.2 Computer Programs

2.2.1 3D Modeling

PTC Creo 4.0 will be the main software used to create accurate models of the physical rocket. Models will be created for the subscale, all systems and payloads and the entire launch vehicle assembled. It is a valuable tool for determining the size, structure and integration of all rocket parts.

2.2.2 Flight Simulations

The two main programs that will be used for flight simulations are OpenRocket and RockSim. These programs have been used successfully by the team in prior years and have provided valuable analyses when used correctly. The software will estimate the apogee, drift distance, stability margin and velocities at different points during the launch. The team will use both programs simultaneously in order to verify each estimate throughout the design process.

2.2.3 Structural and Flow Simulation

The software ADINA will be used in order to calculate the structural loads on the rocket, allowing for the team to gain more information on the structural integrity of the rocket. Due to previous experiences, weaknesses in the design of the rocket is a major focus of mitigation.

For flow analyses, ANSYS will be used to simulate the flow around the rocket during flight. This will provide significant data for the flow over the body and fins that will allow more accurate calculations of the drag coefficients and reactions of an active Air Braking System. The software FinSim will also be used to provide data on the flow over the Air Braking tabs and the launch vehicle fin shapes.

2.2.4 Miscellaneous Programs and Resources

MATLAB is another software program that will be used for simulations, calculations and data analysis. Microsoft Powerpoint will be used for presentation development and conference rooms on campus will be available to use for design review presentations. All conference rooms used will have the video technology as well as broadband internet connection, speakerphones and webcams. The document preparation system Microsoft Word will be used to write all the design reports throughout the year.

The University of Notre Dame provides high speed wired and wireless networks available to all students and faculty. This will allow all team members to use email and the internet for any team-related tasks.

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

2.3 Online Presence

The team will post all documents on its web page whose link will become active in the next two weeks. The website will contain information on each sub-team, each member and all educational outreach events. It will also display a calendar with information on when the team plans to perform test launches and participate in community and educational engagement events. In addition to a website, the team is present on Facebook @ndrocket and on Twitter @NDRocketry. The team plans to update its followers through both sources of media so everyone is aware of the team's status at all milestones.

3 Safety

3.1 Team Safety Protocols

3.1.1 Materials Safety

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 Robert Stiller as the Safety Officer for the 2017-2018 year. This is Robert's second year on the team, and he has rocketry construction experience. He is a senior physics majour at Notre Dame. Robert will oversee 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. MSDS will be heavily emphasized during the 2017-2018 year. 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 mitigations.*

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 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 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, near 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 Design Requirements

- Vehicle must deliver payload(s) to an apogee of 5,280 ft above ground level
- Vehicle must contain at least one commercially available barometric altimeter
- Each altimeter will have a dedicated arming switch that is accessible from the exterior when in launching position and have its own power supply
- Each arming switch must be capable of being locked in the ON position during the launch.
- 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 3 hours
- Vehicle must be capable of remaining in launch ready configuration on pad for at least 1 hour without failure of critical components
- 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
- Pressure vessels must be approved by RSO, have a 4:1 minimum factor of safety, and have a pressure relief valve capable of withstanding maximum flow rate and pressure of the tank
- Total impulse must be 5,120 Ns or less
- 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
- If payload changes the external surfaces of rocket, those system must be active during demonstration
- Additional ballast may not be added without a retesting the launch
- Any structural protuberance on vehicle will be located aft of the burnout center of gravity
- Vehicle ballast will not be greater than 10% of the total weight of the vehicle.
- Vehicles must not
    - Utilize forward canards
    - Utilize forward firing motors
    - Utilize friction fitting for motors
    - Utilize motors that expel titanium sponges
    - Utilize hybrid motors
    - Exceed Mach 1 at any point

4.1.2 Recovery System Requirements

- The launch vehicle is to be equipped with a recovery system that deploys a drogue parachute at apogee and a main parachute at lower altitudes
- Prior to both initial subscale and full-scale launches, the team is required to perform a successful test ejection for both drogue and main parachutes
- Following the recovery process, no independent section of the launch vehicle is to have exceeded a maximum energy of 75 ft-lbf
- All recovery electrical circuits are to be independent of all payload electrical circuits
- The recovery system is to include redundant, commercially available altimeters and be powered by commercially available batteries
- In terms of deployment, motor ejection is not permissible
- Removable shear pins are to be used for both the drogue and main parachute compartments
- The recovery area is limited to a 2500 ft. radius from the launch pad
- An electronic tracking device is to be installed in the launch vehicle in order to transmit the position of any tethered vehicle or section of the vehicle back to a ground receiver

- Any section of the vehicle or payload component that lands untethered to the launch vehicle must have an active electronic tracking device
    - All of these devices must be fully functional on the day of the official launch
- Recovery system electronics must not be adversely affected by other electrical devices on board during the flight (which includes launch and landing)
- Altimeters for the recovery system must be physically housed in a separate compartment from other radio frequency transmitting devices or magnetic wave producing devices
    - Recovery system electronics must be properly shielded from potentially impeding devices

4.1.3 Deployable Rover Payload Requirements

- The team will design a custom rover that will deploy from the internal structure of the launch vehicle.
- At landing, the team will remotely activate a trigger to deploy the trover from the rocket.
- After deployment, the rover will autonomously move at least 5ft. (in any direction) from the launch vehicle.
- Once the rover has reached its final destination, it will deploy a set of foldable solar cell panels.

4.1.4 Air Braking System Payload Requirements

- The team will design a system that will decelerate the rocket, placing apogee at 5280 feet.
    - The system must not create additional moments or instabilities on the rocket.
    - The system must not generate additional thrust along the direction of flight.
    - The system must use a control surface to induce drag.
    - The control surfaces must be aft of the post-motor burnout center of gravity.
    - The system must not operate during motor burn.
    - The system must be controlled by an onboard flight computer.

4.2 Vehicle Design

4.2.1 Vehicle Description

The design of the launch vehicle is aimed towards giving the Rover Payload the maximum amount of space possible while at the same time keeping the overall weight of the rocket at a minimum. Therefore, a larger diameter of 7.5 inches was chosen for the Rover Payload Bay, and the rest of the rocket will have a smaller 5.5 inch diameter. A general, preliminary CAD representation of the vehicle can be found in Appendix C.

The projected vehicle dimensions are shown below in Table 3.

4.2.1.1 Vehicle Dimensions

Table 3. *Projected Vehicle Dimensions and Characteristics.*

Characteristic	Dimension
Length of Rocket (in)	124
Fore Diameter of Rocket (in)	7.5
Aft Diameter of Rocket (in)	5.5
Transition Length (in)	4
Number of Fins	4
Fin Root Chord (in)	7
Fin Tip Chord (in)	7
Fin Sweep Angle (°)	31.6
Fin Height (in) (Main / Payload)	7.2
CG Position from Nose Cone (with motor) (in)	75.92
Weight without Motor (lbs)	36.63
Weight with Motor (lbs)	44.38
Estimated Stability Margin without Motor	4

Estimated Stability Margin with Motor	2.92

4.2.1.2 Vehicle Layout

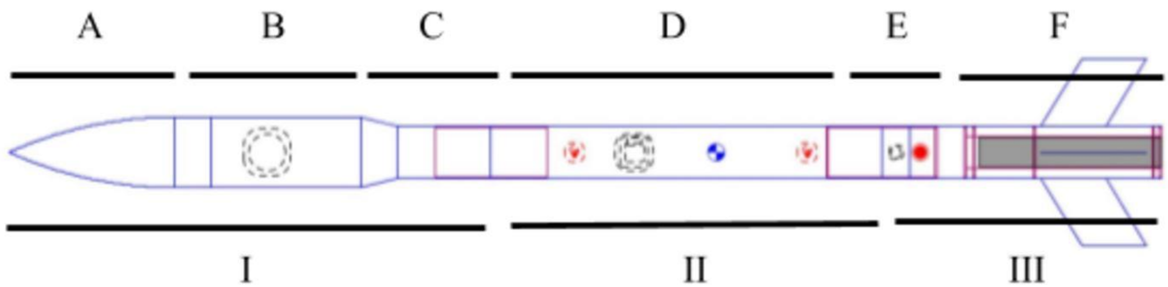


Figure 2. *Vehicle Design Layout (Side View Shown).*

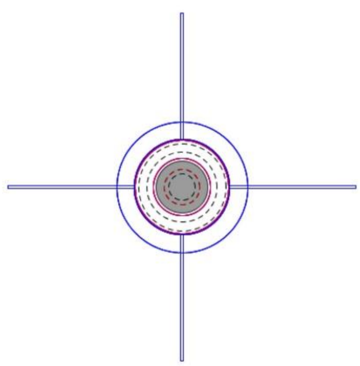


Figure 3. *Vehicle Design Layout (Back View Shown).*

Table 4. *Design Layout.*

Section	Sub-Section	Label	Composed Of	Description
	Nose Cone	A	Hollow ogive shaped nose cone made of PVC	Connected to the rover payload bay (B) and measures 17.7 inches in length and 7.5 inches in diameter
	Rover Payload Bay	B	Fiberglass body tube	Contains rover payload and attaches to body tube transition coupler

I	Transition Tube	C	Fiberglass transition	Transition piece measuring 4 inches long to go from a 7.5 inch diameter body tube to 5.5 inches
II	Parachute Bay	D	Carbon Fiber Body Tube	Holds CRAM (Compact Removable Avionics Module), as well as a main and drogue parachute
III	Air Braking System Bay	E	Carbon fiber body tube and coupler	Secures 3 inch body tube piece to coupler connected to D and F, contains the air braking system
	Fin Can and Motor Mount	F	Carbon fiber body tube and fins	Secures motor mount, motor, and fins to launch vehicle

4.2.1.3 Fins

In order to maintain flight in the vertical direction, a parallelogram fin shape was chosen because at low Reynolds numbers, it is highly effective in maximizing stability and minimizing drag - thereby it also maximizes apogee. Moreover, since all of the fins have the same airfoil shape, there is no drag caused by asymmetry in fin shapes. These fins provide the best stability of the launch vehicle at the speeds it will operate. Apart from the structural advantages of the parallelogram shaped fin, such shape is easy and convenient to make, replicate, carry and assemble.

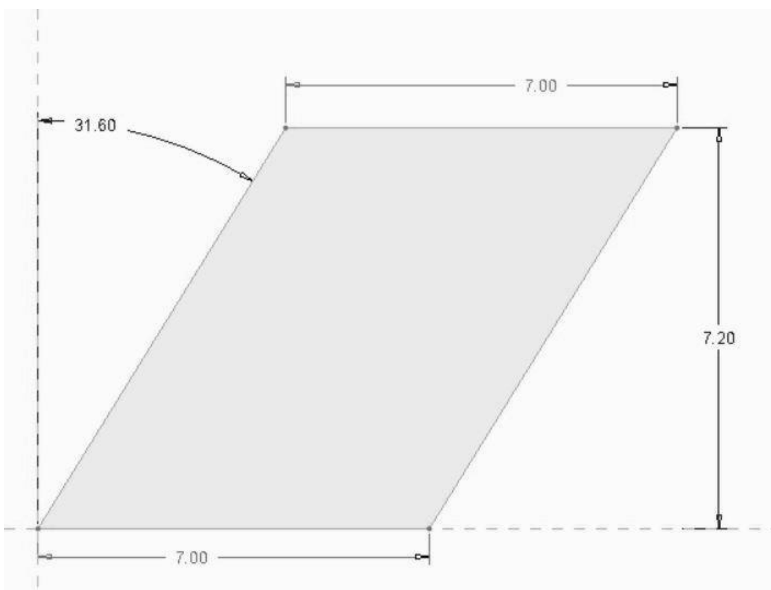


Figure 4. *Swept fin dimensions.*

4.2.2 Applicable Physics

4.2.2.1 Simulations

Two simulations created last year to calculate projected altitude and stability will continue to be revised and upgraded throughout the year. These simulations offer more customizability than OpenRocket and RockSim and allow for a component based approach to calculate how changes in rocket design will impact projected altitude and stability.

4.2.2.2 Projected Altitude

Using the current motor models detailed in Section 4.2.4, the team has conducted simulations for the altitude of the launch vehicle using OpenRocket. The model utilizes a liberal estimate of unknown payload weights, such as the weight of the deployable rover. The currently predicted altitudes are 5470 ft for the Cesaroni L1685-SS motor and 5494 ft for the Cesaroni 1395-BS motor. These altitudes are satisfactory preliminary estimates. The team intentionally chose motors which would achieve an altitude greater than the target altitude of 5,280 ft, with the goal of using an air braking system to increase the drag and reach apogee closer to the goal altitude. As the team continues with the design, it will perform more sophisticated analysis of the coefficient of drag using CFD methods such as ANSYS and/or the campus wind tunnel. Additionally, the team has developed an altitude estimation program in Python which utilizes equations that account for a variable diameter rocket like the one proposed in this report. This program will be more flexible than OpenRocket since the flight path can be split up in multiple parts which more closely model the real flight than the homogeneous flight path approximated in OpenRocket. This will be useful to implement the air braking stage of flight that cannot be implemented in OpenRocket or RockSim.

4.2.2.3 Stability

The stability will also be calculated using OpenRocket and a function in Python. Both OpenRocket and the Python function take into effect the dimensions of the launch vehicle including fin sizes and radii. They both calculate the moment coefficients and return a stability margin. The Python function offers us more flexibility in seeing how different rocket component changes affect stability.

4.2.2.4 Air Braking System

An air braking system, particularly the tabs, will be secured at the center of pressure of the rocket. This is where the moments of the rocket are located, so placing the air braking system in this location will not compromise the overall stability of the rocket. The brakes will deploy after motor burnout. A servo motor will turn and push the tabs of the system out. A proportional–

integral–derivative controller utilizes the current rocket velocity and current altitude to determine the amount of drag the air braking system needs to provide in order to reach the competition goal apogee of 5280 feet.

4.2.3 Material Selection

4.2.3.1 Nosecone

The team will be using a polypropylene plastic nosecone that will likely be bought from Apogee Rockets. The team has used similar nosecones in the past with great success. The material is adequately lightweight and strong, as well as being inexpensive. Other material options were considered, namely carbon fiber, but due to the limitations on sizes available for purchase the team has decided to use polypropylene at this point. The option of a custom built nosecone was explored, but to ensure proper manufacturing a professionally made nosecone was chosen. Table 5 below gives some of the material properties of the material. More specific values will be confirmed by the manufacturer.

Table 5. *Material Properties for Polypropylene Plastic.*

Property	Polypropylene Plastic
Density (lb/in^3)	0.0342
Tensile Strength (psi)	5800
Compressive Strength (psi)	5800
Young's Modulus (ksi)	217-290

4.2.3.2 Body Tube

Different sections of the body tube will use different materials. The top section of the body tube that houses the rover payload will be made using fiberglass, as will the transition section where the body tube changes to a smaller diameter. The smaller section of the body tube will be made using carbon fiber, as will the fin can. Both materials have been used by the team in the past and have performed extremely well. Carolina Rocketry will be our supplier for these materials. The values in the table below will be confirmed by the manufacturer. Both materials are lightweight yet structurally strong. Previous launch vehicles had used phenolic for the body tube, but both carbon fiber and fiberglass offer better performance. The lower density of the material allows for more weight to be allocated for payloads rather than structure, making possible designs more diverse. These materials will be used for other components of the vehicle as well. Table 6 below details the material properties for both fiberglass and carbon fiber.

Table 6. *Material Properties for Carbon Fiber and Fiberglass.*

Property	Carbon Fiber	Fiberglass
Density (lb/in^3)	0.0578	0.055
Tensile Strength (ksi)	300-350	250-300
Tensile Modulus (msi)	15-30	0.8-1.4
Compressive Strength (ksi)	82-120	140-350
Shear Modulus (msi)	0.6-0.725	4.351

4.2.3.3 Fins

The fins are also going to be made of carbon fiber. The team used carbon fiber fins last year and found them relatively easy to work with while providing greatly increased strength when compared to the plywood that teams have previously used. The fins will be cut on Notre Dame's campus like last year, with material bought from Carolina Rocketry. They will be mounted onto the fin can in slits and adhered to the motor mount. Carbon fiber was chosen for its incredible strength to weight ratio and its ability to withstand impact. More information on the fins can be found in Section 4.2.1.3.

4.2.3.4 Integration

All bulkheads are going to be made from fiberglass, as are the centering rings. Previous years have used plywood, 3-D printed material, or fiberglass, and the fiberglass was found to have dramatically increased performance. By using fiberglass as opposed to plywood, the thickness of the bulkheads can decrease significantly while increasing in strength. The same logic applies to the centering rings, which in previous years have either been plywood or fiberglass.

Carbon fiber will be used for couplers and the motor mount. This will be the first year using carbon fiber couplers as opposed to phenolic, but the team is confident that carbon fiber's performance will be better than that of phenolic. Using carbon fiber for the motor mount will allow for a structurally sound location to mount the motor and ensure stability. It also provides adequate thermal properties to handle the heat from the motor. The centering rings serve to keep the motor in a stable position throughout the flight.

The team has used a variety of epoxies and attachment hardware over the years. Great Planes 30 minute cure epoxy is used primarily for phenolic components, and has proven to be extremely strong. This will likely be used prominently during the sub scale construction, where different materials will be used. Glenmarc RocketPoxy will be used for carbon fiber and fiberglass pieces. The team used these materials last year and was impressed with the strength that they provided. The RocketPoxy will be used to secure the fins and centering rings to ensure that they remain stable throughout the flight. This has a much longer cure time than cheaper epoxy. For the motor retention system, JB weld is an option for the motor mount adhesive as it has an extremely high heat tolerance not found in other epoxies. The team has used this for motor retention in the past and it has performed relatively well, though more options will be considered.

More information on specific attachment hardware will be found in later reports once the design of the payloads has been made more concrete. Previously, the team has used hardware that was much stronger than necessary to ensure a large factor of safety, and this trend will continue.

4.2.4 Propulsion

To make an initial motor selection, a number of motor configurations were simulated on a preliminary model of the launch vehicle created in the simulation software OpenRocket. This initial motor selection process focused mainly on estimated apogee. To estimate the altitude at apogee, OpenRocket takes into account many parameters, including the vehicle shape, material finish, and weight. For this initial design, liberal weights were chosen for the various rocket components that will be updated as the vehicle design is finalized, specifically the weights of the air braking system and the rover payload. Due to the presence of the air braking system, motors were selected with an estimated apogee range between 5400 and 5600 ft, with the expectation that the air braking system will be used to decrease the apogee altitude ultimately achieved by the rocket.

After many simulations with a number of Cesaroni, Loki Research, and Aerotech motors, the two motors selected for the current configuration are the Cesaroni L1685-SS and the Cesaroni L1395-BS, which have predicted apogees of 5470 ft and 5494 ft respectively. Though these altitudes are higher than the target altitude, they are within range that can be accounted for by changes in weight or aerodynamic qualities prior to launch. The L1685 has a total impulse of 1140.59 lbf with a maximum and average thrust of 578.23 lbf and 379.31 lbf respectively. The L1395, on the other hand, has a total impulse of 1101.46 lbf with a maximum and average thrust of 400.48 lbf and 314.03 lbf respectively. These and some other important characteristics of these motors are shown below in Table 7. The thrust curves from these two motors are shown below in Figures 5 and 6. To check the simulations, these thrust curves were compared to published thrust curves for these motors and found to show the same trends.

Table 7. *Cesaroni L1685-SS and the Cesaroni L1395-BS Motor Properties.*

Manufacturer	Cesaroni	Cesaroni
Classification	L1685-SS	L1395-BS
Predicted Apogee (ft)	5470	5494
Diameter (in)	2.95	2.95
Length (in)	29.80	24.45
Loaded Weight (lb)	13.24	9.46
Propellant Weight (lb)	8.25	5.17
Average Thrust (lb)	379.31	314.03
Maximum Thrust (lbf)	578.23	400.48
Total Impulse (lbf*s)	1140.59	1101.46
Burn Time (s)	3.01	3.51

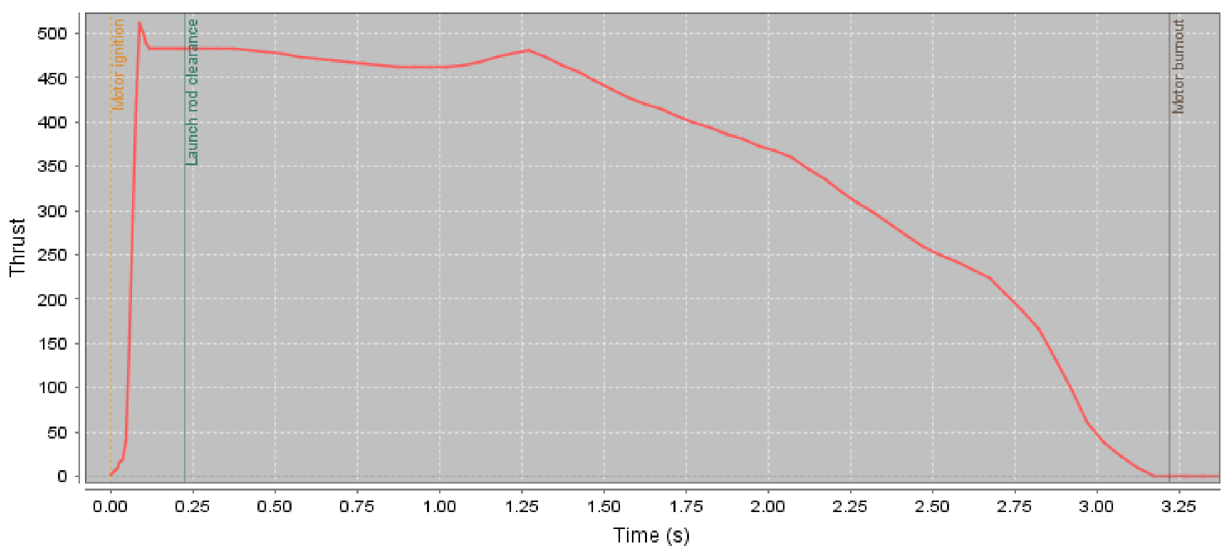


Figure 5. *Thrust Curve of Cesaroni L1685-SS where thrust is in lbf and time is in seconds.*

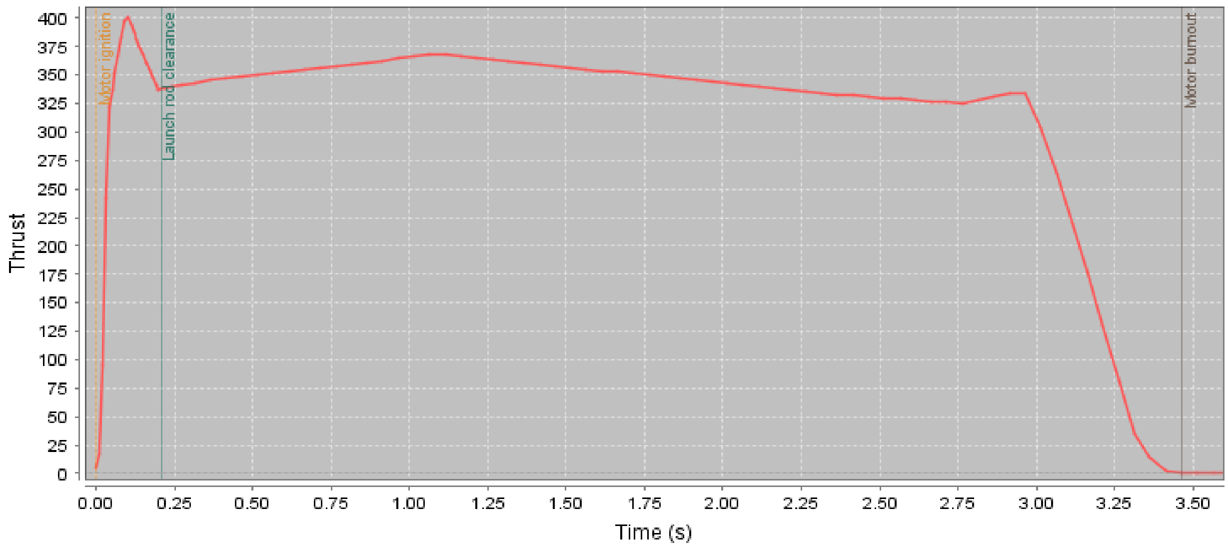


Figure 6. *Thrust Curve of Cesaroni L1395-BS where thrust is in lbf and time is in seconds.*

4.2.5 Recovery System

The recovery system for the proposed launch vehicle will feature dual-stage parachute deployment. A small drogue parachute will deploy at the apogee of the rocket's flight, and a large main parachute will deploy as the vehicle approaches descends at approximately 600 ft above ground level. The parachute will be purchased commercially and be constructed of nylon. Similarly, the shock cords tethering the rocket sections together and to the parachute will be purchased commercially and made of tubular nylon. At the various connection points, steel eyebolts and quick links will secure the separate vehicle sections to the shock cords. The parachute deployment will be controlled by commercially available *Raven 3* altimeters. The altimeters will activate electronic fuses which in turn will ignite black powder charges. The resulting pressure increase will break shear pins between the body tubes, thus separating them and allowing the parachutes to unfurl.

The recovery system will incorporate triple redundancy to ensure a safe and successful landing of the rocket. Three altimeters will be connected to three independent power sources which will ignite three independent black powder charges at each parachute stage. The system will be designed such that any one charge will be capable of deploying the parachute, but the added redundancy will take effect in case of any unanticipated failures. The avionics will be housed within a component called the Compact Removable Avionics Module (CRAM). The CRAM (versions 1, 2 and 3) have been used with a high success rate in the past with only dual-redundancy. Therefore, an even greater reliability can be expected from the CRAM v4 which will be employed this year.

4.2.5.1 Altimeters

The Featherweight brand *Raven 3* altimeter will be used as the primary and redundant controller for the ejection charges. The *Raven* allows for up to four independent launch events although only two (drogue and main) will be utilized. The *Raven* uses barometric pressure sensors operating at 20 Hz to determine altitude and velocity and these quantities will be used to deploy the parachutes at the appropriate times. The altimeters will be armed by means of a screw switch prior to launch which will be accessible from the exterior of the vehicle through designated holes in the body tube. Specifications for the *Raven* altimeter and tentative programming characteristics are shown below in Table 8.

Table 8. *Altimeter specifications.*

Feature	Specification
Power source	9 Volt Battery
Maximum operational 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
Drogue deployment detection	Zero vertical velocity (Apogee)
Primary drogue charge	Apogee
Secondary drogue charge	Apogee +1 sec
Tertiary drogue charge	Apogee +2 sec
Main deployment detection	Feet above ground level (AGL)
Primary main charge	700 ft AGL
Secondary main charge	650 ft AGL
Tertiary main charge	600 ft AGL

4.2.5.2 Miscellaneous Electronics Considerations

All three altimeters will operate from distinct power sources, namely 9v batteries housed within dedicated battery boxes with breakout wires running directly to the altimeters and a common ground. An additional electrical consideration is the possibility of stray electromagnetic waves activating the altimeters prematurely. To alleviate this threat, the avionics will be encapsulated within a coating of copper tape. This will effectively create a Faraday cage protecting the altimeters from other onboard electronic or unknown sources of interference.

4.2.5.3 CRAM Details

The Compact Removable Avionics Module (CRAM) is a Notre Dame Rocket Team original concept now on its fourth iteration. The CRAM is an alternative to the traditional avionics coupler situated between body tube sections. Instead, the CRAM is housed within a dedicated recovery system body tube along with the parachutes and shock cords.

The advantages of the CRAM are multifaceted. Among the benefits are reduced space, reduced size, improved avionics protection, improved vehicles integration, and improved reliability. The CRAM is formed from a central 3D printed structure known as the Core upon which the altimeters and batteries are secured. The Core is housed within the CRAM Body which protects the avionics and integrates into the launch vehicle. The CRAM body is itself protected from the black powder charges by acrylic bulkheads attached above and below and PVC piping to contain the blast. The CRAM Body is fastened within the recovery body tube by integrating with a custom CRAM Mount which will allow for quick and robust insertion and extraction of the CRAM system. Figure 7 below shows the general design principle of the CRAM system.

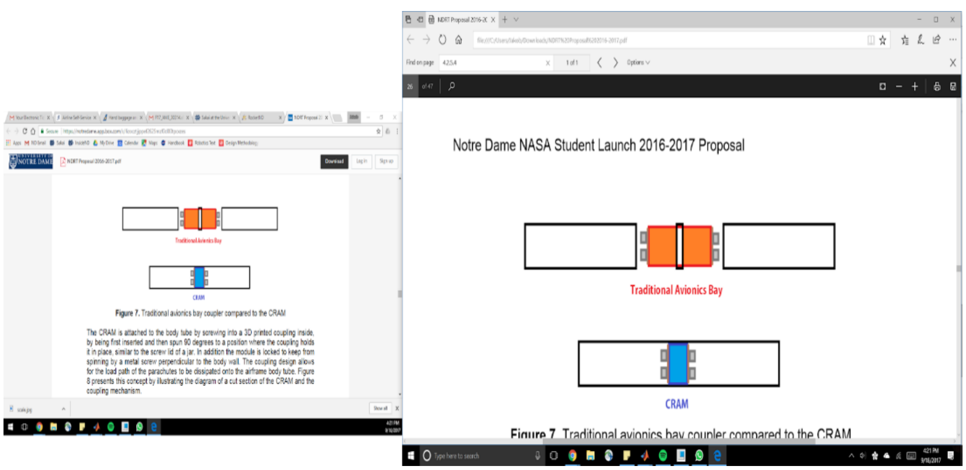


Figure 7. *Traditional avionics bay vs. CRAM.*

Design work is ongoing for the CRAM v4. The integration method into the recovery body tube remains to be decided, but will most likely feature a twist-to-lock mechanism as in previous years and external screws threaded through the body tube. Preliminary CAD renderings serve to demonstrate the basic vision of the system as it stands. Figure 8 below shows the Core along with the location of the altimeters and room allowed for 9V batteries on the periphery. Figure 9 below shows the CRAM Body section. Figure 10 below shows the CRAM v4 assembled with its various components.

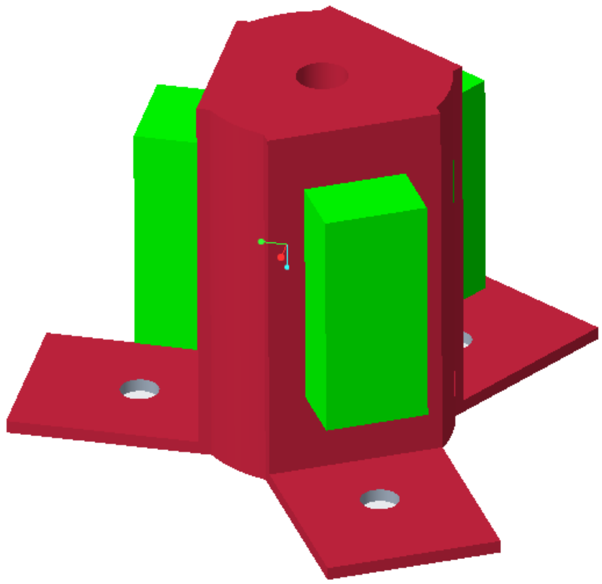


Figure 8. *CRAM Core (red) and altimeters (green).*

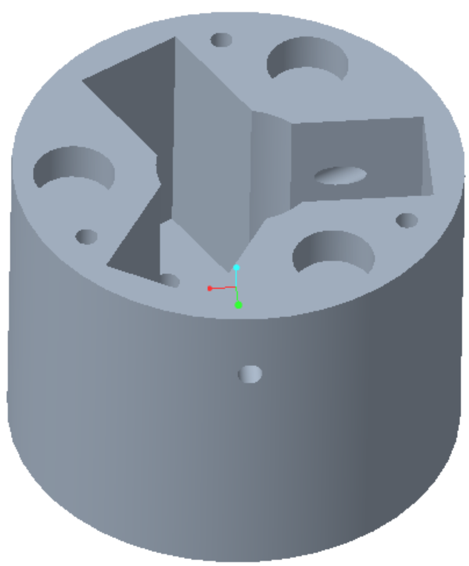


Figure 9. *CRAM body with holes for atmospheric air and black powder charges shown.*

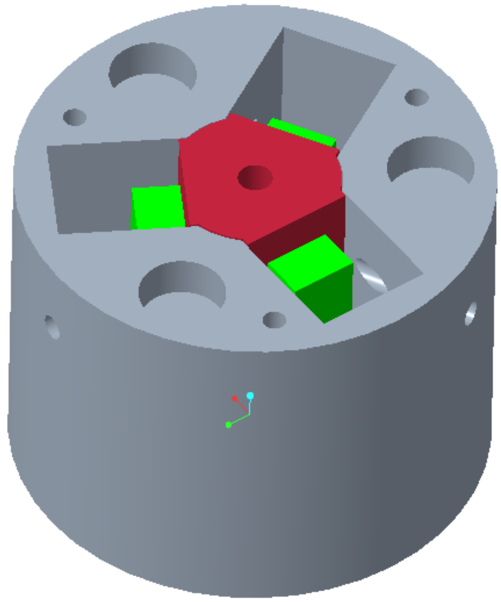


Figure 10. *CRAM assembly (acrylic bulkheads and PVC pipe not shown).*

4.2.5.4 Testing Protocol

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.

Calculations will be performed to determine the necessary amount of black powder for each ejection charge once the exact recovery system dimensions and components are determined. Based on the data from previous years, 3-5 grams can be expected for each charge with increasing amounts designated for the secondary and tertiary charges.

The *Raven* altimeters have the capability to run full flight simulations, which test the onboard components and the ejection charge outputs. These simulations will be run with LEDs instead of electronic matches to verify the altimeters activate at the expected times.

4.2.5.5 Kinetic Energy at Landing

The Student Launch Handbook 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 descent 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.

Three different methods will be used to calculate the descent velocity. The OpenRocket software package will be used to estimate the descent velocity based on the parachute and launch vehicle information inputted. The second method 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 along with relevant physics equations. Third, software on the parachute manufacturer website will be employed further to verify the accuracy of the previous two methods.

4.2.6 Systems 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 1500 lb-rated eye bolt on either side of the CRAM. The quick links connecting the shock cords to the parachutes are rated for 2000 lb. 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 Air Braking Integration

The air braking system will utilize small tabs that protrude from the airframe of the rocket. The tabs 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 Rover Payload Integration

The rover payload will be located in the first section of the rocket, directly beneath the nose cone, and directly above the transition piece to the remaining portions of the rocket. The vehicle design, in particular its integration with the recovery system, keeps in mind the goal to deploy this payload. The recovery system of the rocket is designed with the main parachute attached to the fin can so that the nose cone hits the ground before any of the other components of the rocket. The recovery system is also designed in such a way that all of the other systems land facing away from the nose cone; this is so that the nose cone can be blown off and the rover can be deployed, without affecting any of the other parts of the rocket. The payload will be secured within its own body tube, the specifications of which can be found in Section 4.3.

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 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

Many of the construction methods used in the past were successful, and will be implemented again in the development and composition of the rocket. In order to make minor improvements, the team will confer with Michiana Rocketry Mentor Dave Brunsting. All key components of the rocket, such as body tube, recovery, payload, and fin materials will be purchased from an outside vendor to ensure quality.

In order to maintain attention to detail and the functionality of each piece of the rocket, smaller segments will be constructed individually. Each piece will then be tested in conjunction with the other segments, to confirm that there is no interference between parts. These components will then be assembled, with special attention given to the overall structural integrity of the entire launch vehicle. All stationary components of the rocket will be adhered or bolted together. Pieces of the rocket designed to come apart in descent will be attached with shear pins and dry fitted. This ensures both ease of construction and structural stability during launch.

The materials purchased will be used to construct the body tube, couplers, motor mount, centering rings, bulkheads, fins, and motor mount. At least two team members will be assigned to work on each part as a measure of quality control. After each part is completed, a third team member will evaluate the quality, and the construction co-lead will confirm the functionality of the finished component. While using the machine shop, team members will be under the supervision of professionals as a matter of safety, and quality control.

The fin configuration will be vital to structural stability of the rocket. The fins will be constructed to be durable when subjected to forces experienced during flight. Fins will be secured tightly in designated slots and blended with RocketPoxy fillets to further increase stability and minimize the shearing forces experienced by the fins. Fin alignment will be determined by the fin alignment mount constructed by the team in previous years to ensure a reliable and stable design.

Following construction, tests will take place to determine the rocket's performance when subjected to forces, as well as the aerodynamics and flight capabilities. This data will be collected and used to consider further changes in adherence to flight safety and overall design, which will be outlined in further reports and documents.

4.2.8 Verification Methods

The Vehicle Sub-team has assembled the requirements outlined in the 2018 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 to give NASA SL officials an idea of how the Sub-team will proceed. The plan of verification will be expanded as the year goes on and all requirements will be verified by the *Flight Readiness Review*.

Table 9. *Verification and Plans for Requirements.*

Requirements	Plan of Verifications	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	OpenRocket RockSim

	- Software simulations will be performed to verify apogee calculations - Full Scale Test will verify that the fully-built vehicle will reach target altitude	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, Cesaroni 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	OpenRocket and RockSim Full Scale Test

	ensure the center of gravity is where it should be.	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 measured and the team will verify it is sufficient.	Calculations Full Scale Test
The launch vehicle shall contain a remotely activated rover which will autonomously travel five feet and deploy a set of foldable solar panels.	- The team will build the rocket in such a way as to have sufficient dimensions to contain the rover - Through the sub-scale test, an object will be placed within the sub-scale rocket to simulate the mass of the rover. - Through the full-scale test and inspection, the rover's capability to fulfill the requirements will be verified.	Subscale Test Full Scale Test

4.2.9 Vehicle Test Plans

Table 10. *Vehicle Test Plan.*

Time Period of Test	Test	Purpose of Test
October 2017	FEM Analysis	To analyze load paths and stresses in order to reinforce effectively
November 2017	Subscale Test	To verify simulations performed in OpenRocket and RockSim and utilize correction factors where applicable
November 2017	Material Stress Test	To verify the strength and stress properties of chosen material
November 2017	CFD analysis	To calculate the coefficient of drag To finalize ABP fin design To attain a more refined calculation of altitude
December 2017	Wind Tunnel Analysis	To verify drag estimates during normal flight and during ABP deployment. To attain final calculation of apogee.

January 2018	Full Scale Test	To verify simulations performed in OpenRocket and RockSim To verify the requirements in Section 4.1
February 2018	2nd/Back-up Full Scale Test	To verify the requirements in Section 4.1 To test features added for safety and efficiency post-CDR

4.3 Scoring Payload - Deployable Rover Payload

The purpose of the Deployable Rover Payload is to safely carry a small rover throughout the duration of the flight. Upon safe landing, the rover will be remotely deployed via a ground station. The rover's mission is to drive five feet away from any point of the rocket and deploy folded solar panels. The rover will be carried by four oversized wheels that will enable movement over rough terrain and powered by a brushless motor. In order to detect the rocket and other objects, a LiDAR module will be used along with a gyroscope and accelerometer. This data, through a microcontroller, will be analyzed and then used to control the rover.

4.3.1 Identify Design Criteria

To ensure the payload will meet the design missions the following four criteria have been identified:

1. *Vehicle Stability and Integrity*: The presence of this payload in the rocket must not compromise the stability or the structural integrity of the rocket. All interfaces with the main vehicle will be carefully analyzed and implemented.
2. *Rover Strength*: The rover must have a robust mechanical and electrical system to survive an unintended hard landed and to traverse uneven, rough terrain.
3. *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 mission implementation.
4. *Accuracy*: In order to satisfy the solar panel mission requirement, the rover must accurately detect the position of the rocket.

4.3.2 Physical Implementation and Mechanisms

The rover will consist of four oversized wheels that enable the possibility of inverted driving. Due to this design, the solar panels will unfold from the sides of the rover in an “accordion” fashion and will have the panels right side up for both driving configurations. The motion of the rover will be driven by a brushless motor and the solar panels will be driven by a servomotor. The rover will be secured with a combination of a rail and pin system. This will restrict any motion during flight. The body of the rover will be machined to reduce weight and enable customization. The rover will deploy from the nose cone of the rocket. Compressed air will be used to remove the nose cone and allow the rover to emerge from the rocket.

4.3.3 Electronic Components

A PIC32 microcontroller will be used to control the motions of the robot. To attain the design goal of moving five feet from any part of the launch vehicle, the microcontroller will interface with several sensors. These will include various MEMS motion sensors, such as an accelerometer and gyroscope, to determine the orientation and general motion of the rover. It will also be outfitted with a LiDAR module for obstacle avoidance while in motion.

Additionally, the rover will communicate with the various sections of the rocket using Bluetooth to determine its location relative to those sections. The rover will also have radio communication with the ground station so that it can be deployed. One member of the team currently holds an FCC Part 97 Amateur Extra Radio License and more members are planning on taking the exam in the near future.

4.4 Non-Scoring Payload – Air Braking System

The apogee of the rocket will be controlled using an air braking system. The motor will be designed to overshoot the target apogee of 5280 feet and drag control surfaces will deploy after motor burnout to control the ascent speed of the rocket. These control surfaces will be flat plates, called drag tabs from here on out, extended from the body of the rocket into the surrounding airflow, thus inducing drag. The drag tabs will be controlled using a mechanical system and a motor. The motor will be electronically controlled using a closed-loop control algorithm, which will use data from altimeters to continuously predict the flight path of the rocket, determine the drag required to reach the target apogee, and adjust the extension of the drag tabs accordingly.

4.4.1 Aerodynamics

As previously stated, the rocket will reach the target apogee by designing the motor to overshoot the target apogee and then using the air braking system to control the ascent. The ascent control will be achieved using control surfaces, called drag tabs, to induce additional drag on the rocket, therefore slowing the ascent velocity. The drag tabs will be flat plates extended perpendicularly into the airflow around the rocket as it climbs. The tabs will be able to extend out from the rocket at a variable depth into the flow, effectively controlling the area of the tabs and therefore controlling the amount of drag that they create. The relationship between tab extension and drag will be obtained by wind tunnel testing using the wind tunnel facilities in Hessert Laboratory on campus. The preliminary position of the drag tabs is at the center of pressure so as not to induce any instability in the rocket. There will be four tabs, and they will be offset from the main fins because the nature of their shape will cause the flow to separate from the rocket, which creates the possibility of rendering the main fins ineffective if they are directly in line. The system will not activate until after motor burnout to maintain stability during the acceleration of the rocket, as the forces on the rocket will be at their strongest and most volatile during this time. The system will deactivate, meaning the tabs will not be extended, after apogee is reached to maintain the accuracy of the descent and recovery of the rocket.

4.4.2 Mechanical System

The focus of the mechanical subsystem for the air brake is simplicity. In previous years, the team has worked hard to keep the system compact, and hopes to continue that practice with the air brake. As a result, the main constraint we are imposing on the mechanical subsystem is that all the drag tabs are articulated by a single servomotor, which will simplify control and ensure that all the tabs deploy simultaneously. The other constraint, a function of the aerodynamics, is that the drag tabs will be flat surfaces.

There are currently two variations on the design to deploy the tabs. The first design would use a centrally mounted gear driven by a servo, which will mesh with gear racks on each tab. These tabs would be constrained by some sort of slot or bushing to ensure they slide out straight. The other option uses a similar slot to guide the tabs, but replaces the gear rack with a crank-slider mechanism. The crank-slider uses a centrally mounted rotating hub, with tie rods connecting the hub to each tab. Then, as the hub rotates, the tie rods push the tabs out. The advantage of the gear rack system is that the control of the tabs is effectively linear, that is, at any position the ratio between rotation of the central gear and extension of the flaps is the same. However, the reaction forces from the gear will increase friction in the system, which will be the main force to overcome. The crank-slider reduces this friction, but makes the control of the tabs nonlinear, though this can be addressed using kinematics.

4.4.3 Control Code

The code structure for the air braking system will be a closed-loop controller utilizing a combination of barometer and accelerometer data. It will utilize a pre-calculated velocity vs. altitude curve with a target apogee of 5280 ft. Upon burnout, the algorithm will compare its current velocity to the calculated ideal and determine the difference between the two values. It will then calculate the proportional, integral, and differential components of this error, and scale each value appropriately to determine an extension value. The algorithm will then directly communicate with the servo motor to extend the drag tabs appropriately. Over all, this will result in a continuous modification of the drag tabs' extension to induce a drag force that will produce the ideal velocity necessary to reach the target apogee at the rocket's current altitude.

5 Educational Engagement

5.1 Educational Projects

The Notre Dame Rocketry team plans to engage the community in several 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 events/presentations and smaller, more engaging one-on-one lessons. For the first of these categories, we plan to team up with the St. Joseph County Library, the 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 St. Joseph County, the You Be the Chemist program, the Robinson Community Learning Center, and a few local schools. The team has an educational outreach lead, who is in charge of organizing these various events throughout the year. This past year, NDRT stepped up its educational outreach and made strong connections within the South Bend and Notre Dame communities. The team hopes to build upon this success this year through more intensive outreach programs that will allow us to reach an even larger number of students on a more personal level.

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. A few of these events have been used in the past and have proven successful, but the team has developed some new programs for this year as well. 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.

5.2.1 *Can it fly?*

This lesson introduces the students to the history of flight and spaceflight, 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.

5.2.2 *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.

5.2.3 *Touchdown*

This lesson also looks at some of the basics of physics and a very brief introduction to differential equations, through the concepts of landing systems. This program has been very successful, because students are excited about the concept of landing on the moon and on Mars.

The second half of this program is spent building a shock absorbing system to keep marshmallow "astronauts" safely inside an open container when the container is dropped. This, like many of the team's planned events allow students to use the skills and principles right after they learn them.

5.2.4 *Rocketry 101 Curriculum*

This group of 6 lessons covers 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 is planned with the intent of giving the students a sense of the design process engineers go through. This program was piloted last year with middle school and high school aged students at the Boys and Girls Club of St. Joseph County. The team hopes to expand this program, running it with two more after-school programs, once in the fall and once in the spring.

5.2.5 *What is engineering?*

This year, we are fortunate enough to have engineering majors from nearly all of the engineering disciplines at Notre Dame 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. The team is hoping to expand this activity further to invite students to campus and include professors in the activities.

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 sixth year in a row, Notre Dame will have a table 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 1,500 people.

6 Project Plan

6.1 Development Schedule

Following a project schedule is crucial in any engineering design, test and building process. For this reason, the Notre Dame Rocketry Team is committed to abiding by the following detailed schedule in Figure 11 for the entire NASA Student Launch Competition.

September	
20	Electronic copy of Proposal Submitted
October	
15	FEM and ANSYS Analyses Done
28	Subscale Test Flight
November	
03	PDR Material Submitted
06 – 29	PDR Video Teleconferences
12	Rover Payload Design Completed
19	Order Materials and Perform Stress Tests
December	

03	Rover Payload Construction
10	Wind Tunnel Testing
10	Receive Materials and Begin Construction
<u>January</u>	
12	CDR Material Submitted
16 – 31	CDR Video Teleconferences
21	Rover Final Construction and Testing
28	Full Scale Flight Test
<u>February</u>	
18	Full Scale Flight Test
<u>March</u>	
05	FRR Material Submitted
06 – 22	FRR Video Teleconferences
<u>April</u>	
04	Travel to Huntsville, AL
04 – 05	LRR
05 – 06	Launch Week Activities
07	Launch Day and Banquet
08	Backup Launch Day
27	PLAR Submitted

Figure 11. *Annual schedule.*

6.2 Budget and Funding Plan

Table 11 below summarizes the intended budget plan for the 2017 – 2018 competition year.

Table 11. *Annual budget for each sub-team.*

Allocation Group	Budget
Vehicle Design Sub-team	$ 4,000
Recovery Systems Sub-team	$ 800
Deployable Rover Sub-team	$ 1,200
Air Braking System Sub-team	$ 800
Rocket Subtotal	**$ 6,800**
Educational Outreach Events	$ 300
Miscellaneous	$ 300

Competition Travel	$ 5,000
GRAND TOTAL	**$ 12,400**

The costs shown in Table 11 can be accounted toward the following items:

Vehicle Construction and Propulsion: These costs account for all materials that will be used to build the launch vehicle as well as for the motors used in all launches.

Recovery System: The recovery costs include all parachutes, altimeters, 3D printed materials and all items necessary for a safe and robust integration into the vehicle.

Deployable Rover Payload: The costs associated with the experimental payload include all materials, wheels, solar cells, rover motors, all electronics and items needed to ensure a safe and successful integration.

Air Braking System: The costs for the extra payload account for all materials, electronics, servo motors and 3D printed items needed.

Educational Outreach: These funds are set for use during educational and community engagement events, and are planned to be used to purchase Estes rockets with kids.

Miscellaneous: In this category are costs for posters and other items associated with a professional team image and presentation.

Travel: All costs associated with traveling are included in this number including transportation, food and lodging.

The Notre Dame Rocketry Team draws funding from two main sources. The first is from a general account dedicated to aerospace design projects at the University. 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 annually as deemed necessary by University faculty and staff.

The second source is from sponsorship by The Boeing Company. The team is working hard on securing corporate relations with different aerospace companies, and Boeing has been a pioneer with the Notre Dame Rocketry Team in this effort.

6.3 Community Support

The Notre Dame Rocketry Team has maintained a strong relation with Michiana Rocketry, the local TRA club. The club has provided support and expertise for several years and is always overwhelmingly enthusiastic to provide aide to the team. Several club members have volunteered time and effort to the team, including the team mentor. Helpful suggestions of vendors, supplies and services have been invaluable to the team. For this reason, the team is happy to continue this relation for this year's competition.

6.4 Sustainability

Several measures are in place to ensure that the Notre Dame Rocketry Team will be successful this season and maintain a presence in the following years. This includes the new relations for educational outreach, the continuation and growth of the Corporate Sponsorship Committee, new relations with professors for recruiting purposes and a web account with all team history and data.

For educational outreach, the team has successfully formed a strong partnership with the Boys and Girls Club of South Bend. As previously described in the Educational Engagement section, these events were welcomed by the Club who in response has decided to continue this partnership for this and the following years. This committee has also ensured partnerships with involvement in the Science Alive Fair and other local clubs, which ensures the growth of our presence in the community.

The Corporate Sponsorship Committee was established last year and has continued to grow this year. The committee has successfully received donations from major aerospace companies and continues to build those relations. The financial aspect ensures that the team will be fully funded in the following years. Looking ahead, the Notre Dame Rocketry Team looks to be fully sponsored by corporations and donations so as not to depend on funding from the university.

This year the team saw an increase in new members from a wider variety of majors thanks to a larger recruiting effort. Relations with professors in all branches of engineering have been established as the team presence has grown. The team has also recruited science and non-STEM majors who are as enthusiastic about the project as all other members. Having a wider diversity of majors allows for the team to establish a presence all across the University and will allow anyone who is interested to have the ability to join.

In order to consolidate the resources for incoming teams, the Notre Dame Rocketry Team has a Box account that archives previous designs, reports and media. Each year's team has access to this account and can learn from previous mistakes as well as see what aspects were successful to build upon. This ensures that the next year's team does not have to begin from scratch, but instead 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.

Table 12. *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

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.

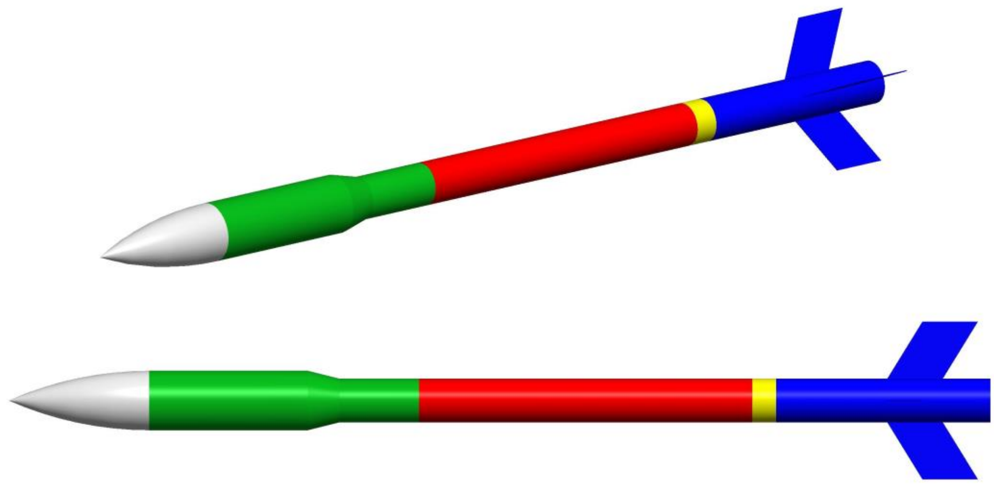
____

(Team Member Name Printed)

____

(Team Member Signature) (Date)

Appendix C: Proposal CAD Representation



University of Notre Dame Rocketry Team			Title: Proposal: Preliminary Rocket Design
Scale: 0.070	Date: Sep-14-2017		Drawn By: George Porter