The Zenith Program

Compiled Risk Assessments

FAMU-FSU College of Engineering

2525 Pottsdamer Street

Tallahassee, FL 32310

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1 Explanation of Structure

As part of the various reports generated thus far for the NASA University Student Launch Initiative, several detailed safety analyses have been conducted at different stages of the project. The intent of this document is to comply with additional requirements of the senior design rubric while presenting the bulk of the risk assessment verbatim from previous work. To that end, the assessment is presented in the following 3 sections, containing:

Section 2: Items required by the senior design rubric. Not part of NASA requirements or submitted reports. Newly generated.

Section 3: Project-wide safety plan and general risk assessment. Taken verbatim from the Project Proposal report submitted to NASA prior to competition acceptance.

Section 4: Failure Mode and Effects Analysis for all subsystems, personnel, and environment. Taken verbatim from the Preliminary Design Review report submitted to NASA during Project Week 12, Phase 2.

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*Referenced appendices in sections 3 and 4 will not be included in this document for brevity. These are available in the full reports submitted to NASA which were provided to Dr. McConomy on submission.

*Since the bulk of this report is sourced from NASA reports, this document formatting follows existing Zenith format for all NASA reporting to avoid extensive reformatting. The decision to reformat for entry to the SD evidence manual or include this document in full as an appendix to the evidence manual will be made at a later date.

2 Senior Design Required Additions

2.1 PPE Summary

PPE is covered in the project proposal safety analysis and mentioned as a mitigation measure in the PDR FMEA study. For ease of reading, hazards requiring PPE and necessary protections are listed below.

Hazard:	Ammonium Perchlorate Rocket Propellant (APCP) **SDS included in proposal safety analysis*
Required PPE:	• Safety goggles • Skin covering: long sleeves/lab coat, pants, closed toed shoes, rubber nitrile gloves

Hazard:	General fabrication shop operations
Required PPE:	• Safety goggles when dealing with any power tool • Respirator when using power-sander, glues, epoxies • Pants and closed toed non-slip shoes at all times

2.2 Emergency Response and Contacts

2.2.1 First Responders

2.2.1.1 Florida State University Police Department
Phone: 9-1-1 (request police)
Non-emergency phone: (850) 644-1234
Reason(s) to contact: Major or catastrophic personnel injury, fire, explosion

2.2.1.2 Tallahassee Fire Department and related Emergency Medical Services
Phone: 9-1-1 (request fire/EMS)
Reason(s) to contact: Major or catastrophic personnel injury, fire, explosion

2.2.2 University Contacts

2.2.2.1 Florida State University Environmental Health and Safety
Phone: (850) 644-6895
Reason(s) to contact: Major or catastrophic personnel injury, fire, explosion, chemical spills/contamination, disposal of energetics (black powder, APCP motors)

2.2.2.2 Mr. Keith Larson
Title: College of Engineering Liaison to Environmental Health and Safety Office
Phone: (850) 410-6108
Email: larson@eng.famu.fsu.edu
Office: COE Building A, Room A108A
Reason(s) to contact: Major or catastrophic personnel injury, fire, explosion, chemical spills/contamination, disposal of energetics (black powder, APCP motors)

2.2.2.3 Dr. Shayne McConomy
Title: Senior Design Professor
Phone: (850) 410-6624
Email: smcconomy@eng.famu.fsu.edu
Office: COE Building B, Room B373C
Reason(s) to contact: Major or catastrophic personnel injury, fire, explosion, chemical spills/contamination, disposal of energetics (black powder, APCP motors)

2.2.3 Non-University Contacts

2.2.3.1 Mr. Tom McKeown – NAR/TRA Certified Team Mentor
Title: Board Member, Spaceport Rocketry Association (NAR #342 / TRA #73)
Phone: (321) 266-1928
Email: mckeownt@ix.netcom.com
Reason(s) to contact: All questions or concerns regarding sub-scale demonstrator, full-scale vehicle, related energetics, and/or manufacturing techniques. Must be informed of all hazards and injuries to team, regardless of severity.

3 Safety Assessment [Project Proposal]

3.1 Safety Plan

3.1.1 Safety Officer

The Safety Officer (Safety Officer) assumes primary responsibility for the safety and training of all individuals involved in the Zenith Program, and the responsible handling, storage, and transportation of hazardous material. The Safety Officer is to act as point of contact for all University safety personnel and departments such as FSU Environmental Health and Safety, FSU Police Department, College of Engineering Facilities, local test launch facility Range Safety Officers (RSO), and NASA launch day Range Safety Officer's.

3.1.2 Chemical Safety

3.1.2.1 Chemical Data Sheet

The fuel to be used in the launch vehicle is Ammonium Perchlorate Composite Propellant. The full chemical safety data sheet for Ammonium Perchlorate is available in Appendix B. High priority sections of the chemical data sheet are as follows:

3.1.2.1.1 Hazard Identification

2. HAZARDS IDENTIFICATION

Classification

This chemical is considered hazardous according to the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

Considered a dangerous substance or mixture according to the Globally Harmonized System (GHS)

Serious eye damage/eye irritation	Category 2B
Explosives	Division 1.1
Oxidizing solids	Category 1

Label elements

Danger

Hazard statements
Causes eye irritation
Explosive; mass explosion hazard
May cause fire or explosion; strong oxidizer

Product code: A1224 **Product name:** AMMONIUM PERCHLORATE, REAGENT **1 / 12**

3.1.2.1.2 First Aid Information

4. FIRST AID MEASURES

First aid measures

General Advice: National Capital Poison Center in the United States can provide assistance if you have a poison emergency and need to talk to a poison specialist. Call 1-800-222-1222.

Skin Contact: Wash off immediately with soap and plenty of water removing all contaminated clothing and shoes. Get medical attention if irritation develops.

Eye Contact: Flush eyes with water for 15 minutes. Get medical attention.

Inhalation: Move to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention.

Product code: A1224 **Product name:** AMMONIUM PERCHLORATE, REAGENT **2 / 12**

Ingestion: Do not induce vomiting without medical advice. Never give anything by mouth to an unconscious person. Consult a physician if necessary.

Most important symptoms and effects, both acute and delayed

Symptoms Mild eye irritation. Mild skin irritation. May cause central nervous system effects. Ataxia. Convulsions. May cause digestive (gastrointestinal) tract irritation. Ingestion may cause nausea, vomiting, and diarrhea. Coughing and wheezing. Dyspnea (Shortness of breath and difficulty breathing).

Indication of any immediate medical attention and special treatment needed

Notes to Physician: Treat symptomatically.

Protection of first-aiders
First-Aid Providers: Avoid exposure to blood or body fluids. Wear gloves and other necessary protective clothing. Dispose of contaminated clothing and equipment as bio-hazardous waste.

3.1.2.1.3 Firefighting Procedures

5. FIRE-FIGHTING MEASURES

Extinguishing Media

Suitable Extinguishing Media:	Water. CO2 may be of no value in extinguishing fires involving oxidizers and may only provide limited control.
Unsuitable Extinguishing Media:	Dry chemical. Foam. Halons.

Specific hazards arising from the chemical

Hazardous Combustion Products:	Nitrogen Oxides. Ammonia. Hydrogen Chloride Gas.
Specific hazards:	May cause fire or explosion: strong oxidizer. Keep away from combustible materials (wood, paper, oil, clothing, etc.). May cause fire when in contact with other material. Contact with combustible or organic materials may cause fire. Will accelerate burning when involved in a fire. Container explosion may occur under fire conditions or when heated. Can ignite or explode on exposure to heat, shock, or friction. Can ignite spontaneously.

Special Protective Actions for Firefighters

Specific Methods:	For large fires, flood fire area with water from a distance. Cool affected containers with flooding quantities of water. In case of major fire and large quantities: Evacuate area. Fight fire remotely due to risk of explosion. Do not get water inside containers. DO NOT use combustible materials such as sawdust.

3.1.2.1.4 Risk and Safety Phrases / Iconography

R-phrase(s)
R 2 - Risk of explosion by shock, friction, fire or other sources of ignition.
R 3 - Extreme risk of explosion by shock, friction, fire or other sources of ignition.
R 9 - Explosive when mixed with combustible material.

Product code: A1224 **Product name:** AMMONIUM PERCHLORATE, REAGENT **11 / 12**

S -phrase(s)
S 2 - Keep out of the reach of children.
S14 - Keep away from easily oxidizable materials.
S16 - Keep away from sources of ignition - No smoking.
S36/37 - Wear suitable protective clothing and gloves.

Components	CAS-No.	**Classification**	**Concentration Limits:**	**Safety Phrases**
Ammonium Perchlorate	7790-98-9	E;R2 or R3; R9	No information	S: (2)-14-16-36/37

The product is classified in accordance with Annex VI to Directive 67/548/EEC

Indication of danger:
E - Explosive.
O - Oxidising.

E

3.1.2.2 Purchasing

All hazardous materials purchasing must be signed off on by an adult educator after coordination with College of Engineering facilities, ensuring the ability to store the purchased material(s) properly and safely upon delivery. For the purposes of the Zenith Program, solid rocket motors will require sign off by both an adult educator after coordination with College of Engineering facilities, and approval by the student team mentor, whose NAR/TRA Level 2+ certification is required to purchase any L-class motor.

3.1.2.3 Transportation, Storage, and Handling

Hazardous material must be transported according to DOT standards. Applicable regulations for transportation can be found in the chemical data sheet. Any vehicle transporting hazardous material will display the proper DOT Hazard Diamonds during transport.

Storage guidance for hazardous materials may be found in the chemical data sheet. College of Engineering Facilities will be consulted and provided the chemical data sheet prior to delivery of material to be stored in College of Engineering Hazardous Materials Storage (Section 4.1.2).

Proper Personal Protective Equipment must always be worn while handling hazardous material. The chemical data sheet lists all ways in which the material may cause harm and provides guidance on the proper Personal Protective Equipment for mitigation of each of these risk modes.

3.1.3 Facilities Safety

It is the intention of the Zenith Program team and FAMU-FSU AIAA Executive Board to operate the AIAA shop, and any other facilities used, under the OSHA guidelines for laboratory safety regardless of whether the facility would be considered a traditional laboratory environment in the pursuit of safe operations. Students will be required to attend a briefing on these guidelines and take a quiz demonstrating understanding before beginning work on any portion of the Zenith Program project.

3.1.3.1 Fabrication Shop

The Sliger Building AIAA Shop is intended as a fabrication space for inert components only. By university regulation, no hazardous materials or pressurized cylinders are to be stored or handled in the project labs. Unpressurized cylinders may be stored in accordance with the laboratory safety regulations discussed below. Electrical work, such as for the avionics systems, will comply with the electrical laboratory safety guidelines outlined below.

3.1.3.2 Laboratory Safety Regulations

Regulations listed are pulled from the OSHA Laboratory Safety Guidance for sections applicable to Zenith Program work, attached in full as Appendix H.

3.1.3.2.1 Chemical Regulations

From OSHA Laboratory Safety Guidance, Hazard Identification:

"Each laboratory must identify which hazardous chemicals will be encountered by its workers. All containers for chemicals must be clearly labeled. An employer must ensure that workers do not use, store, or allow any other person to use or store, any hazardous substance in his or her laboratory if the container does not meet the labeling requirements outlined in the Hazard Communication standard, 29 CFR 1910.1200(f)(4). Labels on chemical containers must not be removed or defaced. Material Safety Data Sheets (MSDSs) for chemicals received by the laboratory must be supplied by the manufacturer, distributor, or importer and must be maintained and readily accessible to laboratory workers. MSDSs are written or printed materials concerning a hazardous chemical. Employers must have an MSDS in the workplace for each hazardous chemical in use."

3.1.3.2.2 Pressure Vessel Regulations

From OSHA Laboratory Safety Guidance, Compressed Gasses:

"…there are hazards from the pressure of the gas and the physical weight of the cylinder. A gas cylinder falling over can break containers and crush feet. The gas cylinder can itself become a missile if the cylinder valve is broken off. Laboratories must include compressed gases in their inventory of chemicals in their Chemical Hygiene Plan…

Store, handle, and use compressed gases in accord with OSHA's Compressed Gases standard (29 CFR 1910.101) and Pamphlet P-1-1965 from the Compressed Gas Association.

- All cylinders whether empty or full must be stored upright.
- Secure cylinders of compressed gases. Cylinders should never be dropped or allowed to strike each other with force.
- Transport compressed gas cylinders with protective caps in place and do not roll or drag the cylinders."

3.1.3.2.3 Electrical Regulations

From OSHA Laboratory Safety Guidance, Electrical:

"Subpart S is comprehensive and addresses electrical safety requirements for the practical safeguarding of workers in their workplaces. This Subpart includes, but is not limited to, these requirements:

- Electrical equipment must be free from recognized hazards, 29 CFR 1910.303(b)(1);
- Listed or labeled equipment must be used or installed in accord with any instructions included in the listing or labeling, 29 CFR 1910.303(b)(2);
- Sufficient access and working space must be provided and maintained around all electrical equipment operating at ≤ 600 volts to permit ready and safe operation and maintenance of such equipment, 29 CFR 1910.303(g)(1);
- Ensure that all electrical service near sources of water is properly grounded.
- Tag out and remove from service all damaged receptacles and portable electrical equipment, 29 CFR 1910.334(a)(2)(ii);
- Repair all damaged receptacles and portable electrical equipment before placing them back into service, 29 CFR 1910.334(a)(2)(ii);
- Ensure that workers are trained not to plug or unplug energized equipment when their hands are wet, 29 CFR 1910.334(a)(5)(i);
- Select and use appropriate work practices, 29 CFR 1910.333; and
- Follow requirements for Hazardous Classified Locations, 29 CFR 1910.307. This section covers the requirements for electric equipment and wiring in locations that are classified based on the properties of the flammable vapors, liquids or gases, or combustible dusts or fibers that may be present therein and the likelihood that a flammable or combustible concentration or quantity is present.

3.1.4 Launch Operations

3.1.4.1 Pre-Launch Briefings

A formal pre-launch meeting shall serve as the hazard recognition and accident avoidance briefing for launch and recovery procedures. The meeting shall also serve as a briefing for proper conduct on the launch site including, but not limited to, the rules of the private property and NAR/TRA safety policies. The Project Manager, Safety Officers, and Leads will conduct the meeting prior to the scheduled launch. Attendance will be mandatory for team members to be present at the launch site.

3.1.4.2 Range Safety Inspection

Before flight of the rocket, permission of the range safety officer must be given. For any reason if the range Safety officer finds an issue with the rocket the team will follow the instruction given by the Range Safety Officer.

3.1.5 Personnel Safety

3.1.5.1 Safety Philosophy of the Zenith Program

In contrast to the mainstream belief that safety comes first, the Zenith Program team is committed to a different philosophy: “Safety Third!”. While seeming incredibly irresponsible at face value, this ideology is meant to combat the dangers of the “Safety First” mentality and underscore the importance of personal responsibility.

The safety-first mentality generally leads individuals to assume that their working environment has been made as safe as possible, with all risks properly mitigated, and their employer or supervisor singularly focused on their personal safety. This could not be farther from the truth. In most cases, the workplace has not been optimized for safety, quite the opposite. The safety-first mentality leads to complacency on the part of management and employees; assuming that all risk has been mitigated causes a sharp drop-off in vigilance by all involved and can lead to higher incidence rates of minor and major accidents.

The safety-third ideology is intended to combat this complacency. By constantly reminding oneself “safety third!”, one is reminded of a harsh reality: nobody is watching out for you! This mentality is meant to create a thought process in the mind of employees that management is primarily concerned with turning profit, and not making sure they are safe while doing it. This puts the impetus on the employee to guarantee their own personal safety by practicing extreme vigilance for hazard identification, and close adherence to policies and procedures in place for risk mitigation, such as the use of Personal Protective Equipment. A safety-first employee may neglect safety goggles in a low-risk activity with the slim possibility of eye injury, while a safety-third employee will always wear their eye protection knowing their judgement and actions are what keep them safe.

The safety third ideology and its’ advantages are eloquently described by Mike Rowe in an episode of his hit TV show “Dirty Jobs”. Mr. Rowe outlines the philosophy above with a touch of humor during a personal anecdote aboard a Bering Sea crab-fishing boat, found at:

[https://www.youtube.com/watch?v=Km8XxRCuCho]

3.1.5.2 Hazard Recognition and Accident Avoidance

From OSHA Laboratory Safety Guidance, Hazard Identification:

"Laboratory workers must be provided with information and training relevant to the hazards of the chemicals present in their laboratory. The training must be provided at the time of initial assignment to a laboratory and prior to assignments involving new exposure situations. The employer must inform workers about the following:

The content of the OSHA Laboratory standard and its appendices (the full text must be made available)

- The location and availability of the Chemical Hygiene Plan
- Permissible exposure limits (PELs) for OSHA regulated substances, or recommended exposure levels for other hazardous chemicals where there is no applicable standard
- Signs and symptoms associated with exposure to hazardous chemicals in the laboratory; and
- The location and availability of reference materials on the hazards, safe handling, storage, and disposal of hazardous chemicals in the laboratory, including, but not limited to, MSDSs.

Training must include the following:

- Methods and observations used to detect the presence or release of a hazardous chemical. These may include employer monitoring, continuous monitoring devices, and familiarity with the appearance and odor of the chemicals
- The physical and health hazards of chemicals in the laboratory work area
- The measures that workers can take to protect themselves from these hazards, including protective equipment, appropriate work practices, and emergency procedures
- Applicable details of the employer's written Chemical Hygiene Plan
- Retraining, if necessary."

3.1.5.3 Personal Protective Equipment

From OSHA Laboratory Safety Guidance:

"Employers must train workers to use the appropriate personal protective equipment (PPE)…This includes:

- face shield or safety goggles
- safety gloves.
- long-sleeved shirts, lab coats, aprons."

3.1.6 Risk Assessment – Personnel

3.1.6.1 General Mitigation Strategies

- Use common sense and never attempt to follow any procedures with uncertainty.
- Be sure to always have an informed team member present when executing tasks.
- Abide by all state, federal and local laws as well as all safety regulations at all times.
- Ensure that proper safety equipment is worn at all times.
- Wear appropriate clothing in the lab.
- Always wear safety glasses/goggles.
- Wear gloves when necessary.
- Wear facial protection when necessary.
- Open toe shoes are prohibited in the lab and machine shop.
- Always be aware of surroundings.
- Ensure that there is a knowledgeable team member present at all times.
- Update and review the safety binder as often as possible.
- Contain Safety Data Sheets (SDS) within the confines of the binder.
- Contain pre-activity and pre-launch checklists.
- Ensure each team member understands all information contained in the binder.

3.1.6.2 In-Depth Risk Assessment

Risk Factor	Possible Outcomes	Mitigation Strategy
Equipment and Tooling	1) Cuts, scrapes, burns, and skin irritations 2) Damage to equipment	1) Be aware of surroundings in the work station 2) Ask if unsure 3) Wear appropriate safety equipment 4) Proceed with caution
Chemical Contact	1) Irritation to skin or eyes. 2) Inhalation of hazardous fumes 3) Fire/explosions 4) Equipment damage	1) Wear appropriate safety gear and clothing 2) Keep workstations clean and well ventilated 3) Refer to Chemical Data Sheets
Rocket Motor Handling	1) Fire/explosion 2) Burns. 3) Motor damage	1) Only certified personnel should store, handle, and transport motor 2) Wear appropriate safety gear and clothing 3) Keep motor away from any gunpowder in storage
Launch Vehicle Handling	1) Damage to rocket 2) Damage to nearby power lines, facilities and cars 3) Fires/explosions 4) Personal injury 5) Death	1) Only certified personnel should store, handle, and transport the rocket 2) Abide by all federal, state, and local laws as well as the NAR safety codes and FAA 3) regulations

		4) Abide by the regulations set forth by the Range Safety Officer (RSO) 5) Use common sense and be aware of surroundings 6) Keep emergency contact information in the safety binder and use accordingly
Machine Shop Usage	1) Cuts, scrapes, burns, and skin irritations 2) Loss of appendages 3) Death	1) Always ensure there is a knowledgeable team member present in the machine shop. 2) Always wear proper safety equipment in the machine shop, especially safety goggles 3) Always wear appropriate clothing in the confines of the machine shop (no open 4) toed shoes or long sleeves). 5) Operate any and all machinery with extreme care. 6) Be aware of surroundings at all times.
Other Facility Usage	1) Improper rocket storage. 2) Failure to abide by the Code of Conduct set forth by the facility/university 3) Damage to equipment	1) Ensure that only authorized personnel store the rocket, motor, and any explosive materials within the facility. 2) Abide by the Code of Conduct to ensure

	4) Not respecting hours of operation	that the use of the facility along with any equipment is not jeopardized 3) Handle all equipment with care and ensure to clean all workstations after completion of tasks 4) Do not use the facility outside of the hours of operation to ensure future use of the facility
Miscellaneous	1) Inclement weather 2) Issues with material acquisitions 3) Not abiding by the Code of Conduct 4) General Injury	1) Schedule backup dates for testing. 2) Order equipment in advance (at least two weeks prior) 3) Abide by the University's Code of Conduct to avoid losing access to lab space, 4) equipment, etc. 5) Respect hours of operation 6) Respect others at all times 7) Review and update safety binder often.

3.1.7 Regulation Compliance

It is of the utmost importance that the Zenith Program team be held to the highest safety standards for the duration of this project. The team must abide by the following rules and regulations to ensure the safety of the team as well as the spectators, competition officials, and any other personnel involved in the development and flight of this high-powered rocket:

1. Prior to launch, the team must assess the pre-launch and safety briefings located in the safety binder.
2. All spectators must stay at least 200 ft. away from the launch pad during any and all test and competition flights.
3. During the development of the rocket, the team should always wear appropriate clothing and proper personal protective equipment to avoid any injuries.
4. The team must review the safety data sheets located in the safety binder often and especially before any launch.
5. Always ensure that there is a knowledgeable team member present during assembly of the rocket.
6. Present the safety binder to the Range Safety Officer (RSO) and await approval for launch.
7. In the event that the RSO does not approve the rocket for flight (for any reason), the team acknowledges and accepts that their rocket will be removed from the competition.

In addition to the safety standards previously stated above, the following regulations will also be complied with during the development, testing, and flight of this rocket:

1. NAR High Power Safety Code
2. FAA regulations, including 14 CFR Subchapter F Part 101 Subpart C
3. NFPA 1127
4. USLI Safety Regulations (listed below)

The team as a whole agrees to abide by the following regulations from the Student Launch Handbook:

1. Range safety inspections of each rocket before it is flown. Each team shall comply with the determination of the safety inspection or may be removed from the program.
2. The Range Safety Officer has the final say on all rocket safety issues. Therefore, the Range Safety Officer has the right to deny the launch of any rocket for safety reasons.
3. Any team that does not comply with the safety requirements will not be allowed to launch their rocket. Any team member who does not agree to any of the rules above may be refused access to rocket construction or assembly, may not be allowed to attend launches, or may even be removed from the team if necessary.

A copy of this agreement along with each team member's signature will be available as Appendix A of this proposal.

4 FMEA Study [Preliminary Design Review]

(section 5 of PDR, hence incorrect table/figure labeling)

4.1 Risk Assessment Matrix and Definitions

To conduct a Failure Mode and Effects Analysis for each vehicle system, environmental risk assessment, and personnel risk assessment, the risk classification matrix in Table 5-1 was used. Tables 5-1 and 5-2 on the following page define each severity and likelihood class.

Table 4-1. Risk Classification Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	**B**	**C**	**D**
Event Severity	Marginal	**1**	1A	1B	1C	1D
	Significant	**2**	2A	2B	2C	2D
	Major	**3**	3A	3B	3C	**3D**
	Catastrophic	**4**	4A	4B	4C	**4D**

Table 4-2. Severity Classification Definitions

Severity	Vehicle Outcomes	Personnel Outcomes
Marginal	Little to no impact to vehicle integrity. Flight profile consistent with expectation. Safe recovery. Payload intact and deployed. Vehicle can be reused.	No potential for injury created.
Significant	Vehicle integrity compromised. Minor repair required. Deviation from expected flight profile. Safe recovery. Payload intact and deployable. Vehicle can be reused.	Minor risk of injury created. No injuries.
Major	Vehicle integrity compromised. Substantial repair required. Large deviation from expected flight profile. Recovery may endanger personnel. Payload and deployment mechanism damaged. Vehicle can be reused.	Great risk of injury created. Injuries reported. Injuries are manageable with basic first-aid.
Catastrophic	Vehicle breakup in flight. Irreparable damage. Unarrested descent. Recovery not possible. Payload destroyed. Complete loss of vehicle and payload.	Great risk of injury created. Injuries reported. Injuries require professional medical attention.

Table 4-3. Likelihood Classification Definitions

Likelihood	Definition
Possible	Within the set of all conceivable outcomes. Not likely to occur.
Plausible	Reasonable chance of occurrence due to uncertainty bounds.
Probable	Likley to occur. Uncertainty is now in whether the event will **not** occur.
Highly Probable	Near certainty. Statistical chance of occurrence far outweighs the chance of no occurrence.

4.2 Vehicle Systems Failure Mode and Effects Analysis

Table 4-4. Avionics and Power Systems FMEA

Failure Mode	Cause(s)	Hazard Category
(PS.1) Power loss on pad	• Dead battery • Disconnection of leads	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of power to flight computer	• Vehicle launch cannot be commanded • Battery replacement required • Personnel must approach cold vehicle – minimal risk	• Ensure battery is charged pre-flight • Have flight computer transmit battery condition • Firm lead attachment • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(PS.2) Power loss in flight	• Dead battery • Disconnection of leads	4A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of power to flight computer	• Loss of vehicle control • No control authority over recovery system • Unable to measure altitude • Unable to command deployment events • Unarrested descent • Risk to personnel	• Ensure battery is charged pre-flight • Have flight computer transmit battery condition • Firm lead attachment • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(PS.3) Power loss after recovery	• Dead battery • Disconnection of leads	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of power to flight computer	• Loss of control authority over payload deployment mechanism • Unable to deploy payload	• Ensure battery is charged pre-flight • Have flight computer transmit battery condition • Firm lead attachment • Redundant power/avionics

Failure Mode	Cause(s)	Hazard Category
(AV.1) In-flight barometer failure	• Bad component • Poor component calibration • Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Altitude cannot be determined from atmospheric pressure	• Vehicle relies on double integration of accelerometer data for altitude • Large compounding errors in integration may cause off-nominal main deployment • Nominal drogue deployment using accelerometer	• Purchase components from reputable dealer • Test components extensively before flight • Firm electrical lead attachments • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.2) In-flight accelerometer failure	• Bad component • Poor component calibration • Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Altitude and velocity cannot be determined by integration of acceleration data	• Vehicle relies on inflection of barometric data to determine apogee (pressure begins increasing) • Potential off-nominal drogue deploy • Nominal main chute deployment using barometer	• Purchase components from reputable dealer • Test components extensively before flight • Firm electrical lead attachments • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.3) Simultaneous in-flight accelerometer/barometer failure	• Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Altitude and velocity cannot be determined	• Recovery events reliant on time-commanded backup charges • Off-nominal drogue deploy • Off-nominal main deploy	• Purchase components from reputable dealer • Test components extensively before flight • Firm electrical lead attachments • Redundant power/avionics

Failure Mode	Cause(s)	Hazard Category
(AV.4) In-flight/post-flight GPS unit failure	• Bad component • Poor component calibration • Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Vehicle landing site cannot be precisely determined	• Sonic beacon becomes primary locator • Visual tracking to ground aids in recovery	• Purchase components from reputable dealer • Test components extensively before flight • Firm electrical lead attachments • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.5) Flight computer failure (pre-flight)	• Bad component • Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over vehicle	• Vehicle launch cannot be commanded • Personnel must approach cold vehicle – minimal risk	• Same as previous
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.6) Flight computer failure (in-flight)	• Bad component • Power loss	4A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over vehicle	• No control authority over recovery system • Unable to measure altitude • Unable to command deployment events • Unarrested descent • Risk to personnel	• Same as previous
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.7) Flight computer failure (post-flight)	• Bad component • Power loss	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over vehicle	• Loss of control authority over payload deployment mechanism • Unable to deploy payload	• Same as previous

Failure Mode	**Cause(s)**	**Hazard Category**
(AV.8) Wire leads disconnect	• Excessive vehicle vibration • Poor terminal connections	4D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Any combination of AV.1 – AV.4, AV.6, and AV.7 failure modes	• Loss of control authority over vehicle • No control authority over recovery system • Unable to measure altitude • Unable to command deployment events • Unarrested descent • Risk to personnel • Loss of control authority over payload deployment mechanism • Unable to deploy payload	• Ensure proper soldering of terminal leads • Extensively test robustness of connections to tension and vibration • Implement vibration damping measures for electrical components • Redundant power/avionics

Table 4-5. Avionics and Power Systems Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	PS.1, 1A, AV.7, PS.3	1B	1C	1D
	Significant	2	AV.1, AV.4, AV.2, 2A, AV.3, AV.5	2B	2C	2D
	Major	3	3A	3B	3C	3D
	Catastrophic	4	PS.2, 4A, AV.6	4B	4C	AV.8, 4D

Table 4-6. Energetics and Pyrotechnics FMEA

Failure Mode	Cause(s)	Hazard Category
(PRO.1) Failed motor igniter	• E-match fails to ignite • Black powder pellet fails to ignite after E-match	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Vehicle remains on launchpad in unknown state	• E-match/igniter replacement required • Personnel must approach warm vehicle – significant risk • Dud ignition converts vehicle cold • Random ignition in time following dud – significant risk to personnel approaching	• Redundant e-matches • E-match close proximity to black powder pellet
Failure Mode	**Cause(s)**	**Hazard Category**
(PRO.2) Ejection charge initiation failure	• E-match fails to ignite	2B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Body sections do not separate	• Separation dependent on backup charge (time initiated) • Off-nominal parachute deployment	• Redundant e-matches
Failure Mode	**Cause(s)**	**Hazard Category**
(PRO.3) Ejection charge fails to separate sections	• Insufficient black powder load • Excessive friction in coupler • Shock cord entanglement	2B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Body sections do not fully separate	• Structural damage between colliding body sections • Separation dependent on backup charge (time initiated) • Off-nominal parachute deployment	• Redundant ejection charges: • Time-commanded backup charge

Failure Mode	Cause(s)	Hazard Category
(EN.1) Unintentional motor ignition	• Static Discharge • Human Error	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Launch vehicle departs launch rails unexpectedly	• Flight computer not prepared to execute profile • Unable to command recovery sequence • Burns and hearing damage to personnel in immediate vicinity of vehicle	• Ensure vehicle is grounded in prep area and on pad • Ensure proper communication during count sequence
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.2) Unintentional ejection charge initiation (pre-flight)	• Static Discharge • Human Error	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Unexpected black powder detonation	• Creation of large audible signature and expulsion of hot exhaust gasses • Great injury to personnel standing in line with and near charge. Medical emergency • Burns and hearing damage to personnel in immediate vicinity of vehicle • Body section(s) are ejected • Body sections impact nearby personnel. Minor to significant injuries	• Ensure vehicle is grounded in prep area and on pad • Ensure proper communication during count sequence • Implement CO2 ejection system

Failure Mode	Cause(s)	Hazard Category
(EN.3) Uneven combustion in solid fuel	• Poor mixing of fuel and oxidizer • Poor distribution of propellant in case	4C
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Asymmetric thrust about vehicle z-axis	• Deviation from expected flight path • Loss of vehicle stability • In-flight break up of vehicle. Loss of vehicle • Unarrested descent. Risk to personnel	• Purchase motor from reputable dealer (Cesaroni is the current selection)
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.4) Motor exhaust in body tube	• Motor case rupture • Nozzle foreword of thrust plate	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Damage to body tube • Loss of vehicle integrity	• Mid-flight fin detachment • Catastrophic body rupture • Vehicle in-flight breakup • Loss of vehicle	• Aluminum motor case, thrust plate, and motor retainer • Extensive sealing in motor compartment
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.5) Motor jettison	• Thrust plate or motor retainer failure	3A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Motor and casing separate from launch vehicle after burnout	• Changes to stability margin as Cg shifts towards nose • Deviation from projected flight profile • Risk to personnel from uncontrolled, unarrested descent of metal motor casing	• Aluminum thrust plate and motor retainer to ensure dynamic loading margins are not exceeded

Failure Mode	Cause(s)	Hazard Category
(EN.6) Avionics damage	• Hot/corrosive ejection charge exhaust gasses	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Development of any AV.1 – AV.4 and AV.6 Failure Modes	• No control authority over recovery system • Unable to measure altitude • Unable to command deployment events • Unarrested descent • Risk to personnel	• Insulate void space in body • Implement CO2 ejection system
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.7) Burned parachute(s)	• Hot/corrosive ejection charge exhaust gasses	4D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Drogue and/or main parachute unable to provide sufficient drag to slow descent	• Partially or fully unarrested descent • Fire inside body tube • Fire in canopy on descent	• Kevlar blankets to retain chutes • Insulate void space • Implement CO2 ejection system
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.8) Chain detonation of ejection charges	• Hot/corrosive ejection charge exhaust gasses	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Multiple separation event at apogee • Simultaneous deployment of drogue and main chute	• Deviation from intended flight profile • Risk to personnel from (4) and (5) • structural damage to colliding body sections • Parachute entanglement. Increased descent rate Uncontrolled descent. • Decreased descent rate. Increased wind drift. Vehicle exits recovery zone	• Insulate void space in body • Implement CO2 cooling system to black powder ejection charges

Table 4-7. Energetics and Pyrotechnics Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	1A	1B	1C	1D
	Significant	2	2A	PRO.2 2B PRO.3	2C	2D
	Major	3	EN.5 3A	PRO.1 3B EN.8	3C	3D
	Catastrophic	4	4A	EN.1 EN.4 4B EN.2 EN.6	EN.3 4C	EN.7 4D

Table 4-8. Recovery System FMEA

Failure Mode	Cause(s)	Hazard Category
(RS.1) Drogue parachute entanglement	• Poor shock cord stowage in body • Snag hazards in deployment path	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• High descent rate after apogee • Main parachute deployment at higher speed	• Main parachute canopy damaged in high-speed deployment • Main parachute cords tear or rupture • Partially or fully unarrested vehicle descent • Over tensioning of vehicle shock cord. Cord tearing or rupture • Unarrested descent of body sections • Risk to personnel • Major repair needed	• Design for no snag hazards in deployment path of parachute • Reeve loose shock cord • Implement cord routing solutions
Failure Mode	**Cause(s)**	**Hazard Category**
(RS.2) Main parachute entanglement	• Poor shock cord stowage in body • Snag hazards in deployment path	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• High descent rate after main deployment • High ground impact velocity	• Partially arrested descent • Damage to vehicle structures • Damage to internal components • Major repair required	• Design for no snag hazards in deployment path of parachute • Reeve loose shock cord • Implement cord routing solutions
Failure Mode	**Cause(s)**	**Hazard Category**
(RS.3) Single electronic chute release failure	• Bad component • Power loss • Debris in latch mechanism	2B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Parachute remains retained in body	• Chute deployment contingent upon second release (timed event) • Off-nominal chute deployment	• Cross connection of retaining cord ends between two chute releases • Reputable distributor

Failure Mode	Cause(s)	Hazard Category
(RS.4) Double electronic chute release failure	• Power loss	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Parachute deployment rendered impossible	• Unarrested descent • Loss of vehicle • Risk to personnel	• Cross connection of retaining cord ends between two chute releases • Reputable distributor
Failure Mode	**Cause(s)**	**Hazard Category**
(RS.5) Shock cord rupture	• Excessive tension on cord	3A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Tether between body sections compromised	• Unarrested descent of body section(s)	• Extensive simulation pre-flight • Select shock cord with large factor of safety
Failure Mode	**Cause(s)**	**Hazard Category**
(RS.6) Shock cord entanglement	• Poor shock cord stowage in body • Snag hazards in deployment path	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Shock cord unable to extend to full length	• Collision of body sections on descent • Very minor damage to structure	• Reeve loose shock cord • Implement cord routing solutions

Table 4-9. Recovery System Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	RS.6 1A	1B	1C	1D
	Significant	2	2A	RS.3 2B	2C	2D
	Major	3	RS.5 3A	RS.2 3B	3C	3D
	Catastrophic	4	4A	RS.1 4B RS.4	4C	4D

Table 4-10. Vehicle Structures FMEA

Failure Mode	Cause(s)	Hazard Category
(STR.1) Melting of fin assembly during motor burn	• Heat transfer from motor case • Lack of heat resistance in fin material	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of flight stability	• Vehicle breakup in-flight • Loss of vehicle • Unarrested descent of body sections • Risk to personnel	• Use heat resistant print material • Treat for heat resistance • Minimize heat transfer
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.2) Fins shear off	• Fin flutter • Aerodynamic loading	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of flight stability	• Vehicle breakup in-flight • Loss of vehicle • Unarrested descent of body sections • Risk to personnel	• Extensive simulation pre-flight • Ensure flutter speed >> max vehicle velocity
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.3) Body tube zippering	• Shock cord contact with body on deployment	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of vehicle integrity	• Vehicle damage on descent • Major repair needed	• Implement “bumpers” to avoid cord contact • Implement cord routing
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.4) Damaged motor retainer	• Defect in part • Excessive dynamic loading	3A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Potential motor jettison after burnout	• Unarrested descent of motor casing • Risk to personnel • Minor repair required	• Aluminum motor retainer to absorb far larger loads than necessary

Failure Mode	Cause(s)	Hazard Category
(STR.5) Bulkhead or U-bolt torn loose	• Excessive loading during chute deployment • Late chute deployment	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Body section(s) disconnected from parachute	• Unarrested descent of body section(s) • Risk to personnel • Major repairs required	• Extensive pre-flight simulation • Extra thick bolts and wide bracing on bulkheads
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.6) Dislodged centering ring(s)	• Defect in part(s) • Excessive dynamic loading • Poor connection to threaded rods	3A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Motor long axis no longer colinear with vehicle z-axis	• Deviation from flight profile • Minor loss of stability • Risk to personnel	• Fix centering rings to threaded rods with hex nuts • Use thread lock to fix nuts
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.7) Damaged rover retainer	• Defect in part(s) • Poor 3D print • Excessive dynamic loading • Excessive ground impact velocity	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Rover sits loose in payload bay	• Minor decrease in vehicle stability • Minor rover damage • Improper or impossible rover deployment	• Extensive pre-flight testing • Minimize ground impact velocity • Cushion landing
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.8) Damaged avionics sled retainer(s)	• Defect in part(s) • Poor 3D print • Excessive dynamic loading • Excessive ground impact velocity	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Avionics sleds sit loose in av bay	• Potential for AV.8 failure mode • Loss of control authority over vehicle	• Extensive pre-flight testing • Minimize ground impact velocity • Cushion landing

Table 4-11. Vehicle Structures Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	STR.7 1A	1B	1C	1D
	Significant	2	2A	STR.4 2B	2C	2D
	Major	3	STR.6 3A	STR.3 3B STR.8	3C	3D
	Catastrophic	4	4A	STR.1 4B STR.5 STR.2	4C	4D

Table 4-12. Payload FMEA

Failure Mode	Cause(s)	Hazard Category
(RVR.1) 3-D printed rover body damaged	• High ground impact velocity • Defects in 3D print	1C
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Structure of rover compromised	• Loose components dig into terrain • Loss of propulsion • Internal wiring shifted. Leads torn from Arduino	• Extensive pre-flight testing • Minimize ground impact velocity • Cushion landing
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.2) 3-D printed rover wheels damaged	• High ground impact velocity • Defects in 3D print	1C
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Traction and/or propulsion negatively impacted • Physical immobilization	• None	• Extensive pre-flight testing • Minimize ground impact velocity • Cushion landing
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.3) Electronic latch fails to release quick link on shock cord	• Power loss • Debris in latch mechanism	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Payload remains tethered to recovered flight vehicle	• Rover can only move as far from vehicle as slack in shock cord will allow	• Ensure firm lead connections • Clean latch mechanism
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.4) Wheels become entrenched in loose terrain	• Insufficient wheel diameter • Insufficient tread on tires	1D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Physical immobilization	• None	• Extensive pre-flight testing

Failure Mode	Cause(s)	Hazard Category
(RVR.5) Rover becomes stuck in furrow of plowed field	• Cylindrical rover geometry	1D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Physical immobilization	• None	• Outrigger/arm in design phase to recover from this condition
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.6) Power loss	• Dead battery • Electrical lead disconnection	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over rover	• Physical immobilization • RAFCO Mission failure	• Charge battery pre-flight • Firm electrical connections
Failure Mode		**Hazard Category**
(RVR.7) Propulsion failure	• Dead battery • Electrical lead disconnection • Bad motor	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Physical immobilization	• None	• Charge battery pre-flight • Firm electrical connections
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.8) Antenna disconnection from GNC	• Excessive vibration in flight • Excessive ground impact velocity	1D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over rover	• Physical immobilization • RAFCO Mission failure	• Firm electrical connections • Pad landing, reduce velocity
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.9) GNC unit failure	• Bad component • Power loss	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over rover	• Physical immobilization • RAFCO Mission failure	• Firm electrical connections

Failure Mode	Cause(s)	Hazard Category
(RVR.10) Foreword looking camera failure	• Broken lens during ground impact • Power loss	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of ability to see terrain ahead of rover	• Technical immobilization • RAFCO Mission failure	• Padding around camera assembly • Firm electrical connections
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.11) Camera actuation system failure	• Motor failure • Obstructed gears • Power loss	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Camera cannot swivel camera	• RAFCO Mission failure	• Firm electrical connections • Clean gear mechanism

Table 4-13. Payload Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	RVR.7 RVR.9 RVR.1 1A	RVR.3 RVR.6 RVR.1 1B	RVR.1 RVR.2 1C	RVR.4 RVR.5 RVR.8 1D
	Significant	2	2A	2B	2C	2D
	Major	3	3A	3B	3C	3D
	Catastrophic	4	4A	4B	4C	4D

Table 4-14. Environment FMEA

Vehicle Risks to Environment		
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.1.1) Launch pad/recovery area fire (energetic initiated)	• Dry vegetation in vicinity of motor ignition	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Danger to wildlife • Danger to habitat • Danger to personnel	• Potential for fire growth if left unmitigated	• Clear launch area of vegetation
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.1.2) Launch pad/recovery area fire (LiPo battery initiated)	• Battery overcharge, over discharge, overtemp	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Danger to wildlife • Danger to habitat • Danger to personnel • HazMat release	• Pollution of crops with HazMat • Pollution of groundwater with HazMat	• Clear launch area of vegetation • Do not use battery improperly
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.1.3) Interstage insulation littered in launch/ recovery area	• Insulation used in body tube to minimize void space and insulate parachutes from ejection charge gasses	1C
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Ingestion of insulation by wildlife	• Disrespectful to property owners to eject litter on their land	• Biodegradable insulation (popcorn)
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.1.4) Litter spread over launch site by personnel	• Lack of trashcans • Poor team leadership	1D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Ingestion of litter by wildlife	• Disrespectful to property owners to litter on their land	• Bring trash bags • Firm leadership. Zero tolerance for littering

Environmental Risks to Vehicle		
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.2.1) Vehicle touches down in nearby trees	• Excessive wind drift	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Difficulty in or inability to recover launch vehicle • Minor damage to vehicle components	• Loss of vehicle • Repairs required	• Extra-long shock cord to bring components closer to ground
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.2.2) Vehicle touches down in nearby body of water	• Excessive wind drift	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Damage to body tube structure • Damage to avionics or payload electronics	• Major repairs required	• Extensive sealing of avionics bay and rover GNC unit
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.2.3) In-flight Collision	• Tall infrastructure (power lines) • Bird strike	4A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of stability • Damage to animal or object impacted	• Loss of vehicle • Repair to damaged infrastructure required	• Ensure vehicle is launched away from all infrastructure • Await clear skies
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.2.4) Vehicle or components dropped	• Uneven launch site terrain causes personnel tripping	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Damage to vehicle structures • Damage to payload structures • Damage to avionics • Damage to payload electronics	• Inability to launch • Repairs required	• Practice extreme caution while handling vehicle components

Table 4-15. Environmental Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	1A	1B	ENV.1.3 1C	ENV.1.4 1D
	Significant	2	2A	2B	2C	2D
	Major	3	3A	ENV.1.1 3B ENV.2.2 ENV.2.4	3C	3D
	Catastrophic	4	ENV.2.3 4A	ENV.1.2 4B ENV.2.1	4C	4D

4.3 Personnel Risk Assessment

Personnel risk assessment was conducted using the same FMEA format as was used for vehicle systems and environmental risk assessment.

Table 4-16. Personnel FMEA

Failure Mode	Cause(s)	Hazard Category
(PPL.1) Skin contact with APCP solid propellant	• Improper material handling • Lack of PPE	3D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Chemical burns • Eye irritation	• None	• Provide safety training • Provide PPE
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.2) Electrocution	• Improper safety procedures followed • Live electrical while wiring	2D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Discomfort/pain • Burns	• Greater or grave injury with prolonged exposure	• Provide safety training
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.3) Proximity to high-pressure burst event (CO2 charge)	• Overpressure in pressure vessel • Pressure vessel tipping • Human error	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Hearing damage • Struck/Impaled by flying object(s)	• None	• Provide safety training • Do not overfill pressure vessels • Pressure vessels chained to walls • Declare all testing and clear area prior to initiation

Failure Mode	Cause(s)	Hazard Category
(PPL.4) Proximity to explosive event (Black powder charge)	• Accidental initiation (human error, static discharge)	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Hearing damage • Burns from expanding hot gasses	• Severity increased with proximity • Severity increased with decreased angle-off-bore of charge	• Ground vehicle components • Minimize personnel handling charges • Isolate firing mechanism until range clear
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.5) Proximity to combustion event	• Motor ignition (intentional) • Motor ignition (unintentional) • Loose black powder burn	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Hearing damage • Burns from expanding hot gasses	• Severity increased with proximity • Severity increased with decreased angle-off-bore of charge	• Ground vehicle components • Minimize personnel handling motor • Isolate ignition mechanism until range clear
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.6) Injury: slip and fall, minor cuts, accidental collisions	• Uneven terrain • Tripping hazards on flat ground • Improperly stored sharp objects	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Pain/discomfort • Bruises • Small lacerations	• Infection of lacerations not immediately treated	• Situational awareness • Clean lab spaces • Proper safety procedures
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.7) Dehydration, heat exhaustion, heat stroke	• Lack of water • Lack of adequate sun protection or shade	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Thirst • Disorientation • Loss of consciousness	• None	• Provide ample water • Bring portable awning/tent • Bring sunscreen, hats, etc.

Failure Mode	Cause(s)	Hazard Category
(PPL.8) Soldering iron burns	• Improper use or stowage of soldering iron	3D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Minor burns	• Increased severity with prolonged contact	• Proper training in use of soldering iron • Minimize personnel involved

Table 4-17. Personnel Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	1A	1B	1C	1D
	Significant	2	2A	2B	2C	PPL.2 2D
	Major	3	3A	PPL.3 3B PPL.6	3C	PPL.1 3D PPL.8
	Catastrophic	4	4A	PPL.4 4B PPL.7 PPL.5	4C	4D

4.4 FMEA Summary

The risk classification matrix is overlayed with the number of risk items and percentage of total items that appear in each risk category. Our assessment identified a total of 63 risk items, with 40% of these items falling into the 3B and 4B categories. These categories represent substantial consequences in the event of failure with only a minor chance of failure, thus we can conclude that the bulk of our risk can be considered tolerable. 30 items fall into the 3D and 4D categories. These risks present substantial consequences and a substantial chance of failure. Mitigation strategies for items in these risk categories must be numerous, effective, and well-implemented by the team to ensure safety and mission success.

All 1-series (~30% of items) and A-series (~30% of items) risks can be considered tolerable risks. 1-series are the most tolerable because regardless of their likelihood of occurrence, the outcomes have marginal impact to safety and mission success. The 3A and 4A risk categories present substantial risk to safety and mission success but have an exceptionally low probability of failure. The entire A-series can be effectively considered negligible with the implementation of mitigation measures discussed.

Table 4-18. Overall Risk Item Distribution

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	**B**	**C**	**D**
Event Severity	Marginal	**1**	1A 8 Items 12.7%	1B 3 Items 4.8%	1C 3 Items 4.8%	1D 4 Items 6.3%
	Significant	**2**	2A 5 Items 7.9%	2B 4 Items 6.3%	2C 0 Items 0.0%	2D 1 Item 1.6%
	Major	**3**	3A 3 Items 4.8%	3B 10 Items 15.9%	3C 0 Items 0.0%	**3D** 2 Items 3.2%
	Catastrophic	**4**	4A 3 Items 4.8%	4B 14 Items 22.2%	4C 1 Item 1.6%	**4D** 2 Items 3.2%

4.5 Project Plan Risk Assessment

Project planning risk assessment was conducted using a similar format as the systems, personnel, and environment failure mode analysis, although for the case of impact to project timeline and budget the severity definitions which define the risk matrix were modified. Project plan risk severities are defined below, which also reiterates the likelihood definitions of previous sections.

Table 4-19. Project Plan Risk Severity Definitions

Severity	Timeline Outcomes	Budget Outcomes
Marginal	All milestones can be met without corrective action.	The project will proceed with no cost overruns. Project is viable.
Significant	Milestones may not be met without minor corrective action.	Cost overruns incurred amount to less than $100 per milestone. Project is viable.
Major	Milestones will not be met without substatial corrective action.	Cost overruns incurred range from $100 to $500 per milestone. Long term viability becomes questionalbe.
Catastrophic	Milestones will be missed entirely with no chance of timely completion.	Cost overruns exceed $500 per milestone. Sponsors and investors doubt viability.

Likelihood	Definition
Possible	Within the set of all conceivable outcomes. Not likely to occur.
Plausible	Reasonable chance of occurrence due to uncertainty bounds.
Probable	Likley to occur. Uncertainty is now in whether the event will **not** occur.
Highly Probable	Near certainty. Statistical chance of occurrence far outweighs the chance of no occurrence.

Using these new definitions, the analysis in the following table was performed. Risk level and mitigation strategies are assessed on a 1-5 scale with 5 suggesting that:

a) The risk to the timeline, budget, or project is substantial, and likelihood of occurrence rises above possible
b) The mitigation strategies are an excellent countermeasure to the risk item, while 1 suggests the mitigation measures have little to no effect.

And 1 suggesting that:

a) The risk to the project is marginal and the likelihood of occurrence is significant or below
b) The mitigation strategy does a poor job of effectively managing the risk to the project

Table 4-20. Project Plan Risk Assessment

Code	Risk Item	Effects	Risk Cat.	Mitigations	Mit. Effect
(PLN.1)	Broken parts and/or tools	• Replacement parts required • Cost incurred • Time delays pending new tools/parts	2	• Handle all parts on steady surfaces • Transport parts carefully and in teams • Use tools within specified operating ranges	3
(PLN.2)	Shop injuries	• Suspension of shop work for safety review • Major time delays • Threat to investor confidence	5	• Provide safety training • Emphasize personal responsibility • Clean shop environment	2
(PLN.3)	Poor meeting attendance	• Slower than projected progress • Inter-department miscommunications	2	• Iterate on meeting date and time to work best for all • Facilitate channels for communication outside of meetings	1
(PLN.4)	Poor communication between departments	• Slower development of interlinked systems • Slower test campaigns • Poor equipment sharing or resource management	3	• Facilitate channels for communication outside of meetings • Ensure communication is documented referenceable	4

Code	Risk Item	Effects	Risk Cat.	Mitigations	Mit. Effect.
(PLN.5)	Insufficient design documentation. Lost documentation	• Poor resource management • People repeating completed tasks or analyses • Time wasted on discarded concepts, ideas, solutions	3	• Facilitate shared team storage (Teams, drop box, slack) • Keep all leads and members appraised of current iteration	5
(PLN.6)	Weeks of increased university coursework	• Reduces availability of team members • Decrease in team attendance	3	• Discuss exam schedules with students, members, and professors • Work exam/project week delays into timeline	1
(PLN.7)	Saturday home football games	• Reduced team member availability on 1 of 2 potential test launch days in each week • Large delays in event of launch failure pending scheduling a re-flight • Reduced team attendance and availability on Saturdays	2	• Plan for launches on away game weekends • Plan for Sunday launches • Explore mid-week launches with professor coordination	3
(PLN.8)	Low stock of commercially sourced items	• Build or testing delayed pending restock • Higher fees for expedited shipping	3	• Purchase items well in advance of deadlines • Source alternative items or distributors	4

Code	Risk Item	Effects	Risk Cat.	Mitigations	Mit. Effect.
(PLN.9)	Test launch weather scrubs	• Large delays pending re-flight scheduling • Cost of new motor incurred • Missed milestones	3	• Use yearly weather patterns for launch facility to anticipate conditions • Monitor conditions week of launch • Schedule backup launch days • Schedule test launches well ahead of time	2
(PLN.10)	Catastrophic test launch failure	• Loss of vehicle • Massive time delays pending full rebuild • Missed milestones • Massive cost incurred • Threat to investor confidence	5	• Extensive simulation and testing before flight • Plan test launches well ahead of milestones in event of failure	2
(PLN.11)	Non-catastrophic test launch failure	• Considerable time delays pending scheduling re-flight • Cost of new motor incurred • Missed milestones	4	• Plan test launches well ahead of milestones in event of failure • Include “padding” in budget to accommodate partial failures resulting in $200-300 expenses	5