NC STATE UNIVERSITY

Tacho Lycos
2018 NASA Student Launch
Proposal

High-Powered Rocketry Team at NCSU
911 Oval Drive
Raleigh, NC 27695

September 20, 2017

Common Abbreviations & Nomenclature

AGL	=	above ground level
APCP	=	ammonium perchlorate composite propellant
ARRD	=	advanced retention and release device
AV	=	avionics
BP	=	black powder
CDR	=	Critical Design Review
CG	=	center of gravity
CP	=	center of pressure
EIT	=	electronics and information technology
FAA	=	Federal Aviation Administration
FMECA	=	failure mode, effects, and criticality analysis
FN	=	foreign national
FRR	=	Flight Readiness Review
HEO	=	Human Exploration and Operations
HPR	=	High Power Rocketry
HPRC	=	High-Powered Rocketry Club
L3CC	=	Level 3 Certification Committee (NAR)
LCO	=	Launch Control Officer
LRR	=	Launch Readiness Review
MAE	=	Mechanical & Aerospace Engineering Department
MSDS	=	Material Safety Data Sheet
MSFC	=	Marshall Space Flight Center
NAR	=	National Association of Rocketry
NCSU	=	North Carolina State University
NFPA	=	National Fire Protection Association
PDR	=	Preliminary Design Review
PLAR	=	Post-Launch Assessment Review
PPE	=	personal protective equipment

RFP	=	Request for Proposal
RSO	=	Range Safety Officer
SL	=	Student Launch
SLS	=	Space Launch System
SME	=	subject matter expert
SOW	=	statement of work
STEM	=	Science, Technology, Engineering, and Mathematics
TAP	=	Technical Advisory Panel (TRA)
TRA	=	Tripoli Rocketry Association

NC STATE UNIVERSITY

Table of Contents

List of Tables

List of Figures

1. General Information

1.1 Team Advisors and Mentors

i. **Name: Dr. Charles (Chuck) Hall**
ii. Email: chall@ncsu.edu
iii. TRA Certification: 14134
iv. Biography: Dr. Hall directs the Flight Research Group in the Mechanical and Aerospace Engineering Department at North Carolina State University. Dr. Hall is the current advisor for the High- Powered Rocketry Club. He is also the professor in charge of the aerospace senior design project. Dr. Hall has level 3 certification with Tripoli Rocketry Association (TRA).

i. **Name: Alan Whitmore**
ii. Email: acwhit@nc.rr.com
iii. Phone: (919) 929-5552
iv. TRA Certification: 05945
v. Biography: Alan became involved in High Power Rocketry in 1997, and has since earned his Level 3 certification for both TRA and NAR. Since 2002, Alan has served as the prefect of the Eastern North Carolina branch of TRA. In 2006, he was accepted onto the TRA Technical Advisory Panel (TAP) to advise the TRA board of directors on technical aspects of propellants, construction material, and recovery techniques. Alan is also a current member of the NAR Level 3 Certification Committee (L3CC), allowing him to supervise individual members during the process of designing, manufacturing, and flying rockets used for Level 3 certification for both NAR and TRA. Alan was recently selected as the Chairman of the Tripoli Motor Testing Committee, which is responsible for testing and certifying all new commercially manufactured hobby rocket motors manufactured in the United States.

i. **Name: James (Jim) Livingston**
ii. Email: livingston@ec.rr.com
iii. Phone: (910) 612-5858
iv. TRA Certification: 02204
v. Biography: Jim joined the TRA in 1993 and achieved his Level 3 certification in 1997. As of 1998, Jim has served as a member of the TRA TAP and has supervised over twenty Tripoli members in their own Level 3 certifications. He has also been involved in Tripoli research since 1997, and manufactures all the motors he uses (sizes I through N).

1.2 High-Powered Rocketry Club

Established in 2009, the High-Powered Rocketry Club (HPRC), team name "Tacho Lycos," is an interdisciplinary student organization within the Department of Mechanical and Aerospace Engineering (MAE) at NC State University. The Club gives undergraduate students the opportunity to gain real-world design and construction experience through participation in the annual Student Launch (SL) competition sponsored by the NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama. Team mentors communicate regularly with club officers to supervise research, design, construction, testing, and launch of high-powered rockets. While all members of the club participate in these activities, they are led by a group of Aerospace Engineering seniors who have chosen to participate in the SL competition to satisfy the requirement for a senior capstone project before graduation. These seniors receive a final grade that corresponds to the final competition score.

1.3 Safety Officer

i. **Name: Erik Benson**
ii. Email: etbenson@ncsu.edu
iii. Responsibilities: Erik will act as the NC State University Safety Officer for the 2017-18 NASA Student Launch competition. Erik is responsible for the safe operation of all equipment in the lab including, but not limited to: power tools, drill presses, hand tools, batteries, and chemicals. He will be present for all aspects of construction to ensure the safety of team members as well as accompanying guests, and to train new members on the proper and safe usage of all equipment. The Safety Officer is required to be present for any testing or vehicle launches. He is also responsible for maintaining a clean working environment in the lab that meets or exceeds safety regulations instituted by the MAE department which includes the maintenance of a flame cabinet and proper stocking of a first aid kit.

1.4 Student Team Leader

i. **Name: Raven Lauer**
ii. Email: relauer@ncsu.edu
iii. Phone: (919) 414-4950
iv. Responsibilities: Raven will act as the NC State University Student Team Leader for the 2017-18 NASA Student Launch competition. Raven is also serving as HPRC president and Team Lead for the Senior Design team which consists of other aerospace engineering seniors: Kevin, Jackson, Graham, Amy, and Eugene.

1.4.1 Senior Design Team

i. Name: Kevin
ii. Subteam: Payload Integration
iii. Biography: Kevin is a 5th year student in Aerospace Engineering working on a Graphic Communication minor. He is the Payload Integration team lead for Tacho Lycos. Kevin enjoys travelling the world, snowboarding, playing soccer, and making new friends from all corners of the globe.

i. Name: Jackson
ii. Subteam: Rover
iii. Biography: Jackson Kyner currently serves as the President of Theta Tau Professional Coed Engineering Fraternity, but has also served as Vice President and Recruitment Chair in the past. Last summer, he was a Research Associate in the Leadership Academy at MSFC. In his free time, he enjoys running, playing video games, and being with friends.

i. Name: Graham
ii. Subteam: Structures
iii. Biography: Graham is a 5th year senior who is also involved with Wolfpack Motorsports and the NC State Engineering Career Fair when not working on Senior Design. In his free time, he enjoys cooking and spending time with friends and family.

i. Name: Amy
ii. Subteam: Propulsion & Recovery
iii. Biography: Amy is a 5^{th} year senior at NCSU and upon graduation is interested in pursuing space medicine and space physiology as a path to astronaut candidacy. In her free time, she travels, spends time outside hiking and rock climbing, volunteering at the local SPCA, and tutoring high school math students.

i. Name: Eugene
ii. Subteam: Avionics & Electronics
iii. Biography: Eugene Zboichyk is a 4^{th} year aerospace engineering student, and oversees avionics and electronics. Originally from Belarus, Eugene is a foreign national team member. In his spare time, he enjoys playing the piano and practicing freerunning.

1.5 Team Organization Matrix

For the 2017-18 school year, the team leadership consists of two major parties: Senior Design and Club Officers. While the two parties interact with each other regularly, they are both responsible for different aspects of the team's operation for the SL competition. Further, the Vice President club officer position has been divided into three different categories to ensure that tasks associated with the operation of a club on NC State campus are completed correctly, efficiently, and on time. Figure 1-1 offers a visual representation of the leadership structure for the team this year.

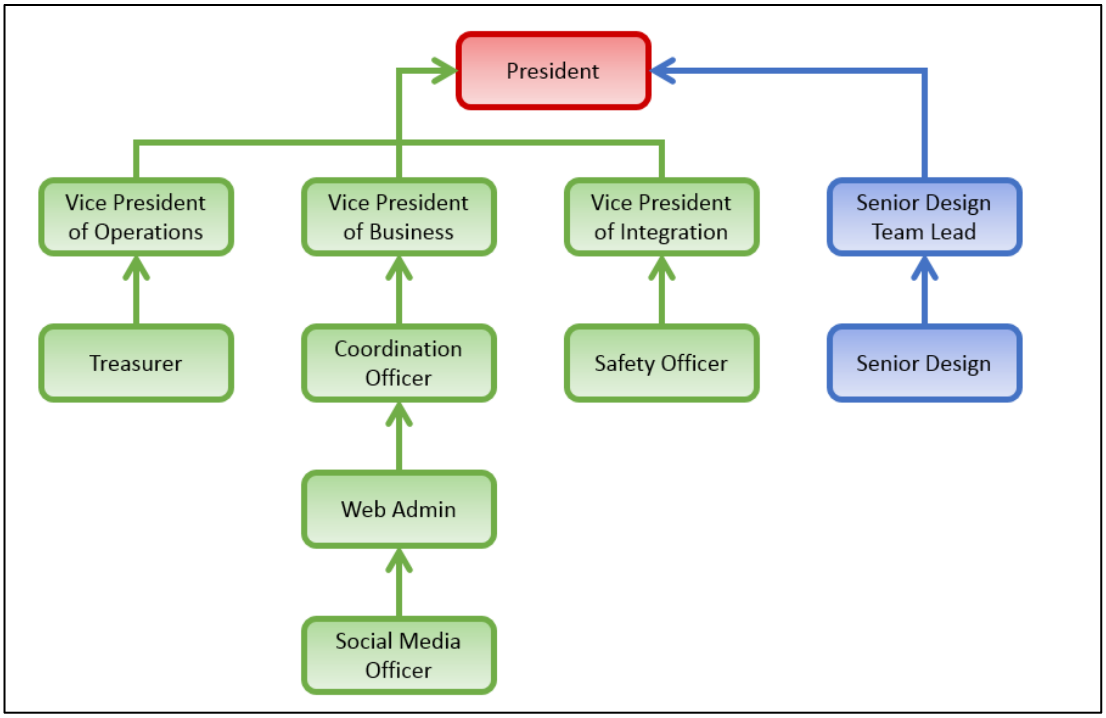

Figure 1-1 Visual Representation of HPRC Leadership Organization Structure

The members of Senior Design as well as their respective responsibilities are listed in Section 1.4. The Club Officers and their respective responsibilities are listed below:

i. **Position: President**
ii. Name: Raven
iii. Years in Club: 6
iv. Prior Experience: Coordination Lead 2014-16, Vice President 2016-17
v. Biography & Responsibilities: Raven is a 6th year student double majoring in Aerospace Engineering and History as part of the Ben Franklin Scholars program. As president, he is expected to preside the weekly club meetings, attend at least half of all outreach events, and represent the club at all NC State Student Organization events. In his spare time, Raven enjoys flying helicopters as a private pilot, reading, and spending time with friends.

i. **Position: Vice President of Operations**
ii. Name: Ashlee
iii. Years in Club: 3
iv. Prior Experience: Assistant Treasurer 2016-17
v. Biography & Responsibilities: Ashlee is a 3rd year Civil Engineering student. As the Vice President of Operations, she is expected to attend outreach events, aid fellow officers in their duties, and manage all general club activities. In her spare time, Ashlee enjoys reading, sketching/designing, and traveling.

i. **Position: Vice President of Development**
ii. Name: David
iii. Years in Club: 3
iv. Prior Experience: Treasurer 2016-17
v. Biography & Responsibilities: David is a 3rd year student studying Mechanical Engineering. As Vice President of Development, he is responsible for expanding the technical scope of the club, and coordinates with the treasurer to develop relationships with sponsors. He has interned with Oracle, MaxPoint, and Johnston Space Center. In his free time, David enjoys overlanding by both SUV and motorcycle, as well as backpacking and canoeing.

i. **Position: Vice President of Integration**
ii. Name: Nathan
iii. Years in Club: 3
iv. Prior Experience: None
v. Biography & Responsibilities: Nathan Cox is a junior studying Aerospace Engineering. As Vice President of Integration, he is responsible for coordinating the goals of the club and the senior design team. In his spare time, Nathan enjoys hiking, backpacking, and kayaking.

i. **Position: Treasurer**
ii. Name: Ashby
iii. Years in Club: 2
iv. Prior Experience: None
v. Biography & Responsibilities: Ashby is a junior studying Aerospace Engineering. In addition to High-Powered Rocketry Club, Ashby is an active member of NC State's section of the Society of Women Engineers and the University Honors Program. As treasurer, Ashby is expected to effectively manage the club funds and plan for future investments. In her free time, Ashby enjoys reading and running.

i. **Position: Safety Officer**
ii. Name: Erik
iii. Years in Club: 1
iv. Prior Experience: None
v. Biography & Responsibilities: Erik is a 2nd year student majoring in Aerospace Engineering while also taking Medical Prerequisites. He is a part of the University Scholars Program as well as Army ROTC. As Safety Officer, he is expected to communicate and enforce the team safety plan and to keep a safe and tidy lab space. In his free time, Erik enjoys playing video games, running, and hiking.

i. **Position: Coordination Officer**
ii. Name: John
iii. Years in Club: 4
iv. Prior Experience: Outreach Coordinator
v. Biography & Responsibilities: John is a 4^{th} year student majoring in Aerospace Engineering with a minor in Music Performance. As Coordination Officer, he is expected to manage all lines of communication within the club and plan all events including outreach. In his free time, John greatly enjoys playing and performing music with one of several groups that he is a member of on campus.

i. **Position: Web Administrator**
ii. Name: Gabe
iii. Years in Club: 1
iv. Prior Experience: None
v. Biography & Responsibilities: Gabe is a sophomore student majoring in Aerospace Engineering and minoring in Mathematics, as well as being part of the University Scholars program. As Website Administrator, he is expected to maintain and update the club website, integrate social media, upload reports, and establish a strong web presence. In his free time, Gabe enjoys playing video games and guitar.

i. **Position: Social Media Officer**
ii. Name: Joseph
iii. Years in Club: 3
iv. Prior Experience: Social Media Officer 2015-17
v. Biography & Responsibilities: Joseph is a 3^{rd} year student studying Environmental Science with a focus on sustainable architecture. As the Social Media Officer, he is responsible for curating and posting content on the team social media pages. He is also an executive member of the Climate Reality Project Campus Corps working to bring renewable energy solutions to NC State campus. In his free time, Joseph enjoys drawing and creative writing.

1.6 Weekly Club Briefings

The Senior Design team and all members of the club meet on campus once per week during the school year to discuss:

- Weekly updates
- Upcoming outreach events
- Ongoing experiments
- Career opportunities
- Topics of special interest

The club strives to provide an atmosphere that fosters learning and facilitates the flow of knowledge from veteran members to newcomers. Beyond the weekly meetings, the rocketry lab space is open for members to work on reports, rocket construction, and/or classwork, as well as for general fraternization amongst members. The Senior Design team also conducts regular meetings amongst the subteams to discuss document and project progress, as well as to resolve any outstanding issues.

1.7 Local TRA/NAR Chapter Information

Alan Whitmore, whose qualifications are described in Section 1.1, is the current prefect of Tripoli East NC (TRA Prefecture 65) and is responsible for the purchase and storage of all motors used for vehicle launches during the competition. These motors are only purchased after his design approval, and are stored according to his safety requirements. At launches, the motors are assembled and installed under his supervision. Dr. Chuck Hall and Jim Livingston are both Level 3 certified with the TRA, and are equally capable of supervising the storage, assembly, and installation of rocket motors.

2. Facilities and Equipment

2.1 Description

The HPRC meets primarily in the MAE Student Fabrication Lab ("Rocketry Lab"), Room 2003, Engineering Building III. The Senior Design team also has access to the Space Senior Design Lab, Room 1224, Engineering Building III. These workspaces are equipped with handheld power tools, small drill presses, and a 3D printer.

Though the labs are equipped with their own basic tools, the club also has access to a precision machine shop in Engineering Building III. The machine shop supervisor is very helpful with design and parts requests, and usually delivers the product of a machine shop request within a week. Raven, President and Senior Design Team Lead, is qualified to use most of the available machines which allows for faster part production. Additionally, the club has access to the structures lab in Engineering Building III which allows for materials testing using the Instron tensile and compression loading machine. If needed, the club can request access to the MAE laser cutter operated by graduate students in Flight Research, which located in the Wind Tunnel High Bay adjacent to Engineering Building III.

2.2 Hours of Accessibility

Monday – Friday: 7am – 10pm for undergraduate student access
10pm – 7am for graduate or professor assisted entry

Saturday – Sunday: All day for graduate or professor assisted entry

2.3 Necessary Personnel

The club safety officer, identified in Section 1.3, must be present in the Rocketry Lab for any construction or testing. Two graduate students are available to club members that need access to the Rocketry Lab after-hours and the weekend. Dr. James Kribs, MAE Lab Director, must approve any testing conducted using the mechanical engineering lab equipment. Dr. Shreyas Narsipur or Dr. Hall must approve any testing conducted in the subsonic or supersonic wind tunnels located at NC State.

2.4 Available Equipment

Equipment relevant to the construction of rockets that are available in the Rocketry Lab:

- Craftsman 1.6" Variable Speed Scroll Saw
- Craftsman 12" Bench Drill Press with Laser
- Task Force 4" Belt & 6" Disc Sander
- 120 Volt 60 Hz Band Saw
- 16 Gallon 6.5 HP Shop Vac
- Dremel 400 XPR Rotary Tools
- Ryobi HG600 Heat Gun
- DeWalt 18V Hand Drill
- Drill Bit Case from 3/64" – ½"
- Ryobi Forstner 7-piece Drill Bit Set 1" - 2"

- Task Force Ratchet/Socket Kit
- Digital Micrometer
- SeeMyCNC Rostok Max V2 3D Printer
- SoftWorks 5lb Food Scale
- AWS 1 kg Digital Scale
- Wilton Bench Vice
- Vacuum hoses for wet layups

2.5 Supplies Required

Materials required to design and build a rocket and payload include, but are not limited to, the following items:

- Safety equipment (fire extinguisher, first aid kit, gloves, goggles, masks, etc.)
- Equipment listed in Section 2.4
- Blue Tube body tubes and couplers
- Fiberglass tubes
- Acrylic tubes
- Motor retainer
- Nose cone
- Birch plywood sheets
- Epoxy
- Fiberglass sheets
- Black powder
- Altimeters
- Wires
- E-matches
- 3D printer and plastic rolls
- Handheld tools
- Screws
- U-bolts
- Shock cord
- Jolly Logic chute release
- ARRD
- Main parachute
- Drogue parachute
- Payload parachute
- Processors
- BeagleBone Black computer
- Batteries
- Software (Microsoft Office, SolidWorks, OpenRocket, MATLAB, Abaqus, ANSYS)

3. Safety

3.1 Federal Regulations

The team will comply with all United States federal regulations with regards to the use of the National Airspace System (FAR 14 CFR, Subchapter F, Part 101, Subpart C) and fire prevention guidelines (NFPA 1127) for the safe and legal operation of high power rockets.

3.1.1 Federal Aviation Regulations 14 CFR, Subchapter F, Part 101, Subpart C

The team will comply with regulations set forth by the FAA to not operate a high-power rocket:

a) At any altitude where clouds or obscuring phenomena of more than five-tenths coverage prevails;
b) At any altitude where the horizontal visibility is less than five miles;
c) Into any cloud;
d) Between sunset and sunrise without prior authorization from the FAA;
e) Within 9.26 kilometers (5 nautical miles) of any airport boundary without prior authorization from the FAA;
f) In controlled airspace without prior authorization from the FAA;
g) Unless you observe the greater of the following separation distances from any person or property that is not associated with the operations:
    1) Not less than one-quarter the maximum expected altitude;
    2) 457 meters (1,500 ft.);
h) Unless a person at least eighteen years old is present, is charged with ensuring the safety of the operation, and has final approval authority for initiating high-power rocket flight; and
i) Unless reasonable precautions are provided to report and control a fire caused by rocket activities.

3.1.2 NFPA 1127 Code for High Power Rocketry

The team will comply to guidelines set forth by the NFPA to allow for the safe operation of high power rockets and to reduce the risk of injury, death, or destruction of property.

3.2 NAR/TRA Personnel Procedures

The safety plan established for use by members of HPRC is a culmination of safety guidelines regarding high power rocketry, handling of hazardous materials, and handling of explosives, rocket motors, and other energetic devices. Members are required to review and apply the safety guidelines presented below at the start of each new school year.

3.2.1 NAR High Power Rocket Safety Code

Table 3-1 contains all components of the NAR High Power Rocket Safety Code (effective August 2012) as well as how the team will show compliance to each item.

Table 3-1 NAR High Power Rocket Safety Code and Compliance Actions

NAR Safety Code Items	Compliance Action
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.	The team mentors (listed in Section 1.1) are all NAR Level 3 certified and will review technical aspects of the vehicle and provide supervision when handling rocket motors.
2. *Materials*. I will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass, or ductile metal when necessary, for the construction of my rocket.	The rocket design uses only Blue Tube composite body tubes, fiberglass, wood, and plastic. The payload contains metal ball bearings and mounts which are critical to its design. The payload bay will use small launch rails made of 6061-T6 aluminum alloy.
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.	The current rocket design utilizes a commercially-available AeroTech L1420R-P motor. The Safety Officer and mentors enforce a no smoking policy within 50 ft of rocket 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.	The team will only fly at launch sites operated by NAR/TRA to ensure that proper ignition systems are installed and working as expected.
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.	The team will rely on instructions from the NAR/TRA RSO at the launch site after a misfire occurs. Once the igniter is installed, only essential personnel may approach the rocket.

NAR Safety Code Items	Compliance Action
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.	The team will rely on the NAR/TRA RSO at the launch site to perform a 5-second countdown prior to launch. Team members are also instructed to always stop working when a launch occurs to increase bystander awareness. Team members are encouraged to communicate with each other during the launch and to point at the rocket during its descent phase to increase bystander awareness. After the rocket is constructed and motor inserted, the CG location will be measured and marked on the rocket using a sticker to confirm that the rocket has a stability margin greater than 2.0 calibers before launch. The team does not intend to perform simultaneous launches.
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.	The team will only use launch rails with blast deflectors provided at the NAR/TRA launch sites that have been approved for use by the RSO. In compliance with competition requirements, rockets will be launched at an angle 85° from horizontal, pointed into the wind. Team members are instructed to stand at least as far back as the Minimum Distance table during launches, and are encouraged to stand farther back for increased safety. The team does not intend to launch any rocket with 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.	The total impulse of the AeroTech L1420R-P motor selected for launch is 4,616 N-sec which is less than the competition maximum of 5,120 N-sec. The full-scale rocket is currently projected to weigh 40.4 lb at launch.

NAR Safety Code Items	Compliance Action
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.	The team will only launch at NAR/TRA approved launch sites with a RSO present to confirm that an FAA-approved TFR is in place over the launch site. Prior to any launch, the sky will be confirmed clear by the RSO and bystanders. If wind speeds exceed 20 mph or if the cloud level is too low, the launch will be scrubbed immediately. The team will use only the motor included in the design for launches to ensure that no part of the vehicle exceeds its expected apogee altitude.
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).	The team will only launch at NAR/TRA approved launch sites. The team plans to launch its subscale and full-scale rockets at the Bayboro, NC launch site which meets the minimum range requirements described. The final, competition launch will occur at another NAR/TRA approved launch site near Huntsville, AL.
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.	Team members are instructed to stand at least as far back as the Minimum Distance table during launches, and are encouraged to stand farther back for increased safety. Traffic at the launch site will be controlled to increase bystander safety.
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.	Both subscale and full-scale rockets will use a dual deploy recovery system with a drogue deployment at apogee and main deployment at approximately 1000 ft AGL. The payload will have its own parachute that will deploy at approximately 800 ft AGL. Kevlar cloths will be used to protect parachutes during flight and separation.

NAR Safety Code Items	Compliance Action
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.	Team members will work with the RSO to ensure that bystanders are all located upwind of the launch site. Team members are instructed to never make contact with a rocket during its descent.

3.2.2 Hazardous Materials Operations and Handling

HPRC works closely with the Department of Environmental Health and Public Safety (EHPS) at NC State to ensure that all hazardous materials are transported, stored, accessed, and used in accordance with their safety guidelines and supervision if applicable. The Rocketry Lab contains a certified flame cabinet for chemical storage that is vented and located outside of the path to the nearest exit from the Rocketry Lab.

The classifications of hazardous materials as defined by EHPS are defined as follows:

<u>Class 1 – Explosives</u>

Division 1.1	Explosives with a mass explosion hazard
Division 1.2	Explosives with a projection hazard
Division 1.3	Explosives with predominately a fire hazard
Division 1.4	Explosives with no significant blast hazard
Division 1.5	Very sensitive explosives; blasting agents
Division 1.6	Extremely insensitive detonating devices

<u>Class 2 – Gases</u>

Division 2.1	Flammable Gases
Division 2.2	Non-flammable, non-toxic compressed gases
Division 2.3	Gases toxic by inhalation

<u>Class 3 – Flammable Liquids (and Combustible Liquids)</u>

Flammable liquid	liquid with a flash point of 140°F or less
Combustible liquid	liquid with a flash point between 140°F and 200°F that does not meet any other hazard class definition.

<u>Class 4 – Flammable Solids; Spontaneously Combustible Materials; Dangerous when Wet Materials</u>

Division 4.1	Flammable solids - wetted class 1 explosives, self-reactive materials or readily combustible solids
Division 4.2	Spontaneously combustible materials -pyrophoric or self-heating materials
Division 4.3	Dangerous when wet materials - gives off flammable or toxic gas or become spontaneously combustible on contact with water

<u>Class 5 -- Oxidizers and Organic Peroxides</u>

Division 5.1 Oxidizers - by yielding oxygen, causes or enhances the combustion of other materials

Division 5.2 Organic peroxides - organic compounds with the bivalent R-O-O-R structure where at least one R is a carbon chain, except for materials that meet class 1 (Explosive) definition, or are *"forbidden"* on the HMT.

Class 6 -- Toxic Materials and Infectious Substances

Division 6.1 Poisonous materials - a liquid with an LD50 oral not more than 500 mg/Kg, or a solid with an LD50 oral not more than 200 mg/Kg, or a compound with a LD50 dermal not more than 1000 mg/Kg, or a dust/mist with a LC50 or not more than 10 mg/L

Division 6.2 Infectious substances – Go to Guide to Shipping Biological Materials and Biological Materials Online Certification for more information.

Class 7 -- Radioactive Materials

Radioactives are any material with a specific activity greater than 0.002 microcuries per gram (mCi/g). The specific activity of a nuclide means the activity of the nuclide per unit mass of that nuclide.

Class 8 -- Corrosive Materials

(Intentionally left blank)

Class 9 -- Miscellaneous Dangerous Goods

Materials that present a hazard during transport but do not meet other hazard class definitions. Examples are dry ice and lithium batteries.

3.2.3 Purchase, Storage, Transport, and Use of Rocket Motors and Energetic Devices

Commercially-produced rocket motors will be purchased from reputable vendors or distributors under the supervision of a team mentor. Motors will be transported and stored by a team mentor in accordance with manufacturer and on-campus EHPS guidelines. The motor will never be stored in the rocket and motor insertion is the final step of rocket construction at the launch site which will be conducted under the close supervision of the RSO and a team mentor.

All black powder will remain in the sealable container provided by the manufacturer for both transport and storage. When not needed, black powder is stored either with a team mentor or in the Rocketry Lab flame cabinet. When ejection charges are necessary for either testing or launch, the proper amount of black powder needed will be determined using Equation 1, below:

$$CD^2L = m_{BP} \tag{1}$$

where C is a pressure-dependent constant, D is the compartment diameter, L is the compartment length, and m_{BP} is the mass of black powder necessary (in grams). Any person handling exposed black powder must do so under the supervision of a team mentor or the Safety Officer and must wear safety glasses, gloves, and a mask in accordance with the established safety plan. Any surface where black powder is poured, measured, or spilled must be cleaned before and after handling.

3.3 Safety Plan

The following safety plan, in conjunction with the NAR and TRA regulations, is designed specifically to keep the members of HPRC and the public out of danger while also minimizing the risk of damaging materials. Clear instructions will be made available at all events with the intent of ensuring that all members follow and comprehend proper safety procedures.

3.3.1 Application of Caution Statements

HPRC will be utilizing a system of warning labels that rely on text, images, and colors to indicate the appropriate level of danger, as shown in below:

This label denotes negligible risk when risk is present. The level of danger is consistent with that which would cause minimal damage to material or user. The maximum injury sustained from this category should only require very basic First-Aid. The complexity involved with any tasks is consistent with proficiency achieved with on-site instructions from a trained member.

This label denotes a moderate level of risk. The level of danger is consistent with that which could cause moderate damage to user or material. The maximum injury sustained from this category should only require advanced First-Aid. The complexity involved is consistent with requiring prior experience or a previous instructional lesson. The area under the label may contain a short description to further inform on the condition for which a warning is necessary.

This label denotes a catastrophic level of risk. The level of danger is consistent with that which could cause major damage to user or material. The maximum level of injury sustained from this category should require hospital care, or may cause death. The complexity of this category requires considerable experience. Items or locations denoted in this way are only open to HPRC officers (Section 1.5), Senior Design (Section 1.4), and mentors (Section 1.1). The area under the label may contain a short description to further inform on the condition for which a warning is necessary.

3.3.2 Team Hazard Recognition, Accident Avoidance, and Pre-Launch Briefings

To increase hazardous awareness and recognition, and to mitigate or avoid any launch accidents, the team will follow the published TRA Pre-Flight Checklist outline:

a. General
   i. Is this member known to the TAP reviewer?
   ii. Does this member have the appropriate Certification Level or will this be a Certification Flight?
   iii. Does the proposed launch site and date have the appropriate recovery area and launch set-up for this flight?
   iv. Does the Prefect require TAP Review?

b. Rocket Review
   i. General
      1. Are there attachments to the Pre-Flight Data Capture?
      2. Drawings: airframe; structures; payloads, etc.
      3. Schematics: avionics, ignition systems, payloads, etc.
      4. Performance calculations: Center of Pressure; Center of Gravity, motor type, altitude, velocity, etc.

   ii. Airframe
      1. Is the design generally suitable for the application?
      2. Is the airframe material suitable for this rocket?
      3. Is the fin material/attachment sound?
      4. Is the motor mount sound?
      5. Is the nosecone suitable?
      6. What are the most probable airframe faults and corrective actions?
      7. What are the safety implications of an airframe failure?
      8. Are there any design change recommendations?

   iii. Recovery System
      1. Is the recovery system attachment secure/suitable?
      2. Does the recovery system have sufficient capacity for a safe descent?
      3. What is the deployment system?
      4. What are the most probable deployment system faults and corrective actions?
      5. What are the safety implications of a recovery system failure?
      6. Are there any design change recommendations?

   iv. Avionics Description
      1. Commercial or unique design?
      2. What are the functions of the avionics components?
      3. Are the avionics appropriate to the application?
      4. Do the avionics have flight safety implications?
      5. Can the avionics and inhibits be accessible from outside the vehicle?
      6. Are there safing/arming indicators?
      7. Are any of the systems redundant?

8. What are the most probable avionics system faults and corrective actions?
9. What are the safety implications of an avionics system failure?
10. Are there any design change recommendations?

v. Motor
1. Is the motor suitable for the rocket?
2. Is the motor Tripoli Certified?
3. Is the motor ignition suitable?
4. What are the most probable motor faults and corrective actions?
5. What are the safety implications of a motor failure?
6. Are there any design change recommendations?

vi. Launcher
1. Is the launcher suitable for the rocket?
2. Is the launch lug, or rail guide suitable for the rocket?
3. What will the launch angle be?
4. Are there any special launch control requirements?
5. What are the most probable faults with the launcher?
6. What are the safety implications of a launcher failure?
7. Are there any design change recommendations?

vii. Performance
1. How were the performance calculations done?
2. Were the calculations done manually?
3. Are the algorithms used correct?
4. Were the calculations accomplished correctly?
5. Was a computer used?
6. What is the source of the software?
7. Is the software suitable for this rocket?
8. Are there printouts?
9. Should the calculations be independently run?
10. What are the safety implications of poor performance data?
11. Are there any changes or recommendations?

viii. Operations
1. Is there a pre-flight checklist?
2. Which operations does it cover?
3. Are each the operations sufficiently documented?
4. Are hazardous operations flagged?
5. What are the safety implications of poor checklists?
6. Are there any changes or recommendations?

3.4 Team Member Safety Compliance

All team members must understand and abide by the guidelines and rules set forth by the NAR/TRA RSO before launching any high-powered rocket. The team understands that the RSO has final authority on determining whether a rocket launch may or may not continue.

3.4.1 Range Safety Inspection

The RSO must perform a safety inspection on the range and rocket before any launch:

Launch Systems

The RSO shall familiarize themselves with the types of launch pads available ensuring that they do not approve any flight for which there isn't a sufficient pad.

The RSO shall make a cursory examination of the Range area to ensure that the pads available have been placed appropriately according to the Safety Code.

The RSO should become familiar with the launch control systems and ensure that sufficient safety interlocks are in place to prevent accidental ignitions.

Emergency

The RSO shall confirm that adequate safety equipment is on site including a portable fire extinguisher, first aid kit, and cellular communications.

The RSO shall have available to them contact numbers for local fire departments, police, emergency medical, and power authority personnel.

Flight Operations

The RSO is to perform a Flight Safety Review (FSR) of all rockets intended for launch. Upon completion of the FSR the RSO will make a flight readiness decision. If the flight is approved this should be indicated by the RSO initialing the flight card. If minor modifications will bring the rocket to flight ready status the flyer should be informed of the required modifications and asked to return only after taking appropriate corrective actions. If a situation arises that the RSO is unfamiliar with and/or feels uncomfortable making a judgment call on, it is their obligation the find one or more experienced Tripoli members on the field to consult with. As always, the final decision rests with the Certificate of Waiver Holder.

Flight Safety Review – Safety First

At all times prior to a safe firing position on the rod, rail, tower, or other suitable ground support facility, the igniter shall not be inside the motor, and all ejection charge related electronics must be off!

Flyer

By asking to see a current membership card: verify that the individual flying the rocket is a current member in good standing of Tripoli Rocketry Association or the National Association or Rocketry; verify the certification level of the individual and that they are flying within their certification level or attempting a new certification level; observe that the individual does not appear impaired by the use of drugs or alcohol. Under no circumstances should someone who has participated in the consumption of alcoholic beverages be allowed to enter the range or launch a rocket.

Flight Card

Verify that an applicable flight card exists, is filled out in a legible manner, and indicates all of the pertinent flight data including but not limited to flyer name and

TRA number, physical vehicle parameters, motor configuration, and recovery systems. Special attention should be given to flights that are indicated as Heads-up or Certification. In the case of a Level 3 certification attempt, verify the presence of associated TAP member.

History

Ask the flyer if they have flown this particular rocket and motor combination. If they have, ask for the results of that flight. If not, ask if they have flown a similar rocket/motor combination and the outcome.

Use the results of this line of questioning to determine into how much detail the remainder of the FSR will go.

IMPORTANT: By no means does a response of "I've flown it just like this perfectly before" exempt the flyer from the remainder of the FSR.

Propulsion

Verify that the motor used is a currently certified motor or that it is on the consumer list.

Verify that the total installed power does not exceed the limitations of the field.

Verify, as best possible, that the vehicle is capable of withstanding the forward thrust that will be produced by the motor.

Verify that the initial thrust of the motor chosen will provide at least a 5:1 thrust-to-weight ratio. This can be done by one of three ways:

1. The flyer can provide documentation that shows the initial thrust produced by the motor. This can then be compared to the GLOW (Gross Lift Off Weight) of the rocket as presented.
2. The peak thrust of the motor can be assumed to be at least equal to the average thrust as indicated in the motor designation. In this case, the average Newtons produced by the motor should be converted to pounds and compared to the GLOW of the rocket as presented.
3. A printout from a flight prediction software package can be presented. In this case the prediction output should indicate the thrust-to-weight of > 5, the initial acceleration of > 5 g's, or the velocity of the rocket at the end of the rod/rail/tower > 45 f/s. The motor installed and the weight of the rocket must also be indicated and shall be verified to match the presented rocket. Verify that a suitable means of aft retention is used to keep the motor in place during the flight and recovery.

Construction

Check the structural integrity of the vehicle including the body tubes, nose cone, and fins to ensure that they are adequate to withstand the forces anticipated during the flight and recovery.

Verify the fit of the nose cone. Whenever possible hang the rocket by the nose cone. The vehicle should stay in place. With agitation however, the nose should come free or begin to come free. Exception: When shear pins are being employed ask the flyer to explain how they determined the number, size, and type of shear pins to use and what special provisions have been taken in regards to calculation of ejection charges.

Compare the fin material, stiffness, size and attachment method to the projected flight velocity and acceleration to avoid the potential for excessive fin flutter and any structural failures. If a questionable situation arises, consider assigning the flyer to a pad that is further away than the minimum setback.

Verify that a suitable launch guidance system is employed. Take into consideration the overall dimensions of the vehicle, the total weight of the vehicle, the predicted acceleration, and the current wind conditions. In the case of launch lugs or rail guides, ensure that mounting of the lug or button is sufficient to withstand the loads.

In the case of a two-stage vehicle, check the strength of the inter-stage connection. Verify that is will not buckle under the acceleration loads, and that it will separate as intended.

Stability

Verify that the rocket is of a stable design.

1. If it has flown in the current configuration with a similar motor and was stable it will likely remain stable.
2. If the design employs unusually small fins be extra careful with the stability verification.
3. Providing the C_p (center of pressure) calculation by Barrowman or other suitable calculation method should be compared to the C_g (center of gravity) as found on the flight ready vehicle. If stability calculations indicate a Cg, its accuracy should always be verified.
4. If no calculations are available or it is an untested design, use past experiences and call upon the expertise of others at the launch in coming to consensus about stability. If the stability is uncertain on an unusual design, ask for proof of stability. Any marginally stable rockets should be treated with extra concern and additional launch safety precautions should be taken.

Recovery

Verify that the parachutes selected for recovery are rated for the weight of the vehicle and the expected conditions at deployment. Confirm that the parachutes intended for the final descent phase to the ground will not allow a decent rate of >30f/s.

Verify that there is an adequate system in place to contain all of the separable parts of the rocket and parachutes at the forces anticipated during deployment. This includes adequate length of retaining cord, strength of retaining cord, and hard points for recovery system attachment.

Ensure that adequate protection is in place to prevent the hot ejection gases from causing burn damage to retaining cords, parachutes, and other vital components.

If electronics are being used to activate the recovery system, verify that an externally controllable method is being used to turn electronics on and that a known good battery is in use.

3.4.2 Range Safety Officer Clearance Policy

The RSO has the final authority to ensure that a range is safe for launch:

Range Operations

The RSO/LSO is responsible for determining the status of range operations. Before any launch begins, or in the event of a breech, the following criteria must be assessed. If not met, it is up to the RSO/LSO to halt any further launches until a safe condition is returned.

Site

The RSO shall make a cursory examination of the Range area to ensure that adequate barriers, markings, and safety measures exist to prevent unauthorized person from entering into the range and alert authorized person as to any hazardous situations.

The RSO shall make themselves aware of the largest motor that can be supported by the site area given the table in the High Power Rocketry Safety Code.

The RSO has the authority to open and close the range to any and all personnel.

Airspace

Where applicable (i.e. when entering controlled airspace):

The RSO must have knowledge that a current Certificate of Waiver issued by the U.S. Department of Transportation is in force and applies to the sections of the Federal Aviation Regulations that will be bypassed.

The RSO should have knowledge of the Special Provisions of the Certificate of Waiver and that they are being adhered to.

The RSO must have knowledge that a Notice to Airman has been issued for the date and times of the launch.

The RSO must not allow launches when aircraft are within a three-mile radius of the projected flight path.

Weather

The RSO must have clear and convincing evidence that the following constraints are not violated.

1. Do not launch if ground level winds exceed 20 mph.
2. Do not launch if the planned flight path will carry the vehicle through any clouds.
3. Do not launch if any type of lightning is detected within 10 miles of the launch site.

Time Interval Determination Method:

1. Visual confirmation of lightning flash
2. Count number of seconds until you hear thunder
3. Divide the result by five (5)
4. Result is in miles

GOOD SENSE RULE: Even when constraints are not violated, if any other hazardous weather conditions exist, the RSO may hold at any time based on the instability of the weather.

3.4.3 Links to Material Safety Data Sheets (MSDS)

GOEX Black Powder
Klean-Strip Acetone
West System 105 Epoxy Resin
West System 206 Slow Hardener
Fiberglass Fabric
Batteries
Cotton Flock
Baby Wipes
Igniters
Liquid Nails
Glass Microspheres
WD-40
Blue Tube

3.4.4 Demonstrated Team Compliance

The safety guidelines, regulations, and plans listed in Section 3 were presented to all HPRC members who then signed the following forms to indicate compliance.

By signing below, I agreed that I have read, understand, and will follow all parts of the Safety Plan shown above.

1. Print Name: Raven Lauer
   Signature & Date: [signature] 09/14/2017
2. Print Name: Graham Roper
   Signature & Date: [signature] 9/14/17
3. Print Name: John Inness
   Signature & Date: John Inness 9/14/17
4. Print Name: Gabriel Buss
   Signature & Date: Gabriel Buss 9/14/17 Ashby Scruggs
5. Print Name: [illegible] 9/14/17
   Signature & Date: ~~Ashlee Bracewell~~ 9/14/17 [signature]
6. Print Name: Ashlee Bracewell
   Signature & Date: ashlee Bracewell 9/14/17
7. Print Name: Joseph Taylor
   Signature & Date: [signature] 9/14/17
8. Print Name: Michael Canziani
   Signature & Date: [signature] 9/14/17
9. Print Name: Timothy Duvill
   Signature & Date: Timothy Duvill 9/14/17
10. Print Name: Ian Hicks
    Signature & Date: [signature] 9/14/17
11. Print Name: Walter (Cade) Buckle?
    Signature & Date: [signature] 9/14/17
12. Print Name: Jacob Sebastian
    Signature & Date: [signature] 9/14/17
13. Print Name: Joseph Richie
    Signature & Date: Joseph Richie 9/14/17
14. Print Name: Eugene Zbeichyk 9/14/17
    Signature & Date: [signature]
15. Print Name: Nolan Hopkins
    Signature & Date: [signature] 9-14-17
16. Print Name: Kaiim Higgins
    Signature & Date: [signature] 9-14-17
17. Print Name: Adithya Balaji ~~[illegible]~~
    Signature & Date: [signature] 9-14-17
18. Print Name: CHRISTOPHER HILL
    Signature & Date: [signature] 9-14-17
19. Print Name: Evan Patterson
    Signature & Date: [signature] 9-14-17

Safety officer: Erik Benson
Eric I. Benson 9-14-17

20. Print Name: David Torres
Signature & Date: [signature] 9/14/17
21. Print Name: Ryan Hollab
Signature & Date: [signature] 9/14/17
22. Print Name: Trenton Abbott
Signature & Date: [signature] 9/14/17
23. Print Name: Kevin Elliott
Signature & Date: [signature] 9/14/17
24. Print Name: Anu Shonk
Signature & Date: [signature] 09/14/17
25. Print Name: Daniel Benitez
Signature & Date: [signature] 09/14/17
26. Print Name: Michelle Nursey
Signature & Date: [signature]
27. Print Name: Andrew May
Signature & Date: [signature] 9/14/17
28. Print Name: Austin Shelton
Signature & Date: Austin Shelton 9/14/17
29. Print Name: SREEVISHNU ORUGANTI
Signature & Date: [signature] 9/14/17
30. Print Name: Brendan D'Angelo
Signature & Date: [signature] 9/14/17
31. Print Name: Michael Robertson
Signature & Date: [signature] 9/14/17
32. Print Name: Benjamin Ensle
Signature & Date: [signature] 9/14/17
33. Print Name: Ethan Johnson
Signature & Date: [signature] 09/14/17
34. Print Name: Joseph Duggan
Signature & Date: [signature] 09/14/17
35. Print Name: Timothy Chen
Signature & Date: [signature]
36. Print Name: Nick Rosato
Signature & Date: [signature] 9/14/17
37. Print Name: Jordan Schuh 9/14/17
Signature & Date: [signature]
38. Print Name: Paul von Hardenberg
Signature & Date: Paul von Hardenberg 9/14/17
39. Print Name: Jeremy Lowe
Signature & Date: Jeremy Lowe 9/14/17
40. Paul Gustman
[signature] 9/14/17
41. William Garrabrant 9/14/17
William Garrabrant
42. Kyle Corcoran 9/14/17
[signature]

3.5 Risk Assessment and Mitigation

The team will define risks according to the level of caution needed per the signage listed in Section 3.3.1. The team will utilize failure mode, effects, and criticality analysis (FMECA) tables to identify and assign risks to different subsystems. These risks will be analyzed to understand the effects of any failures and how these risks can be mitigated or eliminated. See APPENDIX A for FMECA tables.

4. Technical Design

4.1 Launch Vehicle and Experimental Payload Requirements

Per the 2018 NASA SL competition handbook, the team must successfully design, construct, and launch a recoverable and reusable high-powered rocket ("launch vehicle") of original design. Additionally, the launch vehicle must contain an experimental payload to complete one of the challenge options. The team has chosen to include a deployable rover as the experimental payload onboard the full-scale rocket. A deployable rover presents several unique challenges that blend different engineering regimes including, but not limited to, mechatronics, computer science, and mechanical and aerospace engineering. The challenge has also spurred the team to reach out to students in other relevant disciplines for help with rover design which has increased interest in the club and the NASA SL competition itself.

4.1.1 Launch Vehicle Requirements

To complete the challenge requirements, the full-scale launch vehicle must:

1. Reach an apogee altitude of 5,280 ft AGL
2. Carry at least one commercially available barometric altimeter for recording the official altitude used in determining the altitude award winner
   a. Each altimeter must be armed by a dedicated arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad, and must be capable of locking in the ON position for launch
   b. Each altimeter must have a dedicated power supply
3. Be designed to be recoverable and reusable, which is defined as being able to launch again on the same day without repairs or modifications
4. Have a maximum of four (4) independent sections, which is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute
5. Be limited to a single stage
6. Be capable of being prepared for flight at the launch site within three (3) hours of the time the FAA flight waiver opens
7. Be capable of remaining in the launch-ready configuration at the pad for a minimum of one (1) hour without losing the functionality of any critical onboard components
8. Be capable of being launched by a standard 12 V direct current firing system that will be provided by the NASA-designated Range Services Provider
9. Not require any external circuity or special group support equipment to initiate launch (other than what is proved by the Range Services Provider)
10. Use a single commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by NAR, TRA, or the Canadian Association of Rocketry (CAR)
    a. Final motor choices must be made by the Critical Design Review (CDR)
    b. Any motor changes after CDR must be approved by the NASA Range Safety Officer (RSO), and will only be approved if the change is for the sole purpose of increasing the safety margin

   c. The total impulse provided by the launch vehicle must not exceed 5,120 N-s (L-class motor)
11. Have any pressure vessels installed be approved by the RSO and meet the following criteria:
   a. The minimum factor of safety (Burst or Ultimate Pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews
   b. Each pressure vessel will include a pressure relief valve that sees the full pressure of the valve that is capable of withstanding the maximum pressure and flow rate of the tank
   c. Full pedigree of the tank will be described, including the application for which the tank was designed, and the history of the tank, including the number of pressure cycles put on the tank, by whom, and when
12. Have a minimum static stability margin of 2.0 at the point of rail exit, which is defined as the point where the forward rail button loses contact with the rail
13. Accelerate to a minimum velocity of 52 ft/s at rail exit (rail exit velocity)
14. Have a successful launch and recovery of a subscale rocket model prior to CDR
   a. The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale cannot be used as the subscale
   b. The subscale must carry an altimeter capable of reporting the apogee altitude
15. Have a successful launch and recovery, which is defined as a launch where all hardware functioned properly, prior to FRR in its final flight configuration using the same rocket that will be flown on the competition launch day
   a. The vehicle and recovery system must have functioned as designed
   b. The experimental payload does not have to be flown on the full-scale test flight, but the rocket must include mass simulators located in the same approximate location on the rocket as the missing payload mass to simulate the payload as installed
   c. If the experimental payload changes the external surfaces of the rocket or manages the total energy of the vehicle, those systems must be installed and active during the full-scale demonstration flight
   d. The full-scale motor does not have to be flown during the full-scale test flight, however, it is recommended that the full-scale motor be used to demonstrate the full flight readiness and altitude verification
      i. If the full-scale motor is not flown during the full-scale flight, it is desired that the replacement motor simulates, as closely as possible, the predicted maximum velocity and maximum acceleration of the launch day flight
   e. The vehicle must be flown in its fully ballasted configuration, which is defined as the same amount of ballast that will be flown during the launch day flight, during the full-scale test flight
      i. Additional ballast cannot be added without a re-flight of the full-scale launch vehicle
   f. Full-scale flights must be completed by the start of FRRs, and if the SL office determines that a re-flight is necessary, then an extension to March 28, 2018 will be graded and is valid only for re-flights, not first-time flights

   g. After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA RSO
16. Have any structural protuberances on the rocket be located aft of the burnout center of gravity
17. Not include any of the following prohibitions:
    a. The launch vehicle will not utilize forward canards
    b. The launch vehicle will not utilize forward-firing motors
    c. The launch vehicle will not utilize motors that expel titanium sponges
    d. The launch vehicle will not utilize hybrid motors
    e. The launch vehicle will not utilize a cluster of motors
    f. The launch vehicle will not utilize a friction-fitting for motors
    g. The launch vehicle will not exceed Mach 1 at any point during the flight
    h. Vehicle ballast will not exceed 10% of the total weight of the rocket

4.1.2 Recovery System Requirements

To complete the challenge requirements, the launch vehicle and experimental payload recovery systems must:

1. Have staged deployment of its recovery devices, where a drogue parachute is deployed at apogee and a main parachute is deployed at a lower altitude
    a. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provide that the kinetic energy during the drogue-stage descent is reasonable, as deemed by the NASA RSO
2. Have demonstrated successful ground ejection tests for both the drogue and main parachutes which must be done prior to the initial subscale and full-scale launches
3. Have each independent section of the vehicle experience a maximum kinetic energy of 75 ft-lb_f at landing
4. Have electrical circuits that are completely independent of any payload electrical circuits
5. Have all power supplied to recovery electronics be from commercially available batteries
6. Contain redundant, commercially available altimeters, which includes both simple altimeters and more sophisticated flight computers
7. Not rely on motor ejection for a primary or secondary deployment
8. Contain removable shear pins for both the main parachute compartment and drogue parachute compartment
9. Have a recovery area limited to a 2,500 ft radius from the launch pad
10. Include an electronic tracking device that will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver
    a. Any rocket section or payload components that lands untethered to the launch vehicle must also carry an active electronic tracking device
    b. All electronic tracking devices must be fully functional during the official flight on launch day
11. Not be adversely affected by any other onboard electronic devices during flight

a. The recovery system altimeters must be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device
b. The recovery system electronics must be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics
c. The recovery system electronics must be shielded from all onboard devices that may generate magnetic waves to avoid inadvertent excitation of the recovery system
d. The recovery system electronics will be shielded from any other onboard devices that may adversely affect the proper operation of the recovery system electronics

4.1.3 Deployable Rover Requirements

To complete the challenge requirements, the deployable rover must:

1. Deploy from the internal structure of the launch vehicle
2. Receive a remote trigger command to deploy from the rocket after landing
3. Autonomously move at least 5 ft in any direction from the launch vehicle
4. Deploy a set of foldable solar cell panels once it has reached its final destination

4.2 Launch Vehicle Specifications

Per the 2018 NASA SL competition rules, the team must successfully design, construct, and launch a recoverable and reusable high-powered rocket of original design. Additionally, the launch vehicle will contain the deployable rover system as its payload.

4.2.1 Rocket Dimensions

The rocket was designed using OpenRocket, a free software that is utilized by NAR/TRA rocketeers at all certification levels. The rocket is proposed to be 108 in. long with a constant body diameter of 7.5 in. A large diameter was chosen to allow to maximize the amount of space available for the payload with deployable rover. The rocket will have three body sections: nosecone, midsection, and fin can. At launch, the sections will be secured together using couplers with shear pin fasteners to ensure that the rocket will maintain its shape during flight, but can also separate easily during the descent. Figure 4-1, below, shows the OpenRocket 3D schematic with body sections labelled accordingly.

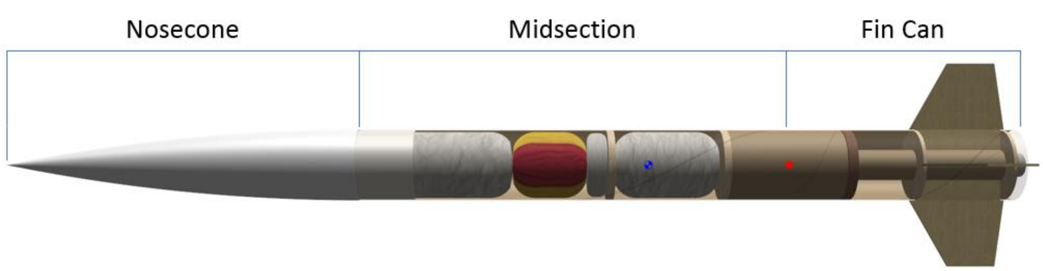

Figure 4-1 OpenRocket 3D Schematic for Rocket

In its current configuration, the rocket CG is located 68.0 in. from the nose tip, and the CP is located 83.3 in. from the nose tip, giving the rocket a static stability margin of 2.04 at full launch weight. At launch the rocket will weigh a predicted 42.1 lb at launch and

36.4 lb at motor burnout. As the rocket motor burns, the CG location will shift forward, thus increasing the static stability margin during flight. This meets the competition requirements of having a static stability margin of at least 2.0 at the rail exit, while also keeping the stability margin low enough that the rocket is less likely to be affected by wind gusts during flight.

4.2.1.1 Nosecone Design

The rocket will use a 5:1 Ogive nosecone, allowing for a base diameter of 7.5 in. to match the body, and a length of 37.5 in. This nosecone shape was chosen for its positive aerodynamic capabilities, commercial availability, and long length. The minor slope from the tip to the base of an Ogive nosecone reduces the amount of drag produced at the surface, which is especially beneficial for a rocket in high-speed flight. Ogive nosecones are a very common product and are available from a variety of rocketry component vendors. Since the rocket will have a wide body tube diameter, the variety in nosecone selection may be smaller than for rockets with more standard diameters of 3-6 in.

Since the rocket is so wide, it was necessary to place the larger mass components closer to the nose to shift the rocket CG forward to achieve the required stability margin of 2.0 at the end of the launch rail. The long length of the nosecone allows any nose ballast to have a greater influence on the position of the CG along the length of the rocket. In its current configuration, the nosecone contains 2 lb of ballast located at the nose tip in the form of a machined metal tip, which is less than 5% the total launch weight. The metal tip will also increase reusability of the rocket since it will protect the fiberglass nosecone body against cracking or chipping when impacting the ground at landing. Figure 4-2, below, shows the side view of the nosecone in OpenRocket, where the metal nose tip is modelled as a point mass located at the nose of the rocket.

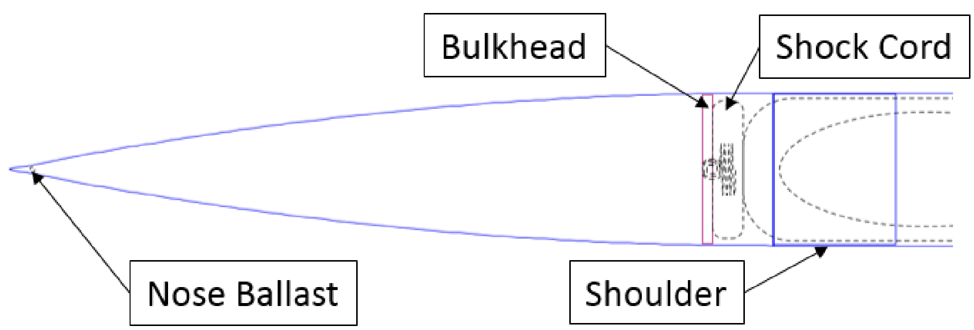

Figure 4-2 OpenRocket Side View Schematic of Nosecone

As shown above, the nosecone will contain a bulkhead installed 3 in above the base of the nosecone to allow for shock cord attachment using a U-bolt. The shock cord will connect to the main parachute and will tether the nosecone and midsection. The nosecone will connect to the midsection through the use of a shoulder that will act as a 6 in long coupler fastened by shear pins for launch. Some vendors offer nosecones with pre-formed shoulders, which would be ideal.

4.2.1.2 Midsection Design

The midsection of the rocket will contain the payload, main parachute, and avionics bay ("AV bay"). To keep the stability margin within acceptable levels, the payload will be stowed at the forward-most point in the midsection, where the nosecone and midsection attach. The main parachute will be packed aft of the payload in the same body compartment. Since the payload will eject with the main parachute, the two will be deployed together using a single black powder charge placed aft of the main parachute. Since the compartment is larger than a simple parachute compartment, the black powder charge will be much larger and the parachute will have to be protected accordingly. Figure 4-3, below, shows the side view schematic of the midsection in OpenRocket, where the entire payload system is modelled as a simple mass component for the proposed design.

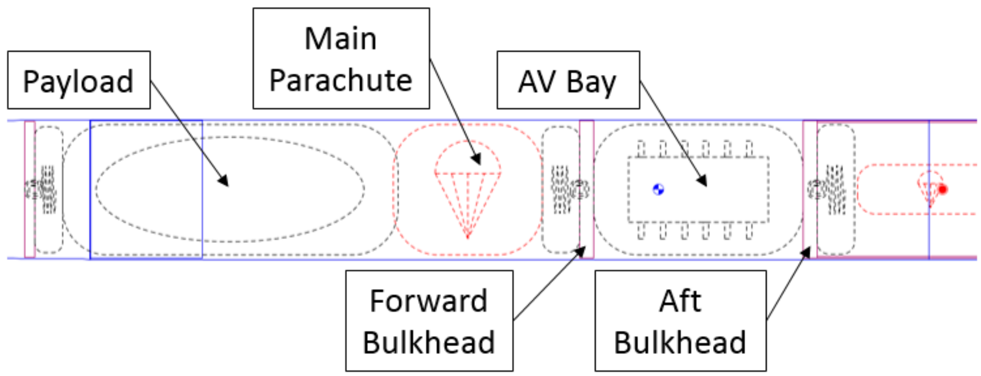

Figure 4-3 OpenRocket Side View Schematic of Midsection

As shown above, the shock cord connected to the forward AV bay bulkhead will be tethered to the nosecone bulkhead. The aft AV bay bulkhead will separate the midsection and the fin can, and the shock cord will connect to the drogue and keep both sections tethered together. A 12 in. long coupler (6 in. on either side of the body tube seam) will be used to connected the midsection and fin can, which will be fastened using shear pins for launch.

To facilitate easier installation of avionics during rocket assembly, a hatch will be utilized as part of the midsection body tube. The hatch will be cut out of the body tube in between the forward and aft AV bay bulkheads. To secure the hatch for flight, holes will be drilled on the corners of the hatch and the sides of the bulkheads. Once all electronics are secured within the AV bay, the hatch will be screwed back on which will secure it for flight.

The AV bay sled will hold three 9 V batteries, one Stratologger altimeter, one Entacore altimeter, and one Redbee 900 GPS tracker. The altimeters and GPS tracker will each be independently powered. The StratoLogger altimeter will be the competition altimeter, and will be wired to two ejection charges: one for the separation of the fin can for drogue deployment and one for the separation of the nosecone for main chute and payload deployment. The Entacore altimeter will be will be wired to two backup charges, one for each separation event, each containing slightly more black powder than the primary charge and activated with a 1 second delay. Since each altimeter will have its own battery, they will have independent circuits and will be independently redundant. Two key switches will be mounted to the body tube of the rocket to allow the altimeters to be powered on using a key. This will also ensure that the switches remain in the ON position once each key is removed.

The altimeters used will not be sensitive to RF radiation, so there will be no interference from the GPS tracker, and no risk from placing the GPS tracker in the same bay as the altimeters. The two altimeters will be of different types to reduce the risk of both altimeters failing due to a manufacturers defect affecting a line of altimeters. To ensure that the altimeters are working correctly, both altimeters will be tested by hooking them up to an LED and sealing them in a vacuum chamber, then checking that the light turns on at the pressure it was programmed to.

4.2.1.3 Fin Can Design

The rocket fin can will contain the engine block, centering rings, and motor, as well as four trapezoidal fins mounted to the body tube and motor tube using fin tabs. The engine block will be 1 in. thick, and will be epoxied into the fin can at the bottom of the coupler. This will allow some loading sharing to occur between the engine block and coupler during flight to reduce stress on the engine block itself. The engine block will also have a U-bolt that will connect to the drogue parachute shock cord to tether the midsection and fin can together after deployment. The fin can and midsection will be connected using a coupler and shear pin fasteners for launch. A inner body tube made of fiberglass will act as the motor tube, which will be held in place by two centering rings: one close to the center and another at the aft-most point of the rocket. Figure 4-4, below, shows the side view schematic of the fin can in OpenRocket.

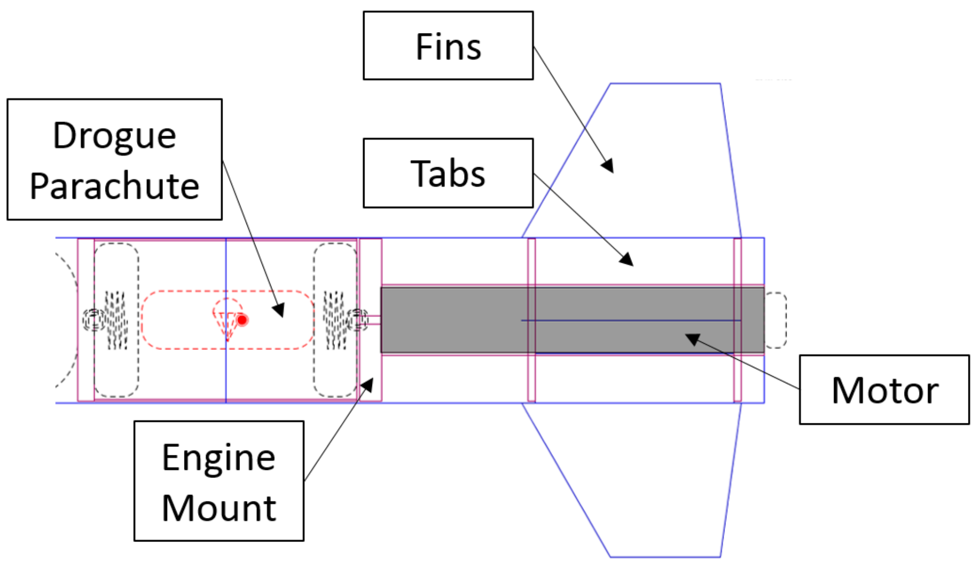

Figure 4-4 OpenRocket Side View Schematic of Fin Can

Each trapezoidal fin will have a root chord of 10 in., tip chord of 5 in., and a sweep angle of 29.7°. The fins will be mounted so that the trailing edge of the root chords will be located 1 in. from the aft-most point of the rocket. This will aid in mitigating damage to fins during assembly and recovery, thus increasing the reusability factor of the entire rocket. The fins will be rounded on the leading and trailing edges to decrease drag. The fin tabs will extend through slits cut in the body tube and will sit against the fiberglass motor tube. This will allow the fins to be epoxied directly to the motor tube. The centering rings will be placed on each end of the fin tabs to keep the motor centered in the body tube while also holding the fins in place. This configuration will increase the strength and stability of the fins and will ensure that the motor does not move during flight.

4.2.2 Material Selection

Analysis in OpenRocket shows that the rocket will not experience supersonic velocity, which allows for a greater selection in body tube material. Since the rocket body will have a 7.5 in. diameter, body tubes made of fiberglass will be excessively large, heavy, expensive, and far stronger than necessary for mission profile. To reduce the weight and cost of the rocket without sacrificing strength, the body tubes will be constructed using Blue Tube 2.0, a high-density, vulcanized fiber product that is commercially available from a variety of venders. Blue Tube is also available in a variety of body tube sizes which will allow for greater design freedom for the rocket. To smooth the outer surface and protect the Blue Tube from moisture and water, the body tube exterior will be coated and sealed using sanding primer. After sealing, the exterior will be lightly sanded to prepare the surfaces for paint. Initial weight calculations show that choosing Blue Tube instead of fiberglass will save over 2 lb of weight in the body tubes alone.

The nosecone will be purchased as a fiberglass component with a machined metal tip. Unlike the body tubes, a fiberglass nosecone is desirable since it weighs more than a plastic nosecone of the same size. Larger weight at the nose will cause the CG to move up the rocket, thus creating a positive effect on the static stability margin. Fiberglass nosecones of the desired shape and size are available for purchase from commercial vendors with or without shoulders at the base.

The motor tube that will contain the motor casing will also be made of fiberglass for the full-scale rocket. This will allow for a stronger surface around the motor casing, and will allow for better load sharing along the fiberglass tube than a Blue Tube of the same size.

The fins will be constructed using two sheets of 1/8 in. birch aircraft plywood mated together and sealed with epoxy resin. Using two sheets reduces the effects of fin flutter during flight, and the simple manufacturing method will decrease the cost to produce each fin. After the fins are produced, the leading and trailing edges will be sanded to a curved shape using small sanding tools available in the lab. In the event of a fin failure after landing, the subject fin can be removed from the body tube and easily replaced with an available spare.

Internally, the nosecone, midsection, and fin can will be supported by several bulkheads to separate individual compartments and serve as attachment points for recovery systems. These bulkheads will be constructed using layers of 3/8 in. birch aircraft plywood joined using epoxy. Some bulkheads may require additional strength which could be achieved by adding layers of fiberglass to the stack up. The engine mount will be constructed using additional layers of birch aircraft plywood and layers of fiberglass for additional strength. These structures will be manufactured via wet layup on a clean surface free of debris. A vacuum will be applied to maintain -20 inHg while the epoxy will be allowed to cure for 8-12 hours.

4.2.3 Motor Selection

With a predicted launchpad weight of 42.1 lb, with the motor and propellant included, an L-class motor is required to reach an apogee of 5,280 ft AGL. Using the results from OpenRocket simulations, the team chose to use the AeroTech L1420R-P motor which has the required thrust and impulse need to reach the required apogee. This motor has a total specific impulse of 4,616 N-s (1037.7 lb_f-s) and a burn time of 3.18 s, which puts it below the maximum impulse allowed by the competition requirements. The motor itself will fit within an AeroTech 75/5120 motor casing which corresponds to a diameter of 2.95 in and a length of 17.4 in. A simulation in OpenRocket shows that this motor will send the rocket to an apogee altitude of approximately 5,300 ft AGL. Though the apogee is slightly higher than the required 5,280 ft, there is room in the rocket design for weight fluctuation which can be controlled using nose ballast to improve the accuracy of the rocket in achieving the goal apogee.

4.2.4 Projected Altitude

Running an OpenRocket launch simulation in ideal conditions has produced a projected apogee altitude of 5,308 ft AGL. The simulation was run with no wind speed, standard temperature and pressure, an 8 ft launch rail, and a launch orientation of 5° from vertical. Figure 4-5, below, shows the OpenRocket simulation plot of altitude (red), vertical velocity (blue), and vertical acceleration (green). Note that the simulation does not include a payload ejection with main parachute, which does not affect apogee.

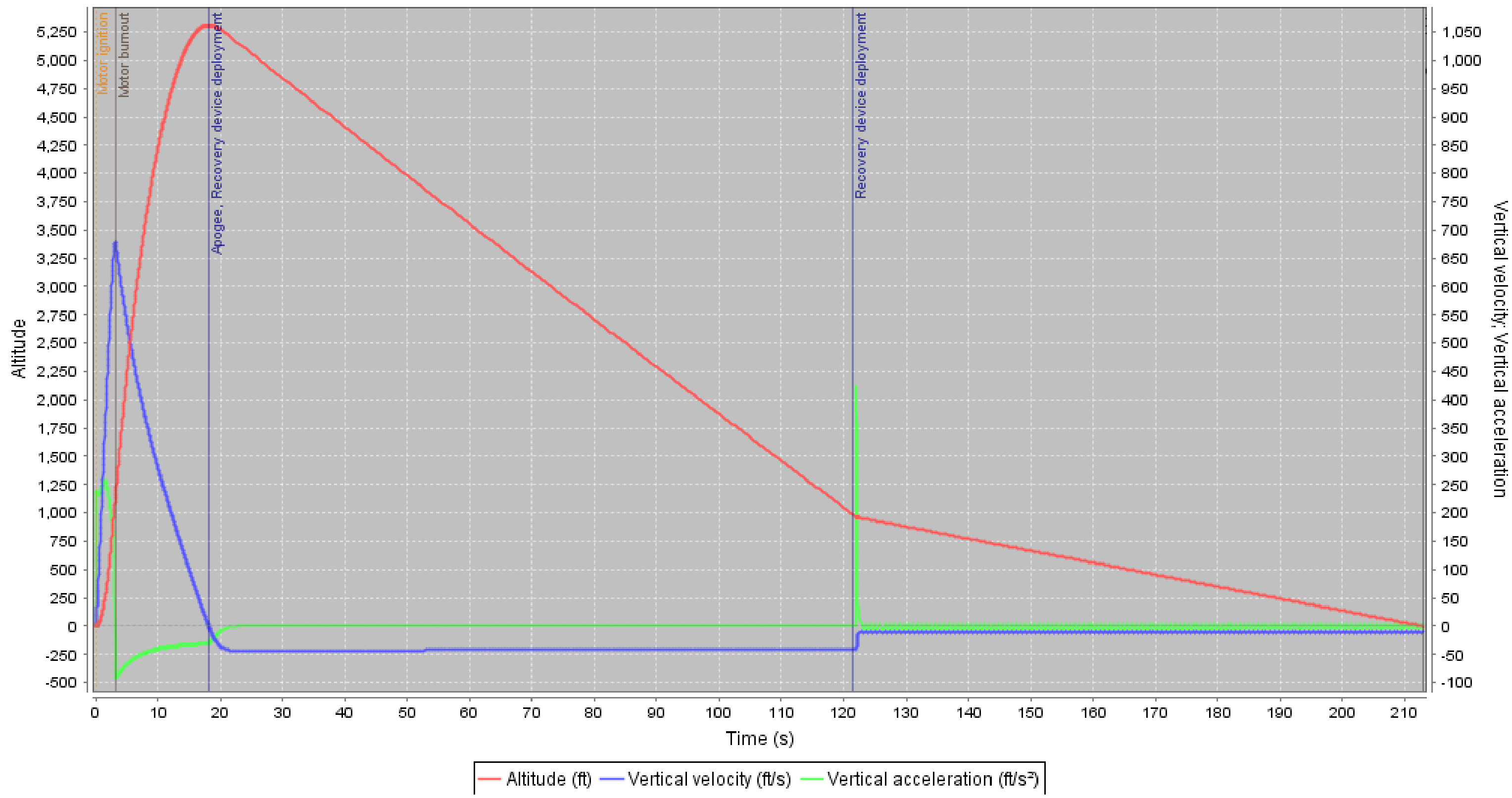

Figure 4-5 OpenRocket Simulation Results for Full-Scale in Ideal Conditions

A predicted altitude of ~5,300 ft AGL is very reasonable and close to the goal altitude of 5,280 ft AGL. The apogee altitude is expected to decrease as epoxy, fasteners, and paint are added to the full-scale rocket. The simulation also assumes a maximum payload weight of 7 lb. The team determined the maximum allowable payload weight using Table 4-1, below, which shows the results of OpenRocket simulations in ideal conditions with varying payload weights.

Table 4-1 OpenRocket Simulation Apogee Results with Varying Payload Weight

Payload Weight (lb)	Rocket Weight (lb)	Necessary Nose Ballast (lb)	Apogee (ft AGL)
5.0	40.7	2.6	5,456
5.5	41.1	2.5	5,416
6.0	41.3	2.3	5,389
6.5	41.7	2.1	5,352
7.0	42.1	2.0	5,308
7.5	42.3	1.7	5,287
8.0	42.6	1.5	5,247

As work on the payload design continues, the team is confident that the final product will fit the 7 lb allowable weight budget. As the projected weight of the payload changes, the OpenRocket model will be updated and re-run accordingly.

Table 4-2, below, shows results for variables listed in the launch vehicle requirements from the NASA SL office (Section 4.1.1) after using the OpenRocket simulation in ideal conditions for the full-scale rocket.

Table 4-2 OpenRocket Simulation Results in Ideal Conditions

Variable	Simulation Result
Apogee	5308 ft
Max Acceleration	260 ft/s^2
Exit Rail Velocity (8 ft rail)	64 ft/s
Maximum Velocity (Mach Number)	683 ft/s (M = 0.61)
Ground Impact Velocity	9.8 ft/s

After analyzing the results of the OpenRocket simulations, the team is confident that the results are reasonable and that the rocket will perform as expected once the design is finalized and constructed.

4.2.5 Rocket Recovery System

The rocket will feature a dual deployment parachute recovery system to ensure that the rocket lands safely after each flight. The recovery system relies on 3 main events, drogue deployment, main parachute deployment, and payload parachute deployment, as shown in Figure 4-6, below.

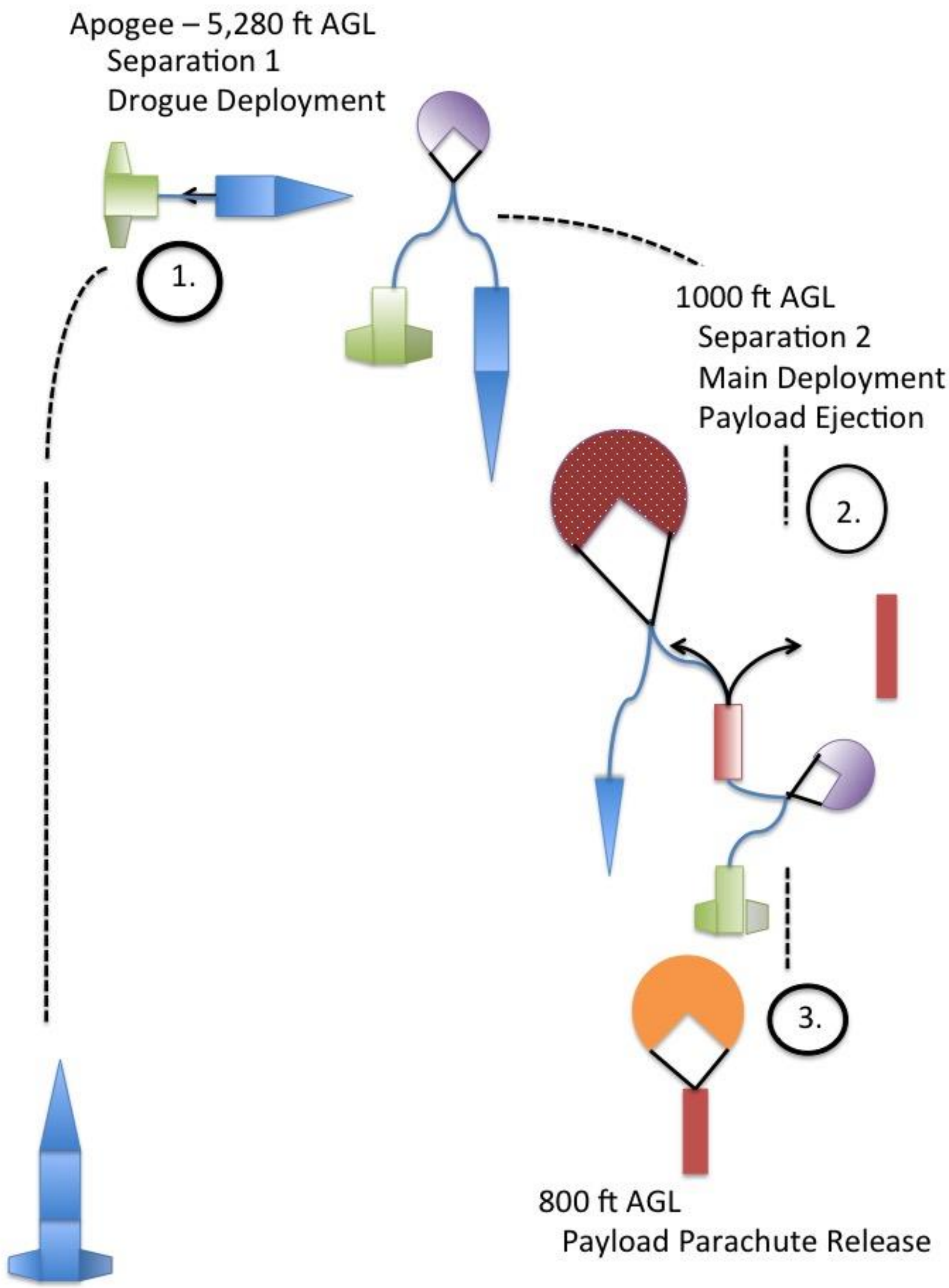

Figure 4-6 Visualization of Rocket and Payload Recovery Systems

At a goal apogee altitude of 5,280 ft AGL, the rocket will have its first black powder event to separate the midsection and fin can to deploy the 48 in. (4 ft) drogue parachute, a Fruity Chutes Iris Ultra 48 in. Standard Parachute IFC-48. Equation 2 was used to determine the descent rate of the empty rocket, weighing 36.4 lb after burnout, while under the drogue:

$$S = \frac{2gm}{C_d \rho V^2} \tag{2}$$

where S is the projected area of the parachute, g is gravity acceleration, m is empty mass of the vehicle under parachute, C_d is the coefficient of drag, ρ is air density, and V is descent velocity. S and C_d were varied in calculations based off of information gathered from the Fruity Chutes website. For the chosen parachute, S = 12.20 ft^2 and C_d = 2.2 which led to a calculated velocity of descent of 32.8 ft/s when assuming standard sea level conditions for the remaining variables. After using this parachute in OpenRocket rocket launch and recovery simulations, it was determined that the drogue size and descent rate of the rocket were acceptable.

To ensure a safe separation distance between the fin can and midsection/nosecone while descending under drogue, a total length of 22 ft of shock cord will be used: 14 ft between the AV bay aft bulkhead and the drogue, and 8 ft between the drogue and the fin can bulkhead. Since the fin can is only 2 ft long, it will ensure a separation of approximately 4 ft between the fin can and midsection while descending under drogue.

At approximately 1,000 ft AGL, the second black powder event will occur to separate the nosecone and midsection to eject the payload and deploy the 144 in. (12 ft) main parachute, a Fruity Chutes Iris Ultra 144 in. Parachute IFC-144, which is shown as Separation 2 in Figure 4-6. While stowed in the payload compartment, the parachute will be housed in a deployment bag to protect it from the black powder ejection charge and to eliminate the risk of the parachute tearing or getting stuck on the payload rails. After the 7 lb payload is ejected, the empty weight of the rocket will decrease to 29.4 lb. Using S = 109.59 ft^2 and C_d = 2.2, both taken from the Fruity Chutes website, the velocity of descent for the rocket after payload ejection was calculated to be 10.1 ft/s, which ensures that the rocket body will land safely. The OpenRocket simulation using this recovery configuration results in a landing velocity between 9.8 and 10.2 ft/s depending on airspeed which matches perfectly with the value calculated above.

To ensure a safe separation distance between the fin can and midsection/nosecone while descending under the main parachute, a total length of 24 ft of shock cord will be used: 8 ft between the nosecone bulkhead and the main, and 16 ft between the main and the AV bay forward bulkhead. Since the nosecone is 3.1 ft long, it will ensure a separation of approximately 5 ft between the nosecone and midsection while descending under the main parachute.

Following the competition rules, the team will always conduct ground tests of black powder ejection events to confirm the quantity necessary to confidently separate rocket sections without damaging any components before each flight.

4.3 Experimental Payload Specifications

Per competition requirements for the deployable rover experimental payload, the team must successfully design a rover that will be stowed within the launch vehicle and deployed after landing to drive 5 ft autonomously, then deploy a set of folding solar panels.

4.3.1 Payload Dimensions

The proposed payload body will consist of two concentric 0.125 in. thick acrylic tubes. The outer tube will have an outer diameter of 6 in. and the inner tube will have an outer diameter of 5.25 in., leaving a 0.25 in. gap between the tubes. The outer tube will have a length of 20 in. and the inner tube will have a length of 12 in. The forward edge of the inner tube will be flush with the forward edge of the body tube, leaving an opening 8 in long to be used for the inner tube mount, payload bulkhead, and payload parachute. As discussed in Section 4.2.4, the entire payload system cannot weigh more than 7 lb. Figure 4-7, below, shows a side view of the entire payload with critical components installed and labeled.

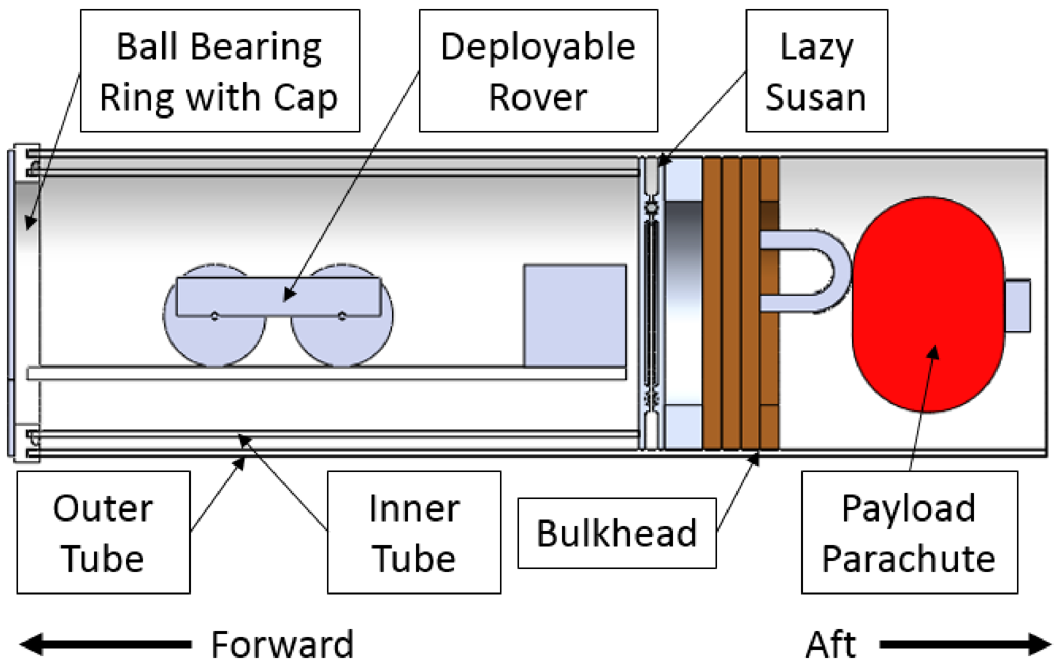

Figure 4-7 Payload Side View with Major Components Labeled

When stowed in the rocket payload compartment, the clearance between the rocket body tube and the outer payload tube will be approximately 0.75 in. A rail system will be mounted to the inner surface of the rocket body tube that will contain the payload during flight using rail buttons mounted to the payload outer tube exterior. This system was used to deploy a similar payload structure during the 2016-17 NASA SL competition. The system was tested many times both on the ground and in flight, and the payload never failed to eject if the correct amount of black powder was used to separate the sections. The gap between the payload and rocket body tube will also allow gases from the black powder charge to expand in the compartment, and will give space to store the shock cord tethering the nosecone, midsection, and main parachute.

4.3.2 Payload Design Aspects

The payload will have two main sections: the rover section and the recovery section. The payload will be designed so that the inner tube will spin freely inside the outer tube during launch, recovery, and landing. This will be accomplished by attaching the inner tube to a Shepherd #TV09547 TV 4 in. Lazy Susan Turntable bearing, which is mounted to the payload bulkhead. To ensure that the inner tube is supported on the forward end, a cap will be 3D printed and fitted over the edges of the two tubes. The cap will include a raceway for 3 mm ball bearings to be mounted within the cap which will allow the inner tube to rotate freely. To ensure that the cap will not detach during descent, it will be mounted to the outer tube while leaving a small amount of clearance around the inner tube as to not impede its rotation.

The payload will have its own suite of electronics in the rover bay separate from the rover itself that will contain a battery, GPS tracker, radio receiver, and small servo to unlatch the rover and operate the tube door. The door will protect the rover from the black powder charge at separation, and will prevent any dirt or debris from entering the rover bay at landing.

The inner tube section will be designed so that the weight distribution will naturally tend to keep the rover on the bottom of the tube when it lands. This will act as a natural self-righting mechanism to allow the rover to exit without any issues. This exiting process will entail a remote trigger to release any latches securing the rover as well as releasing the door latch. The rover then will be able to drive out, pushing the door open as it exits. The team is confident that this design will ensure that the rover is always capable of exiting the payload right-side-up and without any dirt, debris, or damage blocking its path.

4.3.3 Payload Recovery System

As shown in Section 4.2.1.2, the payload will be housed in the same compartment as the main parachute. Since the nosecone and midsection are tethered together, some length of shock cord will be stowed in the space between the payload body and the rocket body tube. Since the rocket will be descending under drogue when the payload is deployed, it can be assumed that the rocket nose will be pointed downward, which will reduce the risk of any midair collisions after the payload is ejected. The team intends to conduct extensive testing to ensure that the first black powder charge is powerful enough to separate the nosecone and eject the 7lb payload without damaging the parachute housed in its deployment bag.

Since the payload will eject completely from the rocket body, it will require its own recovery system. The payload parachute will be packed into the rover deployment tube and will be secured using a Jolly Logic Chute Release (referred to as Jolly Logic) and covered by a Nomex sheet to protect it during the black powder event. After the payload is ejected at 1,000 ft AGL, it will freefall for approximately 200 ft to ensure that the payload is able to distance itself from the rocket before landing. At approximately 800 ft AGL, the Jolly Logic will disconnect to deploy the 60 in. (5 ft) payload parachute, a Fruity Chutes Elliptical Parachute CFC-60. Using S = 18.85 ft^2 and C_d = 1.5, both taken from the Fruity Chutes website, the velocity of descent for the 7 lb payload was calculated to be 14.4 ft/s, which ensures that the payload will land safely. It is also ideal to have the payload descend at a rate faster than the rocket to ensure that it lands first to allow the rocket to drift further away to reduce the risk of collision either midair or on the ground. The team intends to prove that the rocket and payload will maintain sufficient separation in the air and on the ground using OpenRocket and MATLAB to simulate their descent in a variety of environmental scenarios.

4.3.4 Deployable Rover Specifications

In addition to the requirements listed in Section 4.1.3, the rover must be able to fit within the space available in the payload inner tube and be released by a servo latch after landing. The team chose to design a rover with tracks to maximize traction, power efficiency, and volume efficiency. When compared to wheels, treaded tracks allow for greater grip when driving over rough terrain, as will be the case for this rover, and are less susceptible to getting stuck. Tracks also require less power to perform at similar levels to wheels, and the space inside the tracks and between the powered gears can be utilized for additional storage. The team has been able to recruit new members with past rover experience who are familiar with designing tracks and their capabilities. Tracks will also allow for easier assembly and repairs if needed.

During flight, the rover is kept in place by prongs in the front and back of the compartment that force the rover against the floor. Upon landing, the self-righting payload tube will rotate into the correct orientation due to the weight imbalance. A radio signal will be simultaneously sent to the payload and rover after landing is confirmed. Radio receivers on the rover and payload will trigger a chain of events that includes unlatching the rover, unlocking the door, and then driving out of the compartment.

The rover will utilize a single motor located at the front to rotate the front gear wheels, thus pulling the tracks around their housings to drive the rover forward. The motor will remain active long enough for the rover to travel at least 5 ft laterally from the payload landing site, then will stop in place. After stopping, solar panels will be deployed from their stowed position inside the tracks.

The rover body will consist of two 3D printed shells designed to hold all electronics which include an Arduino Pro Mini, GPS transmitter, radio receiver, battery, motor, and servo. Considerations will be made during the rover body design to ensure that all components use minimal wiring to reduce the total volume needed to house all electronics. The shell design will allow for easier rover assembly and will protect the electrical components from dirt and debris after exiting the payload.

An Arduino board was chosen for its simplicity and popularity, and extensive literature is available for reference in case any issues may arise. The rover will use an FS90 servo based on reliability, size, and power availability. An XBee Pro 900 XSC S3B radio transceiver will be used because of its high-performance capabilities, low power consumption, and long range. A small 1000 mAh LiPo battery will be used to power all electronics onboard and should have the power storage necessary to keep the system alive while waiting on the launch pad. To meet the requirement of deployable solar panels, flexible solar panels were chosen. They can be stowed in the track housing for a space efficient design and unfurled after the rover reaches its final destination.

4.4 Alternate Payload Designs

Before deciding to pursue the self-righting payload with a small, treaded rover, the team discussed other possible payload options, as well as the challenges associated with each.

4.4.1 Quad Recovery System

The quad recovery option would have used a self-powered, autonomous quadrotor vehicle to have a powered descent to landing. The quad would have folded its arms up to stow in the payload compartment during launch. At apogee, the quad would deploy and follow a sequence of commands to unfold, check power supply, power individual rotors, then apply power across all rotors. This would allow for a quick system diagnostics test before the rotors are given full power. A back up parachute would be installed and ready to deploy in case the flight computer ever detected an anomaly, or if the RSO triggered the event. After landing, the rover would either fold out from the side of the quad or drive out from a platform suspended below.

The team chose not to pursue this recovery option due to its complexity, high cost, and the team's lack of experience with quadrotor design and autonomous flight. The team approached several other students, clubs, and instructors that had built similar vehicles in the past, and they were very helpful in building a parts list and understanding the full technical requirements.

4.4.2 Omni-Wheel Rover

The omni-wheel rover design is an alternate solution to using a self-righting floor and treads. An omni-wheel is a commercial product that features 6-8 small discs mounts on the outside edges of a single larger wheel. If installed on the rover, it would allow the rover to roll freely within the payload tube and drive out after landing at any angle. The wheels are relatively cheap and would allow for a slightly larger rover since the floor underneath would be unnecessary.

The team chose not to pursue this option because it presented several issues with regards to stowing the rover during flight, as well as battery and radio receiver placement. Since the rover itself is free-spinning, it would not be able to "disconnect" from a payload base like the current payload design, so all payload electronics would have to be housed in the rover itself. This would require larger onboard batteries which would increase the weight of the rover itself.

4.4.3 "Hamster Wheel" Rover

A section of the body tube that could roll around on its own using internal wheels and motors, hence the "hamster wheel" name, would allow the rover to have a large internal volume to store wheels, motors parachutes, electronics, and batteries. The internal portion of the rover would be set within the body tube so that the wheels could run against the inner wall of the body tube. As the powered, internal wheels spin against the inside of the body tube, the entire section would roll around.

The team chose not to pursue this option because it would require a section of the rocket body to separate completely which would require additional parachutes and GPS trackers. Since the rocket is already at its maximum weight to reach an apogee of approximately 5,280 ft AGL, it would not be possible to add all the additional components as well as a larger rover.

5. Educational Engagement

5.1 Description of Outreach

Each outreach event is planned different to correspond with the STEM topics requested by the outreach coordinator or contact. Most outreach events include a presentation on the club, NASA SL details, and a topic in rocket design, STEM, general aerodynamics, or all three. After the presentation, there is a hands-on demo that varies according to the specific event. Most hands-on demos teach participants to build and fly their own water bottle rockets. After each flight, participants are encouraged to make changes to their design to compare the effects of adding fins or nosecones, and how the level of water "propellant" affects the flight. This exposes students (and often parents) to the engineering design cycle that is integral to the field. For the current school year, upcoming demos will include more small experiments to teach participants about other topics including Newton's Laws of Physics, thermodynamics, and dynamics.

5.2 Last Year in Review

During the span of the NASA SL competition last year, HPRC reached over 7,500 students and adults in the local community around Raleigh, NC. The team's outreach helps inspire future scientists, engineers, and others pursuing STEM careers. The team strives to make a difference in the lives of youth by introducing them to STEM careers and by building relationships with local organizations and K-12 schools in the community. The focus for these events is always on quality over quantity and to make a lasting impact on everyone through small group discussions and hands-on activities. Figure 5-1, below, shows three members of HPRC who coached students participating in the Science Olympiad to help them learn basic rocket aerodynamics by building their own water bottle rockets.

Figure 5-1 HPRC Members John, Zach, and Amy After Coaching Science Olympiads

5.3 Planned Outreach

2017 JY Joyner Science Go Round
HPRC plans to attend Science Go Round, a STEM event hosted by JY Joyner Elementary. This event will be set up like classes with groups of students rotating through different classrooms to see presentations. Other science and engineering organizations will be present at the Science Go Round talking about their involvement with STEM.

2018 Astronomy Days
The club will continue its support of Tripoli Rocketry Association to help at their booth for Astronomy Days hosted by the North Carolina Museum of Natural Science. Members of the club will talk to the general public about high-powered rockets and our participation in NASA SL using past rockets as examples of completed projects.

Club members have reached out to various contacts throughout the community to continue adding new outreach events to the schedule and build a stronger STEM network in the Raleigh area.

6. Project Plan

6.1 Development Schedule

Table 6-1, below, lists important dates for reports, presentations, and launches for the 2017-18 NASA SL competition.

Table 6-1 2017-18 NASA SL Competition Development Schedule

Event/Task	Start Date	End Date/Submission
Request for Proposal Released	Aug. 23, 2017	
Proposal	23-Aug-17	Sep. 20, 2017 5:00 pm CST
Preliminary Design Review (PDR) Q&A	Oct. 12, 2017	
PDR	Oct. 12, 2017	Nov. 03, 2017 8:00 am CST
PDR Team Teleconference	(Tentative) Nov. 06-29, 2017	
Subscale Launch Opportunity		Oct. 28-29, 2017
Subscale Launch Opportunity		Nov. 18-19, 2017
Critical Design Review (CDR) Q&A	Dec. 06, 2017	
CDR	Dec. 06, 2017	Jan. 12, 2018 8:00 am CST
CDR Team Teleconference	(Tentative) Jan. 16-31, 2018	
Full-Scale Launch Opportunity		Jan. 27, 2018
Full-Scale Launch Opportunity		Feb. 25, 2018
Flight Readiness Review (FRR) Q&A	Feb. 07, 2018	
FRR	Feb. 07, 2018	Mar. 05, 2018 8:00 am CST
FRR Team Teleconference	(Tentative) Mar. 06-22, 2018	
Team Travel to Huntsville, AL	Apr. 04, 2018	
Launch Readiness Review (LRR)	Apr. 04, 2018	
NASA Safety Briefing	Apr. 05, 2018	
Rocket Fair and Tours of MSFC	Apr. 06, 2018	
Launch Day	Apr. 07, 2018	
Backup Launch Day	Apr. 08, 2018	
Post-Launch Assessment Review (PLAR)	Apr. 16, 2018	Apr. 27, 2018 8:00 am CST

6.2 Project Budget

Table 6-2, below, lists all the projected expenses for the team to compete in the 2017-18 NASA SL challenge.

Table 6-2 HPRC Projected Expenses for 2017-18 School Year

	Item	Quantity	Price per Unit	Item Total
Subscale Rocket	4" Airframe Tubing 31"	2	$14.00	$28.00
	4" Tube Coupler	2	$8.00	$16.00
	4" Plastic Nose Cone Standard	1	$21.00	$21.00
	Aircraft Spruce Domestic Birch Plywood 1/8"x4x4	2	$50.00	$100.00
	Aircraft Spruce Domestic Birch Plywood 3/8"x2x4	1	$70.00	$70.00
	Rail Buttons	4	$2.50	$10.00
	U-Bolts	3	$1.00	$3.00
	Motor (subscale)	2	$200.00	$400.00
	Motor Casing (subscale)	1	$340.00	$340.00
	Motor Retainer	1	$25.00	$25.00
	3" G12 Fiberglass Filament Wound Tube 48" Long	1	$91.00	$91.00
	StratoLogger Altimeters	2	$55.00	$110.00
	Entacore Altimeters	2	$115.00	$230.00
	Key Switches	2	$12.00	$24.00
	Blast Caps	4	$2.50	$10.00
	Terminal Blocks	3	$7.00	$21.00
			Subtotal:	**$1,499.00**
Full-Scale Rocket	Fiberglass 7.5" Filament Wound Metal Tip	1	$170.00	$170.00
	7.5"x 0.08 wall x 12" Blue Tube ARR Standard Coupler	2	$30.00	$60.00
	7.5" x 0.08 wall x 48" ARR Airframe Blue Tube	2	$90.00	$180.00
	Aircraft Spruce Domestic Birch Plywood 1/8"x4x4	3	$50.00	$150.00
	Aircraft Spruce Domestic Birch Plywood 3/8"x2x4	2	$70.00	$140.00
	Rail Buttons	4	$2.50	$10.00
	U-Bolts	3	$1.00	$3.00
	Aerotech L1420R-P	2	$250.00	$500.00
	Motor Casing	1	$390.00	$390.00
	3" G12 Fiberglass Filament Wound Tube 48" Long	1	$91.00	$91.00
	Motor Retainer	1	$25.00	$25.00
	Wires	1	$30.00	$30.00
	Connectors	1	$20.00	$20.00
	StratoLogger Altimeters	3	$55.00	$165.00
	Entacore Altimeters	3	$115.00	$345.00
	BRB 900 Transmitter	3	$200.00	$600.00
	Key Switches	2	$12.00	$24.00

	Item	Quantity	Price per Unit	Item Total
Full-Scale Rocket	Blast Caps	4	$2.50	$10.00
	Terminal Blocks	3	$7.00	$21.00
	E-matches		$20.00	$20.00
	Black Powder (lb)	1	$30.00	$30.00
	Sanding Sealer (qt)	1	$17.00	$17.00
	Epoxy and Hardener	1	$50.00	$50.00
	Paint	1	$30.00	$30.00
	Nuts (box)	1	$5.50	$5.50
	Screws (box)	1	$5.00	$5.00
			Subtotal:	**$3,091.50**
Payload	Acme Plastics ID 5.75" OD 6" 72" long	1	$145.00	$145.00
	ePlastics OD 6" w/ .125" walls 4ft long	4	$50.06	$200.24
	4" lazy susan bearing	2	$10.00	$20.00
	Acme Plastics ID 2.75 OD 3" 72" long	1	$50.00	$50.00
	Acme Plastics ID 2" OD 2.25" 72" long	1	$35.00	$35.00
	100 3mm Chrome steel bearing balls	1	$5.00	$5.00
			Subtotal:	**$455.24**
Rover	Arduino Pro Mini 238	1	$9.95	$9.95
	XBee Pro 900 XSC S3B Wire Rx	1	$66.95	$66.95
	FS90 Servo	1	$4.95	$4.95
	Turnigy 1000mAh 25 20C LiPoly Pack	1	$4.73	$4.73
	1" wide Molded track Set	1	$82.00	$82.00
	Thin-Film Flexible Waterproof Solar panel Cell (0.5W, 1.5V)	2	$9.99	$19.98
			Subtotal:	**$188.56**
Recovery	Jolly Logic Chute Release	1	$130.00	$130.00
	60" Elliptical Parachute	1	$143.00	$143.00
	Iris Ultra 48" Standard Parachute	1	$137.00	$137.00
	Iris Ultra 144" Parachute	1	$490.00	$490.00
	Kevlar Shock Cord (ft)	60	$1.00	$60.00
	Quick Links	5	$1.25	$6.25
			Subtotal:	**$966.25**
Travel	Hotel (7 rooms, 6 days)	7	-	$4,000.00
	Van Rental (2 vans, 1,200 miles each)	2,400	$0.69	$1,656.00
	Gas	-	-	$344.00
			Subtotal:	**$6,000.00**

	Item	Quantity	Price per Unit	Item Total
Promotional	T-Shirts	25	$15.00	$375.00
	Polos	25	$30.00	$750.00
	Pens	500	$0.24	$120.00
	Stickers	500	$0.26	$130.00
			Subtotal:	**$1,375.00**
Other	Incidentals (replacement tools, hardware, safety items)	-	-	$1,000.00
	Shipping Costs	-	-	$750.00
			Subtotal:	**$1,750.00**
			Total Expenses:	**$15,325.55**

6.3 Funding Plan

HPRC gets all of its funding from multiple NC State University organizations as well as the North Carolina Space Grant (NCSG).

The Engineering Technology Fee (ETF) fund from the MAE department at NC State provides monetary support to any student organizations that satisfy the Senior Design project curriculum requirements. Since the NASA SL project will complete the requirements for the Aerospace Engineering Senior Design course, the team will receive approximately $2,000 from the ETF fund for the entire school year.

The Engineers' Council (E-Council) at NC State University is a student-led organization that oversees events hosted by the College of Engineering. E-Council also allocates funds to different engineering organizations through a proposal, presentation, and appeals process that occurs twice per school year. In the 2016-17 academic year, HPRC received a total of $3,830 from E-Council: $2,830 in the fall semester and $1,000 in the spring semester. A request for $4,500 has been placed for the current fall semester and a similar request will be placed in the spring semester, assuming that the E-Council budget will remain the same.

The NC State University Student Government Association's Appropriations Committee is responsible for distributing university funds to campus organizations. The application process is similar to the Engineers' Council with a proposal, presentation, and an in-person interview. In the 2016-17 academic year, HPRC received a total of $2,350: $1,400 in the fall semester and $950 in the spring semester. A request for $2,000 has been placed for the current fall semester and the same amount will be requested in the spring semester, assuming that the Appropriations Committee budget will remain the same.

In addition to funding through NC State organizations, the North Carolina Space Grant will provide a large amount of monetary support to the club. NCSG accepts funding proposals during the fall semester and teams can request up to $5,000 for participation in NASA competitions, and another $2,500 for Senior Design projects related to aerospace research. NCSG will review the proposal and inform the club on the amount awarded, which will likely be the full amount requested since the team received the full amount during the last school year.

These totals are listed in Table 6-3, below, which compares the projected costs and incoming grants for the 2017-18 school year.

Table 6-3 HPRC Projected Funding for 2017-18 School Year

Organization	Fall Semester Amount	Spring Semester Amount	School Year Total
E-Council	$2,830.00	$1,000.00	$3,830.00
SGA Appropriations	$1,400.00	$950.00	$2,350.00
NC Space Grant	-	-	$7,500.00
ETF Fund	-	-	$2,000.00
		Total Funding:	**$15,680.00**
		Total Expenses:	**$15,325.55**
		Difference:	**+$354.45**

6.4 Plan for Sustainability

The club plans to sustain itself by attending on-campus membership events, and by hosting its outreach events at local schools, museums, and/or businesses. These events promote others to participate in the club and provide its newest members a chance to experience what it is like to be a part of the team. New members are not required to possess any existing knowledge of high-power rocketry, and veteran members are encouraged to share their experience with new members. The team will never discriminate against new members, and welcomes anyone with an interest in rocketry to participate and contribute to the success of the team.

HPRC is largely self-sufficient since all of the machines and materials needed for rocket design and manufacturing are available on-site, whether in the rocketry lab or machine shops. If outside help is needed, the team will communicate with the NAR/TRA mentors (listed in Section 1.1) to find a solution.

APPENDIX A FMECA Tables

The FMECA table below uses the following hazard level classification:

1) Rocket mission failure; rocket is not recoverable; payload is not recoverable; rover mission failure
2) Rocket mission failure; rocket is recoverable; payload may be recoverable; rover mission may be complete
3) Rocket mission complete; rocket is recoverable; payload is not recoverable; rover mission failure
4) Rocket mission complete; rocket is recoverable; payload is recoverable; rover mission failure

System	Subsystem/ Component	Failure Mode	Casual Factors	Failure Effects		Hazard	Recommendations
				Subsystem	System		
Launch Vehicle	Nosecone	Cracks or breaks	Object in flight path	Loss of nosecone recoverability	Loss of controlled and stabilized flight	2	Ensure that skies are clear of any foreign objects per NAR operations
			Damaged during handling or assembly			2	Inspect for cracks, chips, or other damage during assembly
			Nosecone collides with other rocket component during recovery		N/A	2	Ensure shock cord is long enough to separate nosecone from other components
			Ground impact			2	Metal nosetip will mitigate damage caused by surface impact
		Premature separation from midsection	Damaged during handling or assembly	Potential for permanent structural damage	Loss of controlled and stabilized flight	2	Inspect for cracks, chips, or other damage during assembly

			Shear pins not installed correctly			2	Follow design specifications for sizing, inspecting, and installing shear pins during assembly
			Epoxy not cured properly			2	Follow proper procedures for mixing, applying, and curing epoxy
	Blue Tube Airframe	Cracks or breaks	Manufacturing defect	Loss of structural integrity or usability of Blue Tube body sections or components	Premature separation of launch vehicle sections during flight	1	Visual inspection after shipping and before assembly
			Loads experienced beyond design specifications			1	Ensure body tube components can hold flight forces in accordance with design specifications Ensure that all components can maintain a factor of safety of at least 1.5 during all regimes of flight

			Damaged during handling or assembly			1	Inspect each body tube component for cracks, bends, warping, or other damage during assembly Replace any damaged components if possible
			Improper storage			2	Store Blue Tube in a dry space and avoid any liquid spills Do not store items on top of Blue Tube
	Fins	Severe weather-cocking	Fin dimensions are not cut according to design	N/A	Decreased flight stability, unpredictable flightpath, and possible damage to other components	2	Laser cut fins to ensure manufacturing precision Ensure that excessive material is not removed during sanding.
			Fins not installed at even increments around fin can (90 degrees to each other)			2	Use laser-cut jig with slots for fins exactly 90 degrees from each other

			Assembled rocket CG is too far forward (Stability Margin >> 2.0)			2	Ensure components and masses are installed according to design specifications
		Fin separation	Loads experienced beyond design specifications	N/A	Any one failure of a fin could lead to additional fin failures which will decrease flight stability and will likely cause a catastrophic failure	1	Analyze flight data and simulations to confirm that factor of safety is sufficient
			Damaged during handling or assembly			1	Inspect for cracks, chips, or other damage during assembly Replace any damaged components
			Fin flutter			2	Rocket will not exceed velocity necessary to induce significant flutter
			Ground impact			2	Implement a recover system design that ensures a low-speed surface impact

	Motor	Motor fails to ignite	Igniter not installed correctly	Failure of vehicle to start launch	Team member and RSO must insert new igniter and restart launch sequence	4	Follow launch checklist and use mentor/RSO supervision to install igniter correctly
			Faulty igniter used			4	Test batch of igniters prior to launch day to ensure quality
			Motor assembled incorrectly			4	Follow launch checklist and use mentor/RSO supervision to install motor correctly
		Catastrophic motor failure	Damaged during handling or assembly	Possible destruction of launch vehicle	Complete mission failure and additional hazard to ground crew and spectators	1	Carefully inspect for cracks, chips, or other damage during assembly
			Motor assembled incorrectly			1	Follow launch checklist and use mentor/RSO supervision to install motor correctly

			Motor casing dislodged during motor burn			1	Ensure all connection points between motor tube, centering rings, and fins are joined properly using epoxy Perform careful inspection of joints prior to launch
		Damage to motor casing	Superficial damage	Motor casing cannot be used	Rocket is not safe to launch if damage is major	4	Carefully inspect for cracks, chips, or other damage during assembly
		Propellant contamination	Rocket fails to launch	Reduced performance of rocket motor	Rocket does not launch or perform as expected	2	Store and maintain motor fuel properly and in isolation/ order from reputable source
			Over-oxidized reaction			2	
			Reduced fuel efficiency			3	
	Bulkheads	Bulkhead separation from airframe during motor burn	Manufacturing defect			1	Visual inspection after shipping and before assembly

			Loads experienced beyond design specifications			1	Ensure body tube components can hold flight forces in accordance with design specifications Ensure that all components can maintain a factor of safety of at least 1.5 during all regimes of flight
			Damaged during handling or assembly			1	Inspect each bulkhead for cracks, warping, chips, or other damage during assembly Replace any damaged bulkheads
			Epoxy not cured properly			1	Follow proper procedures for mixing, applying, and curing epoxy

		U-bolt separation from bulkhead during recovery	Loads experienced beyond design specifications	Launch vehicle components not tethered to a parachute will continue accelerating during descent	Loss of safe and effective recovery system	1	Ensure body tube components can hold flight forces in accordance with design specifications Ensure u-bolt fasteners can handle near-instantaneous loading from parachute deployment
			Epoxy not cured properly			1	Follow proper procedures for mixing, applying, and curing epoxy
	Rail Buttons/ Launch Rail	Vehicle does not leave launch rail as intended	Rail button(s) separate from launch vehicle	Vehicle leaves rail at unpredictable orientation and velocity	Possible mission failure and additional hazard to ground crew and spectators	1	Epoxy rail buttons into body tube to mitigate risk of separation
			Damaged during handling or assembly			1	Inspect each pin for cracks, bends, chips, or other damage during assembly Replace any damaged components
			Launch rail breaks			2	Ensure that the rail is assembled correctly prior to launch

		Vehicle does not leave launch rail at all	Rail button(s) becomes stuck in launch rail	N/A	Mission failure as flight does not take place	2	Ensure that rail buttons match size of launch rail slot Lubricate the launch rail and rail buttons prior to launch Ensure that the vehicle moves smoothly on the launch rail during assembly and launch rail erection
	Shear Pins	Pins break before charge detonation	Manufacturing defect	Loose assembly of compartment	Premature rocket separation and recovery system deployment	2	Visual inspection after shipping and before assembly
			Damaged during handling or assembly			2	Inspect each pin for cracks, bends, chips, or other damage during assembly Replace any damaged components
			Pins fall out of respective holes			2	Ensure size of holes drilled in body tube match diameter of shear pins

			Loads beyond design specifications			2	Ensure pins can hold flight forces in accordance with design specifications
		Pins don't break at charge detonation	Manufacturing defect	Failure to separate compartment	Loss of safe and effective recovery system	1	Inspect each pin for cracks, bends, chips, or other damage during assembly Replace any damaged components
			Pins too tight in body tube holes			1	Ensure size of holes drilled in body tube match diameter of shear pins
			Poor design			1	Use calculations to ensure that pins will break from forces of detonation

	Shock Cord	Incorrect or partial deployment of shock cord	Snags, tears, or rips during ejection	Parachute no longer tethered to entirety of launch vehicle airframe	Loss of safe and effective recovery system	1	Inspect shock cord for damage prior to launch Ensure high-strength shock cord is used with a maximum loading greater than 1,500 lb Ensure shock cord is folded and stowed properly in launch vehicle Reduce/eliminate sharp edges in design to mitigate risk of snagging shock cord and parachutes
			Shock cord disconnects from airframe or parachutes			1	Ensure that connections between the shock cord, airframe, and parachutes are tight and secure

			Shock cord stuck within launch vehicle airframe	Parachute not entirely deployed		1	Ensure that the shock cord and parachutes are folded and stowed properly in launch vehicle Reduce/eliminate sharp edges in design to mitigate risk of blocking shock cord and parachutes
	Parachute Deployment	Drogue parachute fails to deploy correctly	Drogue shock cord tangling	Parachute does not deploy correctly	Rocket is recoverable	2	Ensure that shock cords and parachutes are folded correctly
			Shock cord connections come loose			2	Test shock cord connections before flight, make sure secure
			Parachute bag does not fully open			2	Fold bags correctly and make sure nothing can snag bags
		Parachute does not perform as expected	Tears/holes	Parachute deploys but does not perform as expected	Rocket is recoverable	2	Inspect parachute before folding and packing
		Main parachute fails to deploy correctly	Charge is inadequate	Parachute does not deploy correctly	Separation 2 is not successful, rocket is not recovered safely	1	Test charge measurements before flight

			Payload blocks parachute		Separation 2 is not successful, rocket is not recovered safely	1	Make sure payload ejection hardware does not impact parachute release path
			Shock cords tangled		Rocket is recoverable	2	Ensure shock cords and parachutes are folded correctly
			Shock cord connections loose		Rocket is not recovered safely	1	Test shock cord connections before flight, make sure secure
	Black Powder Charges	Single detonation failure	E-match doesn't light	Failure of one or more black powder charges	Will result in loss of safe and effective recovery system if redundant black powder charge(s) do not detonate	2	Conduct ground tests to ensure that enough black powder will be used for proper separation Thoroughly check redundant systems prior to launch Confirm that wires are attached per design specifications
			Altimeter Malfunction			2	Ensure altimeters are functional prior to launch Test altimeters regularly to ensure component integrity

		Redundant detonation failure	E-match doesn't light	Failure of both ejection charges	Rocket fails to separate and deploy parachutes	1	Conduct ground tests to ensure that enough black powder will be used for proper separation Thoroughly check redundant systems prior to launch Confirm that wires are attached per design specifications
			Altimeter Malfunction			1	Ensure altimeters are functional prior to launch Test altimeters regularly to ensure component integrity

		Charge causes damage to any component other than shear pins	Charge is too big	Causes violent separation and/or damage to surrounding area	Potential to cause permanent damage to bulkheads or shock cord, resulting in a possible failure of parachute deployment	2	Verify that charges are sealed properly and the correct amount of black powder is used with pre-flight checklist Conduct ground tests to ensure that enough black powder will be used for proper separation without damage to other components
		Charge ignites but fails to cause separation	Charge is too small	No ejection	Failure of parachute deployment	1	Conduct ground tests to ensure that enough black powder will be used for proper separation
	Altimeters	No power to altimeters	Uncharged or insufficiently charged batteries	Loss of real-time altitude data, failure to ignite e-match	Failure of parachute deployment	1	Install new/unopened batteries at each launch Confirm that all batteries have the correct voltage before flight using a multimeter

			Battery becomes disconnected from altimeter			1	Ensure that altimeters are properly wired and that wires are secure prior to launch Listen for appropriate chirps when powering on altimeters
			Wiring short			1	Ensure that all wire is properly insulated and that all wires are securely contained in their respective terminals
		No launch detected	Manufacturing defect	Lack of flight data	Failure of parachute deployment	1	Test altimeters in vacuum chamber prior to launch Listen for fault codes at launch site
		False apogee detected	Manufacturing defect	Premature/late ejection of drogue parachutes	Increased load on drogue recovery hardware and bulkheads	2	Test altimeters in vacuum chamber prior to launch Listen for fault codes at launch site

			Incorrect altimeter readings			2	Ensure that pressure ports are sized correctly and listen for fault codes at launch site
		Main parachute deploys at wrong altitude	Incorrect pressure readings or improper programming	Main deployment between apogee and 1,200 ft	Excessive drift, but surface impact will remain below required maximums	2	Verify each altimeter chirps the appropriate program at the launch site Test altimeters in vacuum chamber prior to launch date Ensure pressure ports are sized correctly
				Main deployment lower than 800 ft	Kinetic energy at surface impact will likely exceed 75 ft-lb parachute	1	
	GPS	Ground system failure	Loss of power to ground receiver or the laptop	Inability to receive data from the GPS	Inability to track and recover the rocket in less than an hour	3	Ensure that the receiver and laptop are fully charged at least 6 hours prior to flight
		Loss of signal	Environment or rocket materials blocking signal			3	Perform range tests to ensure reliability of the system at simulated altitudes and ground distances

		Radio interference	Multiple radio devices on the same local frequency and channel			3	Ensure that all transmitting devices are on separate channels and confirm with other teams and launch officials that no frequency conflict exists
		Loss of power	Flight forces cause GPS to disconnect from power supply			3	Ensure that all GPS units are fully charged and use simulated load tests to determine the necessary procedures to secure the units
	Avionics Sled	Detaches from secure position	Loads beyond design specifications	Damage to/loose wiring of avionics components	Loss of recovery system initiation	1	Use simulated load tests and add a sufficient factor of safety when designing sled
			Damage during handling			1	Team members will be taught proper handling and installation procedures for the avionics sled
			Improper maintenance			1	Pre- and post-launch thorough inspections of the avionics sled
Payload	Payload Parachute	Payload parachute fails to deploy correctly	Charge is inadequate	Parachute does not deploy correctly	Payload does not deploy, rocket is not	1	Test charge measurements before flight

					recovered safely		
			Shock cords tangled		Rocket recoverable, Payload failure	3	Ensure shock cords and parachutes are folded correctly
			Shock cord connections loose		Rocket recoverable, Payload failure	3	Test shock cord connections before flight, make sure secure
			Payload caught in recovery system		Rocket recoverable, Payload potentially recovered	4	During construction ensure payload has clean path for ejection
		Parachute does not perform as expected	Tears/holes	Parachute deploys but does not perform as expected	Rocket is recoverable	2	Inspect parachute before folding and packing
	Payload Exterior	Acrylic Tube fracture	Manufacturing defects	Rover system at risk	Electronics and rover can be damaged	3	Visual inspection prior to use
		Door fails to open	Servo fails	Rover deployment	Rover will not complete its task	3	Test servo connection prior to use
			Blocked by dirt after landing	Prevents rover deployment		3	Shape the end of the payload to ensure it falls
		Cap detaches	Screws not properly set	Prevent inner tube from rolling freely	Possible structural	3	Perform visual inspection prior to use

			Manufacturing defect	Damage structure at landing	damage to the payload	3	
	Payload Bulkhead	Separation of bulkhead from the payload	Poor design	Unable to transfer loads	Increased loads on other structural members	2	FEA of bulkhead fixed support
			Manufacturing defect			2	QC of manufacturing process
			Loads greater than designed			2	Maintain vehicle within planned design
			Damaged during handling			2	Ensure analysis includes handling loads/adhere to proper handling procedure
			Improper attachment			2	Pre/post launch inspection
		Damage/ separation from parachute deployment	Poor design	Unable to support loads of chute deployment	Loss of safe and effective recovery system	2	FEA of bulkhead stress
			Manufacturing defect				QC of manufacturing process
	Rover Bay	Separation of weight from platform	Improper attachment	Rocket weight imbalance during flight	Rocket flight disrupted	3	Test the attachment of the weight
				Rover fails to rest at bottom of tube	Prevents proper rover deployment	3	
		Electronics Fails	Circuitry is disrupted/damaged	Payload hardware experiences	Rover fails to deploy	3	Electronics tested thoroughly

				catastrophic failure			
	Parachute Deployment	Fails to deploy	Jolly Logic fails	Payload landing	Payload decent velocity is not decreased	1	Test the Jolly Logic prior to use
			Does not open			1	Carefully packing of parachute recovery system
			Shock cord connections come loose			1	
		Premature detonation	Improper wiring/attachment	Jolly Logic releases prematurely	Payload drifts farther than planned	3	Complete testing of electronic devices
			RF Interference			3	
	Hardware	Bearings do not spin freely	Malfunction in turntable	Rover deployment	Prevents rover from deploying at the correct orientation	3	Make sure the bearing systems are well lubricated before flight
		Rail button sheared off upon payload jettison	Excessive Loading	Structural defects encountered	Possible damage to other components	4	Testing during build and pre-flight checklist
	Rover Tracks	Break	Damage during flight	Rover performance hindered	N/A	4	Test multiple tread materials to determine highest performance
			Snag on obstruction	Rover performance hindered		4	Test multiple tread materials to determine highest performance
			Encounter sharp object	Rover performance hindered		4	Test multiple tread materials to determine highest performance

		Malfunction	Unable to gain traction	Rover cannot move forward		4	Test treads on various services
			Cannot traverse obstruction	Rover cannot move forward		4	Test treads on various terrain
	Rover Body	Cracks or Breaks	Damage during flight	Rover performance hindered	N/A	4	Run structural analysis
			Manufacturing defect	Rover performance hindered		4	Follow proper additive manufacturing technique
			Damge during rover operation	Rover performance hindered		4	Test rover on various terrains
	Rover Gears/ Motor System	Break	Damage during flight	Rover cannot complete mission	N/A	4	Test the structural integrity of the parts and run structural analysis
			Manufacturing defect	Rover cannot complete mission		4	Follow proper additive manufacturing technique
			Damage during rover operation	Rover cannot complete mission		4	Run tests to determine rover capabilities
		Jammed	Foreign objects get stuck in the gears/motor	Rover performance hindered		4	Run tests in similar conditions to landing site
		Do not operate	Dead battery	Rover cannot complete mission		4	Ensure proper battery charging and handling techniques are followed

			Signal is not sent properly	Rover cannot complete mission		4	Extensively test transceiver in all conditions
			Programming bug	Rover cannot complete mission		4	Run tests on Arduino to ensure high performance
	Rover Solar Panels	Do not deploy	Signal is not sent properly	Design challenge is not completed	N/A	4	Extensively test transceiver in all conditions
			Foreign objects get stuck in solar panel housing	Design challenge is not completed		4	Test solar panels in conditions similar to landing site
			Dead battery	Design challenge is not completed		4	Ensure proper battery charging and handling techniques are followed
	Rover Battery	Low Charge	Improper charging techniques	Rover performance hindered	N/A	4	Adhere to proper charging technique
			Improper storage	Rover performance hindered		4	Adhere to proper storage technique
		Fire	Not following proper safety protocol	Rover cannot complete mission	Damage to payload	3	Maintain a high level of safety