Preliminary Design Review
Team 22
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Abbreviation	Definition
ADV	Advisory
CDH	Command and Data Handling
CDR	Critical Design Review
CEH	Cost Estimating Handbook
CER	Cost Estimating Relationship
COTS	Commercial-Off-The-Shelf
DRR	Decommissioning Readiness Review
EDL	Entry, Descent, & Landing
ESDMD	Exploration Systems Development Mission Directorate
FMEA	Failure Mode and Effect Analysis
FY	Fiscal Year
GRNS	Gamma-Ray and Neutron Spectrometer
HGA	High-Gain Antenna
JPL	Jet Propulsion Laboratory
KDP	Key Decision Points
LOTO	Lockout/Tagout
LRR	Launch Readiness Review
MCCET	Mission Concept Cost Estimation Tool
MLI	Multi-Layer Insulation

MSDS	Material Safety Data Sheets
NICM	NASA Instrument Cost Model
NIRVSS	Near-Infrared Volatile Spectrometer System
NSS	Neutron Spectrometer System
OBC	Onboard Computer
PDR	Preliminary Design Review
PLAR	Post-Launch Assessment Review (PLAR)
PMS	Power Management Subsystem
RFA	Request For Action
SMD	Science Mission Directorate
SOC	State of Charge
SOH	State of Health
SSA	Student Success Advisor
STM	Science Traceability Matrix

1. Mission Overview

1.1. Mission Statement

The goal of Team 22's mission is to determine the viability of developing safe and sustainable habitation systems within lunar volcanic tubes to protect future lunar exploration teams and human settlement on The Moon, through the use of an unmanned lunar rover. This mission will focus on identifying and discovering potentially useful resources such as water, ice, and other lunar minerals to further understanding of lunar formation and geology, as well as for in-situ resource utilization. Lunar volcanic tubes serve as a relic from the formation of the Moon, studying these sites may offer scientists on earth a closer look at this period of formation, revealing previously unknown aspects and features. An important aspect for future habitation of the moon is available resources that can be accessed and utilized by modern technology. Exploration and analysis of lunar volcanic tube geological makeup may reveal important resources that can be harvested for on-site usage in future human settlements. This data will be collected through the use of a land rover designed to analyze the lunar surface, crater, and interior of the volcanic tube. The rover will be equipped with sufficient instrumentation to collect, analyze, and transmit scientific data. Data will be collected from environments within and outside the chosen mission location, offering a full picture of potential habitation sites. Discovery of useful resources within or in the surrounding area of these lunar volcanic tubes could offer a great settlement site for future human habitation. In order for human settlement of the moon to begin full consideration of potential sites and their characteristics must be fully explored. This mission aims to create a deeper understanding of lunar volcanic tubes, in the context of human settlement, paving a path towards sustainable lunar exploration and habitation for humanity.

1.2. Science Traceability Matrix

The Science Traceability Matrix (STM) provides information on the mission's science objective to the performance and operational requirements. The mission aligns closely with NASA's long-term exploration goals by advancing robotic precursor missions to prepare for future sustainable human exploration. Our focus is on understanding the potential of lunar caves to support sustainable human habitation, as well as discovering insights into lunar geology, in which the STM ensures that all objectives address the customer-defined science priorities. The STM translates these goals into specific objectives, measurable physical parameters, and observables. The table maps out how each instrument was chosen for its ability to meet specific performance requirements and ensures that all objectives are achievable within the constraints provided. This clear and structured approach outlines measurable and actionable goals that ensure the mission is both practical and impactful.

Science Goals	Science Objectives	Science Measurement Requirements: Physical Parameters	Science Measurement Requirements: Observables	Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
SMD Goal: "Develop precursor lunar robotic missions and define those scientific activities that astronauts will conduct on the Moon" – Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032.	Determine the composition of vital resources such as water, ice, and carbon-rich compounds, as well as the regolith composition within a 5 km radius of the lunar surface.	Identify ice and carbon-rich compounds within 5 km radius of lunar caves or pits.	Water and ice distribution data based on absorption characteristics.	Wavelength Range:	1000–2500 nm (ice); 400–4000 nm (organics)	950–2550 nm (ice); 395–4050 nm (organics)	NIRVSS (Near Infrared Volatile Spectrometer System)	The mission shall collect spectral data within a 5 km radius to detect and quantify water ice, carbon-rich compounds, and terrain stability with a sensitivity of 0.1% by mass, a spatial resolution of 30 cm, and hydrogen detection sensitivity of 0.1%.
				Integration Time:	1 s	0.8 seconds (ice); 0.9 seconds (organics)		
				Sensitivity:	0.1% by mass	0.1% by mass with 95% accuracy		
				Spectral Resolution:	5 nm	4.8 nm		
	Characterize terrain, thermal properties, and structural stability of lunar caves for habitability potential.	Analyze terrain variations and structural integrity of cave walls.	Organic compound data indicating the presence and distribution of carbon-rich materials.	Detection Depth:	Up to 1 meter	Up to 1.2 meters	NSS (Neutron Spectrometer System)	The mission shall land within 100 meters of the central peak at Tycho 29B region and comply with a mass limit of 350 kg and vehicle dimensions of 2 m × 1.25 m × 1.25 m.
				Signal-to-Noise Ratio:	Minimum of 100:1	120:1 (ice); 110:1 (organics)		
				Operating Temperature:	-150°C to +50°C	-160°C to +55°C		
				Spatial Resolution:	30 cm	25 cm		

ESDMD Goal: Life Support & Habitat: mLSH1 -	Assess depth, terrain variations, temperature	Measure temperature gradients and radiation levels	Temperature gradient data showing	Wavelength Range:	3000 - 15000 nm	3000 - 15500 nm	Diviner Lunar Radiometer	The mission shall measure temperature gradients across a complete lunar day-night cycle with a
				Integration	1 s	0.7 s		

"Provide safe and enduring habitation systems to protect individuals, equipment, and infrastructure in lunar pits and caves, supporting long-term human exploration and habitation" (Lunar Exploration Analysis Group (LEAG) Habitation: HAB-SAT Report, Priority Objectives)	gradients, and radiation levels within lunar pits and caves to evaluate their suitability for safe and sustainable human habitation.	within and outside caves over a complete lunar day-night cycle.	variations across lunar day-night cycles.	Time:				spatial resolution of 200 m and a sensitivity of ±0.01°C.
				Spectral Resolution:	10 nm	9 nm		
				Detection Depth:	Surface-level	Surface-level		
		Assess terrain height, depth, and variations to determine cave geometry and accessibility for habitation systems.		Spatial Resolution:	200 m	180 m		
			Radiation flux and intensity levels inside and outside caves.	Detection Depth:	Up to 1 meter	Up to 1.2 meters	Gamma Ray and Neutron Spectrometer	The mission shall measure radiation levels up to 1.2 m in depth and across a 5 km radius with a sensitivity of ±5% radiation intensity and a spatial resolution of 200 m.
				Spatial Resolution:	200 m	200 m		
				Sensitivity:	±1% radiation intensity	±5% radiation intensity		
	Determine rock density and elemental composition to evaluate the load-bearing capacity and structural stability of cave walls for long-term habitation systems.	Quantify elemental composition (e.g., iron, silicon, calcium, phosphorus, magnesium) to assess load-bearing capacity and cave wall stability.	Elemental composition data showing concentrations of Fe, Si, Mg, and other materials for structural analysis.	Wavelength Range:	100-1500 nm	95-1575 nm	Raman Spectrometer	The mission shall collect elemental composition data with a sensitivity of 0.03% concentration and a spatial resolution of 950 nm to assess load-bearing capacity and structural stability.
				Integration Time:	1 s	0.8 s		
				Sensitivity:	Detect low concentration minerals 0.01%	Detect mineral low concentration at 0.03%		
				Spatial Resolution:	1,000 nm	950 nm		

Table 1.2.1. Science Traceability Matrix outlining the mission's alignment with science goals and objectives, mapping these to measurable requirements, physical parameters, and observables.

1.3. Summary of Mission Location

Criteria	Explanation	Grade	Weight	Tycho 29B	King 34A	Kepler 4A
Resource Availability	Proximity to lunar poles and potential ice deposits are essential for sustaining human exploration and scientific study. Sites closer to the poles are more likely to have water ice.	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	7	6
Temperature Stability	Sites with greater depth have natural thermal regulation, minimizing temperature fluctuations and supporting long-term equipment functionality and habitation needs.	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	8	6
Radiation Protection	Lunar caves with substantial overhangs provide shielding from solar and cosmic radiation, critical for astronaut safety and long-term exploration.	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	7	5
Accessibility	Features such as ramps and flat terrain at the site's entrance make it easier to deploy equipment and collect samples.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	6	5
		TOTALS:	100%	92.50%	70%	55%

Table 1.3.1. Evaluation of potential mission locations (Tycho 29B, King 34A, and Kepler 4A) based on key criteria for lunar exploration, including resource availability, temperature stability, radiation protection, and accessibility.

The chosen mission location is Tycho 29B, which was selected after a trade study (Table 1.2.1), compared to two other locations, King 34A and Kepler 4A. Tycho 29B is an ideal site for achieving the mission's science objectives, which involves analyzing water ice, organic materials, and regolith within a 5-kilometer radius of a lunar pit. This location is also an ideal site that provides the necessary conditions to support analysis for potential long-term habitation. A visual representation of Tycho 29B's surface characteristics and surrounding terrain is provided in the accompanying JMARS image, displayed in Figure 1.3.1. The four criteria observed included resource availability, in which Tycho 29B is located near the lunar poles, where water ice deposits are more likely to be found. This makes it valuable for resource sampling, along with supporting future human exploration. The site also has a significant depth that helps regulate temperatures, which minimizes fluctuations that could potentially interfere with equipment functionality. The overhang provides critical shielding from harmful solar and cosmic radiation, and Tycho 29B's terrain is relatively flat and stable, which makes the deployment of equipment, such as the Diviner Lunar Radiometer, and sample collection more efficient, which will measure thermal gradients, radiation levels, and the elemental compositions of the area. Each criteria was assigned equal weight of 25%, and Tycho 28B consistently outperformed the two other candidates. King 34A and Kepler 4A lacked proximity to critical resources and have challenging terrain conditions. The site's unique features align with the mission's goals, which are outlined in the STM and provide ideal conditions for achieving all the science objectives.

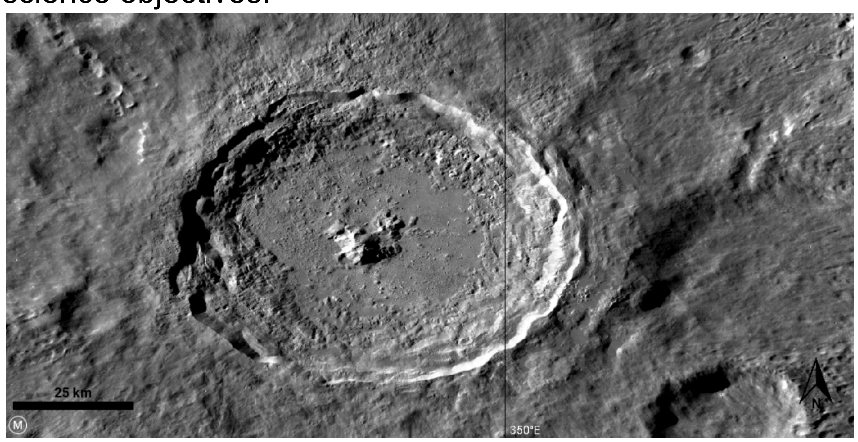


Figure 1.3.1. This image shows the central pit of Tycho 29B and its surrounding terrain. The visible geographic features align with the mission's objectives outlined in the STM (Section 1.2).

1.4. Mission Requirements (1 page recommended)

Following the customer constraints and the adjusted budget scope, the team will design a cost-effective spacecraft to carry out the mission. The spacecraft shall have a combined mass that does not exceed 350 kilograms and, during launching and deploying, it shall fit within the dimensions of 2 meters x 1.25 meters x 1.25 meters. To comply with safety and budgetary requirements, the spacecraft shall not incorporate any form of a Radioisotope Thermoelectric Generator (RTG) and shall limit onboard radioactive material to no more than 5 grams.

Given the descope budget decrease, the team optimized the design to prioritize critical scientific and operational capabilities while maintaining financial feasibility. The spacecraft will be transported to the Moon on a rocket designed to allow minimal power consumption during transit while maintaining adequate thermal stability. Upon landing, the mission will commence immediately, with all systems operating under the revised budget constraints.

Communication with Earth will be achieved by directly relaying information through a lunar-orbiting spacecraft at 100 kilometers in polar orbit. To ensure mission success, the spacecraft design will undergo rigorous analog testing under Earth-based conditions simulating the lunar environment, ensuring functionality within the constraints of the adjusted budget.

The total cost of the mission, including all secondary objectives, shall not exceed $425 million. A Land Rover system has been selected to perform the lunar exploration and data collection tasks. The Requirements Table below outlines the top-level mission requirements, addressing customer-provided guidelines and the objectives determined by the foundational science and preliminary mission planning.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem

0.1	The system shall identify, measure, and classify volatiles such as water and ice, as well as elements, found on the surface of the Moon	Foundational science driver for mission	-	ALL	Demonstration	ALL
0.2	System shall analyze and test the reliability of Tycho 29 B lunar pit	Preliminary mission to provide safety for future astronauts	-	ALL	Demonstration	ALL
PM.1	System shall adhere to all constraints provided by the customer	The system's components and objectives need to fit within the customer's constraints	0.1, 0.2	PM.2 PM.3 PM.4	Inspection	ALL
PM.2	The system should have a combined mass of 350 kg	Defined by customer	PM.1	-	Inspection	ALL
PM.3	System should fit within the dimensions of 2m x 1.25m x 1.25m	Defined by the customer	PM.1	-	Inspection	ALL
PM.4	System shall not exceed the cost of $425 million	Defined by the customer	PM.1	-	Inspection	Payload
PM.5	The system shall not use radioactive material (e.g., no RTG).	Defined by the customer	PM.1	-	Inspection	Electrical, Safety
SYS.1	System shall have sufficient power for the mission	The system needs power to carry out testing,	0.1, 0.2	SYS.3	Demonstration	Electrical, Mechanical, Thermal

		analysis, and to move around				
SYS.2	System shall land within TBD meters of TBD region	System needs to land at an appropriate distance from the sites	0.1, 0.2	-	Demonstration	Mechanical, Electrical
SYS.3	The system shall move to and from selected sites on the lunar surface	The system needs to move from the landing site to the pit and foundational science site	SYS.1	-	Test, Demonstration	Mechanical, Electrical, Thermal
SYS.4	System shall be able to descend down the lunar pit	The system must go down the pit to test and verify its characteristics and structural stability	0.2	SYS.6	Test, Demonstration	Mechanical, Electrical, Thermal
SYS.5	The system shall collect samples from the lunar surface	The system should collect samples to bring back to Earth	0.1	-	Demonstration	CDH
SYS.6	System shall assess the structure of the Tycho 29 B	The system should collect data about the lunar pit's interior	0.2	-	Demonstration	Mechanical, Electrical, Thermal, CDH
SYS.7	The system shall travel a minimum distance of 5 km during the mission.	Ensures sufficient exploration coverage of the lunar surface.	PM.1	-	Test, Demonstration	Mechanical, CDH

1.5. Concept of Operations (ConOps)

In Phase 1, the rover is deployed from the primary launch vehicle and lands on the moon's surface. To ensure mission readiness, it conducts a thorough analysis and verification of each instrument and subsystem. Starting with the Electronic System, the rover confirms that each subsystem is receiving adequate, predetermined power, including that needed for mobility, imaging, thermal control, software activation, and instrument operation. It then verifies that communication systems are fully operational and synchronized with the intermediary satellite, enabling reliable data feedback to Earth. To check the functionality of scientific instruments, the rover runs brief test sequences to confirm accurate data transmission. Once complete, the rover transmits the overall system status to mission control on Earth. This entire process takes about one day, setting the stage for Phase 2.

Phase 2 of the mission begins the rover’s journey towards the entrance ramp of Tycho 29B. Journey towards the entrance ramp will commence from the landing site and is conducted through manual operation of rover driving capabilities. The driving team of the rover communicates through the usage of an intermediary satellite. Operators of the rover are assisted through the use of hazard cameras placed upon the rover to facilitate manual operation. These hazard cameras provide operators with relevant information that serve as further guidance towards the volcanic tube site, along with positional data communicated from the rover’s Inertial Movement system. In order to effectively travel in a safe manner minimizing risk to the rover, travel is limited to speeds of 1 cm/sec. The rover utilizes the use of night modes in which non-essential instrumentation and functions of the rover are minimized to assure sufficient power supplies during the lunar night.

Once the rover arrives at the “lip” of the entrance ramp of Tycho 29B, it begins its first scientific collections. A TBD amount of samples taken from the lunar surface regolith surrounding Tycho 29B for further analysis by the onboard Raman Spectrometer and NIRVSS Spectrometer. Analyzation by these systems will reveal presence of possible beneficial volatiles within regolith from the area as well as chemical structure of the collected samples. Understanding of the lunar mineral composition is vital to fully discovering the potential usage of lunar volcanic tubes as a point for human lunar habitation in the future. If beneficial materials are found to be within the lunar volcanic tube, this could hint at the possibility of future human settlement. The rover also begins initial temperature analysis through the usage of the onboard radiometer. Temperature plays a critical factor in the potential habitation of the moon, and it is currently believed that lunar pit caves could offer more stable temperature than that of the surface of the moon. Information on science collection and data will be sent to the relay network at the next available uplink.

After collection of samples are completed within Phase 2, Phase 3 will begin. The rover begins an arduous descent down the entrance of Tycho 29B. This process will be extremely slow in order to ensure the safety and protection of onboard systems and instrumentation as well as the rover itself. As with Phase 2, traversal within Phase 3 are conducted by a team of drivers, utilizing information from rover internal systems and Hazcams through a communication relay network. This process is largely marked by the attempts to create a sustainable path down the slope. Angles of 40 degrees or above are to be avoided in attempts of hazard deterrence. This process will almost likely take the rover multiple days, thus during lunar nights the rover enters the previously mentioned night mode in which the inessential capacities of the rover are limited.

Once reaching the pit floor the second phase of sample collection begins. Samples collected from the cave floor may further reveal evidence of beneficial volatiles such as water. Rover collects samples for analysis by scientific instrumentation. Water/ice and elements such as iron, silicon, calcium, phosphorus, and magnesium, are resources that, if found, would constitute ISRU for human utilization. Absorption spectra are used to identify water/ice, and fluorescence spectra for the presence of other elements. Furthermore, the amount of regolith would be important to determine as it is a crucial insulator to help stabilize the wide range of temperatures on the Moon. Photos and imagery is collected alongside This data is then sent back at the nearest available uplink. Transmission of scientific data will conclude Phase 3, and the predetermined life cycle of the rover.

At this point the rover enters into its post mission phase. Within this phase the rover continues to store samples collected from scientific analysis for potential future collection. Depending on whether further entry into the cave is possible, the rover will continue to explore and document the geography and makeup of the cave floor. At this point, new scientific objectives may be created in order to direct continuous rover usage on the cave floor. If possible exploration of the interior of the pit cave may be pursued. Communication may be limited within the cave interior, however, positives and negatives to this possibility will need to be discovered upon reaching Phase 3.

1.6. Vehicle Design Summary (1 page recommended)

The Lunar Cave Exploration Rover was skillfully constructed to investigate underground residences and navigate the difficult terrain of the moon. To reliably and effectively accomplish its mission objectives, it is designed with modern communication, power management, mobility, navigation, and scientific research technology. Mars rovers such as Curiosity and Perseverance have long utilized the rover's rocker-bogie suspension mechanism. This system ensures stability and dependability in uncertain subterranean conditions by permitting the rover to climb steep inclines and traverse tough, uneven terrain. The rover has a thorough view of its surroundings because to its engineering cameras and Hazard Cameras (HazCams). These cameras provide in-depth three-dimensional maps of the lunar environment.This capability is crucial for operating within the moon's intricate and shadowed cave systems. The rover carries a robotic arm outfitted with tools for sample collection and close-up analysis of cave walls. The arm's design allows it to reach narrow crevices and shaded areas. Key instruments onboard include:

Near-Infrared Volatile Spectrometer System (NIRVSS): Detects water and organic compounds.
Neutron Spectrometer System (NSS): Locates hydrogen deposits to identify water reserves.
Diviner Lunar Radiometer: Monitors thermal conditions.
Raman Spectrometer: Analyzes the chemical composition of cave surfaces.

Together, these resources offer important information about the lunar environment and resource availability. Lithium-ion batteries and solar panels power the rover. When solar panels gather solar energy in dimly lit spaces, like caverns, batteries provide electricity. Effective energy distribution throughout all systems is guaranteed by a complex power management system.
Communication and Core Systems The rover's main processor, the BAE RAD750, handles all operations and decodes scientific data. It is securely stored on an 8GB Phison uSSD and sent to Earth via an X-band High-Gain Antenna with error detection and correction capabilities. The

rover's systems can communicate reliably thanks to the MIL-STD-1553 data buses.

Designed with robust and mission-proven technologies, the Lunar Cave Exploration Rover is an essential tool for advancing lunar science and preparing for future human exploration. Its specialized systems enable it to navigate, analyze, and survive the moon's challenging terrain while uncovering valuable data about its resources and environment.

1.7. Science Instrumentation Summary

The mission utilizes five core instruments integrated to our rover in order to achieve its science objectives outlined in the Science Traceability Matrix (STM) in Section 1.2, ensuring consistency with the mission goals.

1. Near-Infrared Volatile Spectrometer System (NIRVSS): Designed to identify water, ice, and carbon-rich compounds on the lunar surface. It operates in the 1000–2500 nm wavelength range for ice detection and 400–4000 nm for organics, detecting absorption spectra indicative of these volatiles. It assesses the in-situ resource utilization (ISRU) potential, which is essential for future sustainable lunar exploration.
2. Neutron Spectrometer System (NSS): Designed to detect hydrogen concentrations by measuring neutron flux variations. By quantifying hydrogen, the NSS helps located valuable water reserves, which are essential for future sustainable lunar operations.
3. Raman Spectrometer: Analyzes elemental composition by scattering laser light off the lunar regolith. It evaluates critical elements like iron, silicon, magnesium, and calcium which provides data that helps determine the structural stability and load-bearing capacity of cave walls.
4. Diviner Lunar Radiometer: Measures temperature gradients and thermal properties which assesses environmental stability. It operates in the 3000-15,000 nm wavelength range. This produces high-resolution thermal maps that help ensure lunar caves provide a stable environment for human exploration.
5. Gamma-Ray and Neutron Spectrometer: Evaluates radiation levels and identifies hydrogen concentrations. This is important for assessing

astronaut safety and locating potential water reserves. Measuring gamma-ray and neutron flux with high precision provides insights into radiation shielding capabilities of lunar caves.

These instruments were selected based on their ability to meet the goals and outcomes defined in the STM. They are designed to operate effectively under harsh conditions of the lunar surface. By analyzing volatiles, structural stability, temperature gradients, and radiation levels, they can meet the mission's science objectives.

1.8. Programmatic Summary

1.8.1. Team Introduction

Joshua Walters | Project Manager & Electrical Engineer

Rowan College of South Jersey - Sewell, New Jersey

Joshua Walters is currently beginning his journey in the study of electrical engineering as a freshman at the Rowan College of South Jersey. Joshua has worked on student projects before and loves working with other people throughout his studies.

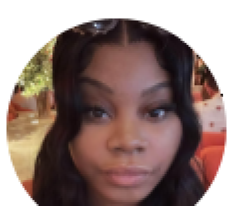
Jenelle Maldonado | Chief Scientist
Villanova University - Villanova, Pennsylvania

Jenelle Maldonado has done astronomy research for the past two years at Villanova University. As a senior, Jenelle enjoys deep diving into new concepts, along with continuously learning new skills in order to apply that knowledge to real world-projects.

Jodi Joven | Deputy Project Manager of Resources & Outreach Officer
University of Michigan - Dearborn, Michigan

Jodi Joven is a senior majoring in computer science at the University of Michigan. Jodi has experience as a software engineering intern in both the engineering and aerospace fields, which enhance skills in team management, project analysis, and multidisciplinary team collaboration.

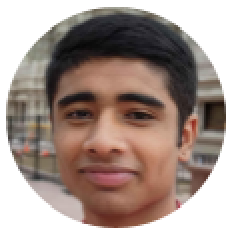
Faith Robinson | Lead System Engineer & Mechanical Engineer
LaGuardia Community College - New York City, New



York

Faith Robinson is a sophomore at LaGuardia Community College, having completed a year as a software engineer. Faith brings a passion for teamwork and delivering high-quality products, developing effective problem solving skills and tackling complex technical challenges.

Spandan Belbase | Computer Hardware Engineer & Thermal Engineer
University of Maryland - College Park, Maryland



Spandan Belbase is an aspiring aerospace engineering student with experience in programming IT. Spandan is an analytical problem solver that troubleshoots technical issues and manages technology infrastructure, providing meaningful outcomes for the team.

Chawin Mingsuwan | Scientist & Computer Hardware Engineer
Purdue University - West Lafayette, Indiana

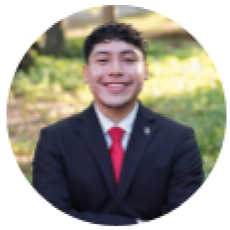
Chawin Mingsuwan is a game development student at Purdue University. As a software engineering intern with study-abroad experience in Lima, Peru, Chawin's skills include user experience and cross-team collaboration in order to design and prototype a final product.

Deeya Mitra | Scientist & Mission Assurance Specialist

Georgia Institute of Technology - Atlanta, Georgia

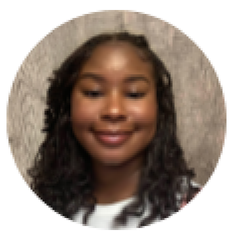
Deeya Mitra is a double major in computer science and aerospace engineering at Georgia Tech. With experience in developing a path-planning algorithm for the Martian rover, Deeya engages in interdisciplinary projects and utilizes technical knowledge to advance space exploration.

Juan J. Rosales | Mission Assurance Specialist & Mechanical Engineer
University of Georgia - Athens, Georgia



Juan J. Rosales is a mechanical engineer at the University of Georgia. Juan has had the opportunity to do hands-on work and research through coursework projects, providing practical skills in sketching, CAD modeling, and effective problem solving.

Jayla Sanders | Scientist
American Military University - Charles-towne, West Virginia



Jayla Sanders is a space studies major at the American Military University. Jayla brings excellent science research on planetary science, specializing in black holes, while also expanding knowledge on scientific research and sharing teamwork experience.

Garrick D. Smith | Scientist & Outreach Officer
Wayne County Community College - Detroit, Michigan

Garrick D. Smith has experience in engineering and IT work as a student at Wayne County Community College. Garrick's IT work at a computer repair shop and engineering competition awards at the Henry Ford College provide essential problem solving skills.

Rajdeep Villuri | Computer Hardware Engineer
Rutgers University - New Brunswick, New Jersey

Rajdeep Villuri is a sophomore studying computer science at Rutgers University. By taking classes involving computer architecture, processors, and memory, Rajdeep has an understanding of the intersection between hardware and software in order to build comprehensive computer systems.

Manas Vohal | Program Analyst
Rutgers University - New Brunswick, New Jersey

Manas Vohal double majors in computer science and data science at Rutgers University. Manas gained relevant experience working on data-driven projects, and the combination of technical and analytical skills allows Manas to excel in cost analysis and data-driven decision making.

Samuel Volchansky | Mission Assurance Specialist & Program Analyst
Rutgers University - New Brunswick, New Jersey

Samuel Volchansky has gained experience in iOS development and CAD design at Rutgers University. With skills gained from participating in the design and build teams in high-school robotics, combined with coursework, Samuel's experiences allow for insightful analysis and collaboration.

1.8.2. Team Management Overview

The organization within the team was determined by the L'SPACE Mission Concept Academy - Team Organization Guide (L'SPACE Mission Concept Academy).The official organization chart for Team 22 is as follows:

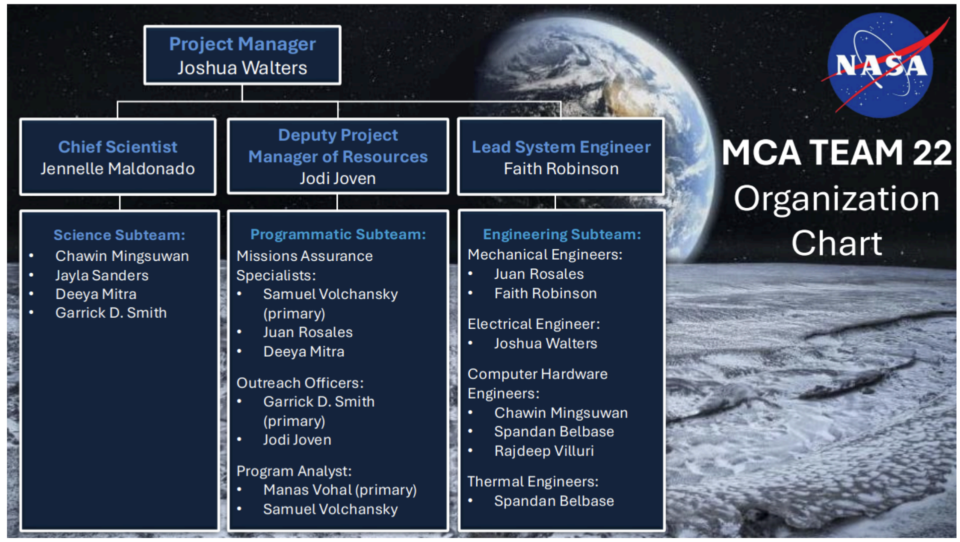


Figure 1.5.1 - MCA Team 22 Organization Chart

Based on the organization and collaboration among members thus far, Team 22 is equipped to handle the mission. Each member of the team contributes unique talents, skills, and perspectives that effectively accomplish the mission tasks at hand. The team members each have a diverse base of expertise from educational, professional, and personal life experiences that allows them to find answers to the questions that the mission poses. Students on the science sub-team have backgrounds in fields such as astronomy or astrophysics, which gives them a strong foundation for the scientific analysis of the mission's objectives. Students on the engineering sub-team have engineering related majors, such as mechanical engineering, electrical engineering, or computer science, that aids in the vehicle and payload designs for the lunar rover's system. Students on the programmatics sub-team–although not directly enrolled in business-related majors or programs–have experience in critical analysis and iterative learning, which has allowed them to learn the new skills required to make cost & schedule estimates, along with tracking risks and changes.

Since the team is entirely composed of college students, additional technical skills that are learned through professional, full-time careers are skills that members of Team 22 have not been exposed to. Many tools for ideation, development, and estimation have not been utilized by members of the team before, and it requires additional time to become familiar with these technologies that more experienced professionals in the field already possess. For example, it was essential for the programmatics team members to understand to process needed to derive cost and schedule estimates, and an additional 1-2 hours were required in order to take the NASA L'SPACE MCA Project Management skill module in addition to the work initially required from the sections relating to those topics. However, despite any information gaps that may be present as a result of newer levels of experience, each member of Team 22 is dedicated to learning more about developing mission concepts and enhancing technical skills. Through the weekly sessions hosted by the NASA L'SPACE MCA team, along with the skill modules that are presented by the academy, Team 22 is able to fill in any gaps and strengthen individual skills and knowledge bases.

Team members accomplish work both collaboratively and individually. Each team member is expected to work together in order to complete tasks related to each deliverable. Team members do have differing schedules that may lead them to initially work asynchronously and independently on a task. However, once the initial independent work is complete, team members will collaborate in order to develop and finalize all tasks in a balanced manner. This collaboration has been accomplished both synchronously or asynchronously, in order to account for any scheduling challenges and overlaps. By allowing both individual and collaborative work, all members of the team are able to input personal perspectives and ideas into the main body of work, while simultaneously weaving individual ideas together into a cohesive, final deliverable.

In regards to major decisions surrounding Team 22's team structure, one of the Thermal Engineers has dropped the Academy since the submission of the System Requirements Review. Due to this change, there is only one team member that possesses the title of Thermal Engineer, but other engineers are willing and capable to assist the current Thermal Engineer when needed. A decision has been made to appoint no official secondary team members for the Electrical Engineer and Thermal Engineer roles due to team bandwidth. All other team members have remained in the positions they have been initially assigned and are actively fulfilling their responsibilities as designated by their current role or roles. When assigned work by the Project Manager or sub-team leaders, team members are able to complete their assigned sections on a deliverable within a timely manner, and communicate any setbacks or delays that may arise when delivering their work. Team members will typically only be assigned sections related to their sub-team. However, depending on the bandwidth required for certain tasks (such as the programmatic-heavy nature of the MDR document), teams from a sub-team may be asked to help complete tasks for other sub-teams, given that the initial work for their original sub-team is finished and that member has the bandwidth to help a sub-team they are not officially a member of.

Team 22 has addressed issues within the team through the guidance of the team leaders, team mentor, and Student Success Advisor (SSA). Any technical concerns–such as mission task issues or time management conflicts–have been brought to the attention of the relevant sub-team leader and project manager. That sub-team leader will address the issue by directly contacting the team member(s) involved in the conflict in order to create a solution. These solutions include finding an additional team member that is able to aid with any time management issues that may affect the original team member's ability to submit content by the internal due date, or answering a question in order to fill any information gaps. Any concerns that cannot be resolved by a team leader have been made aware to the Team 22's mentor, who will answer any questions or resolve the problem at hand.

In situations involving team relations, the relevant sub-team leader will first reach out to the team member that may be struggling with communication or submitting work on time. This sub-team leader will contact this team member on the Team 22 Discord through the use of a private thread that is only accessible to the sub-team leader, involved team member, and NASA L'SPACE MCA staff in order to comply with ITAR rules but respect the individual or private concerns of the team members. This communication is completed in order to understand the underlying cause of these delays or act as a resource for any questions the team member may have. However, if a team member is not responding for two consecutive days after an initial check in, the sub-team leader will contact the SSA. Then, the SSA will reach out to the team member in order to understand the circumstances that may be causing this delay. In cases where a team member has dropped the academy after a prolonged absence, the SSA has announced this information to the entire team. Upon the announcement of a team member dropping the academy, the affected sub-team will work together in order to reallocate the work among other team members.

1.8.3. Major Milestones Schedule

The major milestones for the mission, which includes both completed and current phases, are listed below. The scope of all schedule estimates moving forward will focus on Phase C (Final Design & Fabrication) onwards, since the scope of the NASA L'SPACE Mission Concept Academy conducts Pre-Phase A, Phase A, and Phase B.

Pre-Phase A:

- **Preformulation (Completed)**
  - Tasks: Early concept exploration and basic feasibility studies.

Phase A:

- **Concept & Technology Development (Completed)**
  - Tasks: Identify mission goals, perform initial feasibility assessments, and develop early concepts.

Phase B:

- **Preliminary Design & Technology Completion (Current Phase)**
  - **Milestone:** Preliminary Design Review (PDR) is underway and scheduled to be completed by **December 2024**.
  - Deliverables: All prior deliverables leading up to this phase have been completed.

Phase C:

- **Final Design & Fabrication**
  - **Milestone:** Critical Design Review (CDR) scheduled for **December 2025**.
  - Deliverables: Detailed engineering design and fabrication of mission systems.

Phase D:

- **System Assembly, Integration & Test, Launch & Checkout**
  - **Milestone:** Assembly, testing, and initial launch preparations by **November 2027**.
  - Deliverables: Vibration and navigational system testing, final system integration, and launch readiness.

Phase E:

- **Operations**
  - **Milestones:**
    - Launch: **March 1, 2030**
    - Entry, descent, and landing sequence: **TBD after launch**
    - Surface operations: Lunar rover will conduct predetermined science objectives.

Phase F:

- **Closeout**
  - End of prime mission: **March 15, 2035**
  - Closeout will begin on March 1, 2035. The Decommissioning Readiness

Review will then occur on March 15, 3035.

1.8.4. Budget Overview

The budget cap for this mission is $300M, which is a $150M decrease from the initial mission budget of $450M. A change request form was submitted by Team 22 in order to request an additional $20M dollars to the budget in order to support the replacement of a science instrument, which was approved by the stakeholders. The following table reflects the updated budget and specifications that shaped the budget. The total estimated budget is $313.M, which adheres to the current budget cap of $320M.

Subsystem	Specifications	Cost
Science Instruments	NIRVSS Spectrometer System, NSS, Diviner Lunar Radiometer Estimate, and Raman Spectrometer	$160M
Mechanical	Rocker Bogie Suspension System, Inertial Movement System, Rover Chassis, Individually Actuated Geared Cleated Wheels, Robotic Arms, and Camera System	$100M
Thermal	Active Heating and Cooling Components: Heaters, coolers (thermoelectric coolers, vapor compression systems, pumped fluid loops, lovers, & shutters) Passive Heating and Cooling Components: Thermal coatings, insulation materials, heat pipes, thermal straps, radiators	$16M
CDH	Communication, OBC, Data Storage, and Data Buses	$2M
Travel	Including Flights, Hotels, Transportation Rental Costs, Major Reviews at NASA Centers,	$2M

	Inspections, Team Meetings, Morale Trips	
Personnel	Estimates of Personnel Salaries for each specific phase and fiscal year (FY), based on the number of personnel and role types.	$32M
Outreach	Cost estimates for mission awareness activities, building on your previous research.	$1.3M
Total		**$313.3M**

Table 1.8.4.1 - Budget Overview

2. Overall Vehicle and System Design

2.1. Spacecraft Overview

The lunar cave exploration rover has been carefully designed to handle the unique challenges of the moon's surface and caves. Each part of the rover plays an important role in making sure it can complete its mission safely and successfully. The design includes systems for mobility, scientific studies, power, and communication, all working together to achieve the mission goals.

The rover uses a rocker-bogie suspension system for its wheels and chassis. This system is highly reliable and has been used on other space missions, like NASA's Mars rovers. It helps the rover drive over rough terrain, climb over rocks, and stay stable on steep slopes. This is especially important for exploring deep pits and uneven cave floors, where the ground can be unpredictable.

To see and avoid obstacles, the rover is equipped with Hazard Cameras (HazCams) and engineering cameras, similar to those on the Perseverance rover. These cameras give the rover a clear view of its surroundings, helping it plan safe routes and detect hazards in real time. The cameras also create 3D maps of the terrain, which are critical for navigating the difficult lunar environment.

A robotic arm is included in the rover's design to perform scientific tasks. This arm will hold tools for analyzing samples and studying the cave walls. It can reach into cracks and dark areas that might be hard to access otherwise. By using the arm, the rover can gather important data about the lunar surface and underground environment.

The rover is powered by solar arrays and lithium-ion batteries. The solar panels generate electricity from sunlight, while the batteries store energy for use when the rover is in shadowed areas, like inside caves. A power management system ensures the energy is used efficiently, providing just the right amount of power to each system when needed.

The payload, or the scientific equipment the rover carries, includes five key instruments designed to meet the mission's science objectives. These instruments are mapped out in the Science Traceability Matrix (STM) to ensure they align with the mission's goals. For example, the Near-Infrared Volatile Spectrometer System (NIRVSS) will search for water and carbon compounds, while the Neutron Spectrometer System (NSS) will measure hydrogen levels to locate water reserves. Other tools, like the Diviner Lunar Radiometer, will check temperature changes, and a Raman Spectrometer will study the composition of cave walls. Together, these instruments will provide the data needed to understand the lunar environment and its potential for human exploration.

At the heart of the rover is the Command and Data Handling (CDH) subsystem, which serves as its brain. The onboard computer, a BAE RAD750 processor, runs the software that controls the rover's systems and processes the data collected by its instruments. This processor is highly reliable and has been used in many space missions. The CDH system also includes data storage, provided by a Phison 8GB uSSD, which securely stores mission data and telemetry. Data buses, specifically MIL-STD-1553, allow for smooth communication between the CDH and other subsystems, ensuring everything works together seamlessly.

The communication subassembly, featuring an X-band High-Gain Antenna, is responsible for sending data from the rover back to Earth and receiving commands from the ground station. This system ensures smooth communication, even over long distances. It also has error detection software to monitor the system's health and fix any issues that arise during the mission.

To make sure the rover is ready for the lunar mission, it will go through thorough testing. This includes inspections of individual components, simulations of how the rover will operate on the moon, and trials in environments on Earth that mimic lunar conditions. These steps ensure that the rover can handle the harsh environment and carry out its tasks effectively.

Overall, this rover is designed with robust and proven systems to explore lunar caves, collect valuable data, and support future human exploration. Each component, from the suspension system to the scientific instruments, has been chosen to meet the mission's needs and overcome the challenges of the moon's unique environment.

2.1.1. Mechanical Subsystem Overview

The mechanical subsystem of the lunar rover is a key part that makes sure the rover can move, stay stable, and perform its tasks. It includes several important parts, such as the Rocker-Bogie Suspension System, wheels, navigational cameras (Navcams), Hazard Avoidance Cameras (HazCams), and a robotic arm. These parts work together to handle the tough challenges of the lunar surface while staying within limits for size, weight, and performance.

Key Features and Functions

The Rocker-Bogie Suspension System is the main part of the mechanical subsystem. It helps the rover drive over rough ground and climb steep slopes. This system spreads out the weight evenly, making the rover more stable and less likely to tip over. The suspension system is both strong and lightweight, with a mass of 30 kg and compact dimensions of 1 m x 0.8 m x 0.2 m. It uses six cleated wheels, each controlled by its own motor and gears, to move smoothly across the lunar surface.

•*Wheels*:

The wheels are made of lightweight aluminum. Each wheel has a diameter of 0.5 m and weighs 8 kg. Aluminum was chosen because it's light, durable, and cost-effective. The cleats on the wheels provide extra grip, helping the rover move across soft or uneven ground.

Another important part is the camera system, which helps the rover navigate and avoid obstacles. The Navcams are mounted at the top of the rover, giving a clear view of the surroundings. These cameras are essential for planning paths and steering the rover safely.

•*Hazard Avoidance Cameras (HazCams):*

The rover has six HazCams placed around its body. These cameras detect obstacles and help the rover find the safest route, especially when going down steep slopes like those in a lunar pit.

The rover also has a robotic arm that adds to its capabilities. This arm helps keep the rover stable during delicate maneuvers and is also used to collect rock samples. The arm allows the rover to interact with its environment and perform scientific experiments.

Material Optimization and Compliance

Choosing the right materials was an important part of the design. The wheels and suspension system are made from aluminum because it's light, strong, and able to handle the harsh lunar environment. These materials help the system stay within weight limits while still being durable.

The design also meets strict requirements for size and performance. The Rocker-Bogie System can carry up to 230 kg, which includes the rover's main body and instruments. It can also handle slopes as steep as 45 degrees, making it reliable for exploring rough terrain.

Verification and Validation

To make sure the mechanical subsystem works as expected, it goes through a detailed testing process:

•*Demonstration*: The rover's ability to move, stay stable, and climb slopes is tested in simulated lunar conditions.

•*Inspection*: Materials, dimensions, and weight are checked to ensure they meet requirements.

•*Testing*: The system is tested for strength and performance under extreme temperatures.

•*Analysis*: The HazCams are analyzed to confirm they can find safe paths for the rover.

This thorough process ensures the mechanical subsystem is ready to help the rover succeed on its mission. It provides the mobility, stability, and functionality needed to explore the lunar surface effectively.

2.1.1.1. Mechanical Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem
MCHE 1.0	The system shall transport through a Rocker Bogie Suspension System	The rover needs to transport from one place to another	SYS.3	MCHE 1.1 MCHE 1.2 MCHE 1.3 MCHE 1.4 MCHE 1.5	Demonstration	Mechanical
MCHE 2.0	The mechanical subsystem shall provide visuals through a Navigational camera system (Navcam)	The camera system is used to help visualize where the rover is going	SYS.3 SYS.6	MCHE 2.1	Testing	Mechanical
MCHE 3.0	The mechanical subsystem shall include 6 Hazard Avoidance Cameras (Hazcam)	To find the best path down lunar put Tycho	SYS.4	MCHE 3.1	Inspection	Mechanical
MCHE 4.0	The mechanical system shall carry 1 robotic arm	Robotic arm will be used for stability and for sample collection	SYS.5	MCHE 4.1	Inspection	Mechanical

MCHE 1.1	Rocker Bogie system shall have a mass of 30kg	The system has to stay under the the total mass constraint of 350 kg	MCHE 1.0	MCHE 1.1.1	Inspection	Mechanical
MCHE 1.2	Rocker Bogie system frame shall have a length of 1 m, width of 0.80m , and height of 0.20m	The system needs to be constrained to customer given dimension constraints	MCHE 1.0	-	Inspection	Mechanical
MCHE 1.3	Rocker Bogie system shall use 6 individually actuated and geared cleated wheels	The rover needs wheels to travel	MCHE 1.0	MCHE 1.3.1 MCHE 1.3.2	Demonstration	Mechanical
MCHE 1.4	Rocker Bogie system shall be able to support up to 230 kg	The system needs to be able to support the chassis and carry the body of the rover	MCHE 1.0	-	Test	Mechanical
MCHE 1.5	Rocker Bogie system shall withstand a tilt of up to 45 degrees	The rover should be prevented from turning over and falling	MCHE 1.0	-	Test	Mechanical
MCHE 2.1	The Navcam shall be mounted at the head of the rover, which connects to the neck and body	The Navcam needs to provide feedback from a ideal height	MCHE 2.0	-	Inspection	Mechanical
MCHE 3.1	The Hazcams shall find the best path down lunar pit Tycho 29 B	The rover would go through various routes until finding the safest option to go down the pit	MCHE 3.0	-	Analysis, Demonstration	Mechanical

MCHE 1.1.1	Rocker Bogie frame and wheels shall be of Aluminum	Material makeup of the systems	MCHE 1.1	-	Inspection	Mechanical
MCHE 1.3.1	Wheels shall be of diameter 0.5 m	Dimensions allocated to wheels	MCHE 1.1	-	Inspection	Mechanical
MCHE 1.3.2	Wheels shall have a mass equal to 8 kg each	Wheel mass needs to be significantly less than constraint mass	MCHE 1.3	-	Inspection	Mechanical

2.1.1.2. Mechanical Sub-Assembly Overview

Rover Chassis

The rover chassis is the main structural component that holds the mechanical subassemblies, adjacent subsystems, and the instrument deck in place. This rover's chassis has length, width, and height dimensions of 90m x .70m x .50m respectively and has a hollow material profile made of aluminum. An aluminum chassis reduces the total mass makeup from the amount of mass allocated to the entire mechanical subsystem. The chassis takes up a mass of 100 kg. One of the underlying risks that could affect the rover chassis is being struck by micrometeoroids. Therefore, the chassis was designed to combat this by using micrometeoroid shielding surrounding the body. The chassis was heavily influenced by NASA's Curiosity and Perseverance rovers which have been proven successful in their mission operations throughout the years, therefore this rover chassis is placed as TRL 9.

Rocker Bogie-Suspension System

The Rocker-Bogie Suspension System functions as the frame that joins the wheels to the entire system, and allows the rover to travel across the bumpy, unleveled lunar terrains. The system has overall dimensions of 1m x 0.80m x 0.20m in length, width, and height, respectively, and is constructed entirely of titanium tubing. One of the major risks involving this subassembly was its sensitivity to the extreme temperatures, and fluctuations of the temperatures, on the lunar surface. Different temperatures could lead to the expansion or contraction of the frame which ultimately results in mechanical failure over time. Considering this risk, titanium was the optimal material for the frame durability, resisting changes in temperature better than steel and aluminum, which were other materials considered for the frame. Although titanium takes up a higher portion of allocated mass and cost, the material compensates through high strength, ideal for the system and its relation to durability. The overall mass of the rocker-bogie suspension system is 30 kg. Essentially, since this subassembly is one of the major components for the mobility of the rover, other missions operations where this system was proven successful were considered for the design, placing it with a TRL 9.

The Inertial Movement System (Unit)

Individual Actuated Geared Cleated Wheels
The rover consists of six Individual Actuated Geard Cleated Wheels, which are integral for the mobility of the rover on the lunar surface, and are attached to the titanium tubing ends of the rocker-bogie suspension system with 3 wheels on opposite sides of the system. All six wheels are identical, each having a diameter of 0.5m and a mass of 8 kg. The wheels are made of aluminum material which is ideal for mitigating possible risks during the mission. Just like the rocker-bogie suspension system and the rover chassis, the wheels of the rover are subject to extreme temperatures, and particle strikes from space and the rocky terrain of the moon. For this reason, aluminum was chosen as the material, which not only is suitable in counteracting these dangers, but is also light enough and cost-friendly when considering the allocated mass and budget to the mechanical subsystem. The wheels are considered TRL 8

Robotic Arm
The rover includes a robotic arm that is capable of performing tasks, such as the collection of samples for the mission’s science, as well as an aid to the rover's mobility. The arm’s length, width, and height dimensions are 1.5m x .20m x .20m respectively and is made entirely of aluminum alloy. Similar to the wheels and chassis, having the robotic arm made of aluminum material is cost effective and works for optimizing the allocated mass. The arm takes up a mass of 45 kg. The arm is considered as having a TRL 7 as the

Camera System and Rover Neck

The camera system consists of two different classes. The first class of camera is referred to as the Navigation camera, or Navcam. The Navcam is designed to provide visuals for the team back on Earth. As the rover moves along the surface of the moon, the Navcam shows the surrounding area. The Navcam is attached to the camera mount at the top of the rover's neck, which the neck itself is made of aluminum alloy and has a mass of 15 kg. For sufficient imaging, the Navcam has a 12-bit 1024 x 1024 pixel resolution. The other cameras on the rover are the Hazard-Avoidance cameras, or Hazcams. These are one of the most important installations on the vehicle as they not only capture images to plan the best route as it travels on the lunar surface, but it is also the technology that will safely guide the rover down the lunar pit Tycho-29B. There are a total of 6 Hazcams on the rover and are located around the sides of the vehicle in order to capture visuals on all sides of the rover. This is especially useful as the rover slowly goes down the lunar pit. The Hazams also have a 12-bit 1024 x 1024 resolution to capture clear images. The camera system has a TRL of 8 as the same system was already used and successful on similar missions.

The Mechanical Subsystem has a total TRL of 7.

2.1.1.3. Mechanical Subsystem Recovery and Redundancy

Redundancy Plan

The Rocker-Bogie Suspension System and wheels are essential components of the rover, responsible for ensuring mobility and stability across challenging lunar terrain. However, due to the stringent constraints on mass (350 kg), cost, and dimensions, we have not included full redundancy for these components. Instead, our redundancy approach focuses on incorporating critical failure-resistant materials and designing subassemblies with fault tolerance.

For example, the titanium frame of the Rocker-Bogie Suspension System is highly durable and resistant to temperature deformation caused by the extreme lunar environment. Titanium's robustness minimizes the risk of failure over the mission's lifetime, making a duplicate frame unnecessary. Similarly, the aluminum wheels, while lightweight and cost-effective, are optimized for durability to endure extended wear from abrasive regolith. The trade studies conducted demonstrate that these materials provide a balanced solution to avoid critical failures while adhering to constraints.

In addition to material selection, adaptive control algorithms within the Command and Data Handling (CDH) subsystem can mitigate the impact of a single wheel or suspension malfunction. This includes redistributing the load to functioning components and dynamically adjusting mobility to maintain progress toward mission objectives. These strategies reduce the likelihood of total mission failure in case of partial subsystem degradation.

Recovery Plan

In the event of a partial or complete mechanical failure, the rover's modular design enables localized fault isolation and workarounds. For instance:

1. Wheels: If a wheel becomes non-functional due to mechanical damage, the rover can utilize its other five wheels to continue mobility. The Rocker-Bogie Suspension System can redistribute weight and compensate for a missing wheel's contribution to propulsion.

2. Suspension System: If a suspension component is damaged, the system's inherent compliance allows it to adapt to terrain irregularities, reducing the immediate impact of failure. Additionally, the CDH subsystem can identify and adjust operational parameters to prevent further stress on compromised components.

3. Rover Chassis: The chassis, constructed with durable titanium, is designed to endure significant strain. However, in the unlikely event of structural deformation, the modular nature of the rover allows continued operations with reduced functionality in other mission areas (e.g., limited movement but functional science instrumentation).

Failures that cannot be physically resolved are mitigated by the prioritization of science objectives. The rover's scientific payloads can perform stationary measurements if mobility is lost, ensuring partial mission success.

Why No Full Redundancy

While full redundancy for subassemblies like suspension or wheels could provide additional assurance against failure, the mass and cost constraints make duplication impractical. For instance:

•Adding duplicate wheels or suspension components would result in exceeding the 350 kg limit and significantly increase costs, reducing the payload allocation for science instruments.

•The likelihood of total subsystem failure is minimal due to the use of robust materials and fault-tolerant designs.

•The mission plan includes rigorous Earth-based testing under lunar analog conditions to validate the mechanical subsystem's reliability.

This approach balances risk mitigation with feasibility, ensuring that the rover remains within mass and budgetary constraints while retaining high confidence in its mechanical subsystem's performance.

2.1.1.4. Mechanical Subsystem Manufacturing and Procurement Plans

The rover is composed of subassemblies manufactured In-House at NASA and other NASA suppliers. A majority of the rover's mechanical system has specific requirements that need to be met in order to survive on the lunar surface and execute scientific tasks. Therefore, resources available right at NASA are provided to construct the integral parts of the system.

The NASA Jet Propulsion Laboratory (JPL) is a sector that specializes in robotic space missions, and most notable, the Perseverance and Curiosity rovers. The mission's rover is heavily influenced by previous missions, which is why JPL is in charge of manufacturing the rover's Rocker Bogie Suspension System, chassis, individually actuated geared cleated wheels, and the camera system. Both the rocker-bogie suspension system and the rover chassis have an estimated cost of $30 million with a lead time of 8 months. The six individually actuated geared cleated wheels have an estimated total cost of $25 million and lead time of 4 months. The camera system has an estimated total cost of

$18 million, which includes the Navcam and the 6 Hazcams, and an approximate lead time of 16 months.

As mentioned, the rover also utilizes components manufactured by suppliers contracted by NASA. Northrop Grumman supplies the rover with the Inertial Movement Unit. Northrop Grumman is a defense and aerospace company who also specialize in the inertial movement units as they integrate them into their spacecraft. Raytheon Technologies is the backup supplier to this component, but going with this supplier might take a bit longer since Northrop Grumman already has a rover compatible system at hand, such as the LN-200 and LN-200HPS. The estimated cost for these units is $2 million and have a lead time of 4 months. Motiv Space Systems provides the rover's robotic arm. This supplier specializes in robotic technologies for space and NASA already has experience with their solutions with the Perseverance rover. The backup supplier is MAXAR Technologies who also specializes in robotic solutions and have experience with mars rover and lander components. The estimated cost for the robotic arm is $5 million and a lead time of 3 years. The rover's neck is supplied by MAXAR Technologies with a similar estimated cost to the arm of $5 million and a lead time of 3 years.
The following table outlines the details:

Component	**Estimated Cost ($)**	**Lead Time (approximately)**	**Procurement Source**
Rocker Bogie Suspension System	$30 million	8 months	Primary: **NASA Jet Propulsion Laboratory**
Inertial Movement System/Unit	$2 million	4 months	Primary: **Northrop Grumman** Backup: Raytheon Technologies
Rover Chassis	$30 million	8 months	**Primary: NASA Jet Propulsion Laboratory**

			Backup: Motiv Space Systems
Individually Actuated Geared Cleated Wheels	$25 million	4 months	**Primary: NASA Jet Propulsion Laboratory** Backup:
Robotic Arm	$5 million	36 months	**Primary: Motiv Space Systems** Backup: MAXAR Technologies
Camera Systems (Navcams & Hazcams)	$18 million	16 months	**Primary: NASA Jet Propulsion Laboratory** Backup: Malin Space Science Systems
Rover Neck	$5 million	36 months	**Primary: MAXAR Technologie**s Backup: Motiv Space Systems

2.1.1.5. Mechanical Subsystem Verification Plans

In order to confirm that requirements for the Mechanical Subsystem are met, a series of verification procedures are taken to action, depending on the type of verification method being conducted. The four methods that can be used to verify the system meets the requirements are through Inspection, Analysis, Demonstration, or Test.

The table below lays out the mechanical subsystem Requirement, Method of Verification, Rationale for Method, and the Preliminary Verification Plan.

Req #	Requireme nt Summary	Verification Method	Rationale for Method	Preliminary Verification Plan

MCHE 1.0	The system shall transport through a Rocker Bogie Suspension System	Demonstration	Real time operation is needed to know if the rover can travel with this system	Apply loads equal to that of the entire weight of the rover to make sure it is stable when traveling. Make the system travel and assure it can pivot and overcome unleveled ground.
MCHE 2.0	The mechanical subsystem shall provide visuals through a Navigational camera system (Navcam)	Test	Testing assure function and desired visuals	Take various snapshots and video recordings on the cameras and assure desired results are there.
MCHE 3.0	The mechanical subsystem shall include 6 Hazard Avoidance Cameras (Hazcam)	Inspection	Determine if the Hazcams are set and included in the system	Visual inspection writing down on paper or chart confirming the cameras are where they should be and functioning
MCHE 4.0	The mechanical system shall carry 1 robotic arm	Inspection	Determine if the robotic arm is set and included in the system	Visual inspection writing down on paper or chart confirming the arm is where it should be and functioning
MCHE 1.1	Rocker Bogie system shall have a mass of 30kg	Inspection	Recording; no need for special equipment, just confirmation	Weighing the rover. Recording on paper or digital charts that the mass does not not exceed constraint.
MCHE 1.2	Rocker Bogie system frame shall have a length of 1 m, width of 0.80m , and height of 0.20m	Inspection	Recording; no need for special equipment or procedures	Visual confirmation through drawings. Recording on paper or digital charts that the dimensions do not exceed constraints.
MCHE 1.3	Rocker Bogie system shall use 6	Demonstration	Real time operation is needed to	Placing a similar loading system on the wheels and driving them while recording to adjust for frictional damping.

	individually actuated and geared cleated wheels		know if the wheels function correctly	Driving the wheels down different angles of elevations to account for grip strength and adjusting as needed.
MCHE 1.4	Rocker Bogie system shall be able to support up to 230 kg	Test	Specific procedure are needed	Placing increments of weight, monitor the system ensuring failure does not occur at all. This is crucial in confirming the system is ready to move the entire rover.
MCHE 1.5	Rocker Bogie system shall withstand a tilt of up to 45 degrees	Test	Specific procedures are needed	Driving the system up different tilts and increasing the tilt until reaching 45 degrees.
MCHE 2.1	The Navcam shall be mounted at the head of the rover, which connects to the neck and body	Inspection	Recording; no need for special equipment or procedures	Visual confirmation of the actual rover. Recording on paper or digital charts that the Navcam is mounted correctly to the neck.
MCHE 3.1	The Hazcams shall find the best path down lunar pit Tycho 29 B	Analysis	Computer data from the Hazcam visuals is looked over	Data is transmitted from the Hazcams to the computer which is looked over to and confirm the best path
MCHE 1.1.1	Rocker Bogie frame and wheels shall be of Aluminum	Inspection	Recording; no need for special equipment or procedures	Visual confirmation of the actual rover. Recording on paper or digital charts that the right material was used.
MCHE 1.3.1	Wheels shall be of diameter 0.5 m	Inspection	Recording; no need for special equipment or procedures	Visual confirmation of drawings. Recording on paper or digital charts that the dimensions of the wheels fall in line with the dimension constraints for the entire rover.
MCHE 1.3.2	Wheels shall have a mass equal to 8 kg each	Inspection	Recording; no need for special equipment or procedures	Weighing the wheels. Recording on paper or digital charts that the mass does not not exceed constraint.

2.1.2. Power Subsystem Overview

The Power subsystem of the rover is an integral component which allows the rover to function efficiently throughout the mission lifecycle. In order to pursue this objective within the lunar environment this system is designed to address its multiple unique hurdles, while maintaining reliability and capability. Three sub-assemblies make up the subsystem, including the Power Management Sub-assembly, Power Storage Sub-assembly and Power Generation Sub-assembly. Each of these components serves a critical role in maintaining rover power capabilities.

Functionally, the flow of the Power Sub-system can be seen to start with power generation. The lunar environment offers an abundance of potential solar energy to be utilized due to its lack of atmosphere. This lack of atmosphere results in prolonged exposure to sunlight during lunar days. Lunar days on any given point on the moon are characterized by approximately 14 earth days of continuous sunlight followed by 14 earth days of continuous night. The unique lunar day-night cycle is a challenge that will be addressed by subsequent design decisions with the power storage, needing to be capable of storing sufficient energy to provide continuous power during lunar nights.

Generation of power and charging of batteries will occur primarily during these lunar days, through the use of Multijunction Photovoltaic Solar Cells. Along with generation of power, activities requiring higher levels of power usage will preferentially occur during solar days, in which continuous power generation will be available. During solar nights power generation will be halted, thus requiring usage of stored power. Energy generated within the will be stored within the power storage sub-assembly through the use of lithium ion batteries. This enables the rover to continue limited function off of stored power when power generation is not available such as the previously mentioned lunar nights.

Allocations and movement of electrical power will be controlled by the Power Management Sub-assembly. This system regulates the distribution of power that is continuously stable and reliable. It is important to efficiently manage and distribute power to critical subsystems due to the longer periods without energy generation due to solar nights. The Power management system also contains safeguards and monitors to prevent damage from anomalous events such as power surges.

2.1.2.1. Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
PWR.01	Power Subsystem will provide continuous electrical power to Spacecraft subsystems.	Sufficient power will be required for all subsystems for the Spacecraft to operate at 100% capability	SYS.1		Testing	Met
PWR.02	Power Subsystem must not include usage of RTGs	Required by Mission Concepts	Customer		Inspection	Met
PWR.03	Power Generation Subassemblies must generate enough to fully charge Power Storage Subassembly	Full power generation enables efficient operation of adjacent subsystem requiring continuous power	PWR.01		Testing	Met

PWR.04	Power Subsystem must be able to safely distribute and control power generated.	Safe distribution of Power generated insures full power coverage of Spacecraft subsystems.	PWR.01, SYS.1		Testing	Met
PWR.05	Power Subsystem must include internal protection systems against faults	Internal protections systems allow the Power Subsystem to remain working in case of faults such as short circuits.	PWR.04		Testing	Met
PWR.06	Power Subsystem must be able to store and distribute enough power for peak and average draw.	Though mission lifecycle power demands will vary; The Power subsystem must be able to account for the highs and lows of the power consumption.	PWR.01		Testing	Met

PWR.07	Power Subsystem must be able to report internal system status	Reporting of internal system status allows for detections of faults and or errors within the system.	PWR.04		Testing	Met

2.1.2.2. Power Sub-Assembly Overview

The Power Subsystem consists of three subassemblies: Power Management Subassembly, Power Storage Subassembly, and Power Generation Subassembly. Each of these subassemblies work to fulfill the mission requirements, system and subsystem requirements.

Power will be managed by a custom manufactured power management system (PMS), in order to serve the specific needs of the Spacecraft. The PMS has the tasks of managing the efficiency of the power distribution and generation, reporting status of the entire power subsystem through data, and managing power loads. The PMS will consist of a custom configuration of a control unit, DC-DC converters, a battery management system, and safety fuses.

The control unit will be able to process data from internal sensors within the power system in order to automatically tweak aspects of the system to insure efficiency. This data processing will rely on sensors integrated into the system monitoring from the battery management system such as battery health and battery charge, internal factors such as various charges and current voltages, and temperatures throughout the system. The control unit will work with the data gathered from these sensors in order to make decisions to optimize the entirety of the Power Sub-system. This can be seen primarily in the conservation of power during lunar nights, in which it will be important to prioritize Furthermore the control unit will determine the amount of power allocated to each subsystem based on the current status of the rover and the power needs of that relevant subsystem. Power allocation will be largely automatic based on a pre-set algorithm that will prioritize critical subsystems during times of lower power supplies.

DC-DC converters will ensure compatibility between other spacecraft subsystems and the power subsystems. Convertors allow for the conversions of electrical power from one voltage to another. As previously stated this ensures the compatibility between the two power sources, the solar cells and lithium-ion batteries, and components that require specific operating voltages. Functionally DC-DC serves multiple purposes. Besides voltage adaptation, the converters also serve to aid in power efficiency and overall voltage regulation. The inclusion of DC-DC is determined through a pursuit of efficiency in terms of power management. Buck-Boost converter allows for step-ups or step-down in voltage. This is important for situations in which the rover may experience extreme fluctuations in input voltage. This allows for all subsystems to receive a stable input regardless of various environmental factors that may impact the power sources. They also serve the purpose of keeping voltage within expected values in order to maintain efficiency throughout rover operation. In collaboration with the control unit voltage conversion may be adjusted in order to serve more specific use cases.

Usage of a battery management system will protect the health of the power storage system, and report relevant data on battery health. The batteries serve as an integral part of the rover's overall functionality, allowing the rover to store energy during harsh lunar nights. Ensuring optimum health of the batteries prolongs their lifespan to ensure they last throughout the mission and beyond, and prevent potential damage that may hinder or destroy the critical component. Battery management system will also oversee the cycles of battery discharge and charging. The system will measure a variety of useful metrics including State of Charge (SOC) , State of Health (SOH) , and temperature. The SOC measures the overall amount of charge within the battery compared to its total capacity. This is needed to be continually tracked in order to ensure that the battery is sufficiently charged through its lifecycle. This would mainly prevent discharging from the battery when SOC is too low, or overcharging the battery. SOH measures the overall condition of the battery in terms of capacity and efficiency. These values will be compared over time to measure relevant capacity degradation. Measuring temperature further allows for information to be sent towards the thermal subsystem to regulate battery temperatures.

Safety fuses and relays fulfill the requirement of internal safety precautions with the Power System. They protect the system from events of voltage surges, short circuits, and current surges. Safety fuses protect from overcurrent that would otherwise represent catastrophic damage to subsystems within the rover. Fuses must be reusable and effective within their functionality, encouraging the use of Polymeric Positive Temperature Coefficient devices. These Polyfuses offer a solution towards reusability. In the case of a fault condition like an overcurrent, these fuse will be able cut the current until the overcurrent condition is cleared. Once normal operation is resumed the fuse is able to be reused in the same manner, unlike traditional fuses.

The technologies have been used widely commercially, proving their use and efficiency within power management. However due to the custom configuration of the system further testing will be required to see their functionality in this mission environment. Currently the system only included parts that have had use in weakly relevant fields. Although research on these designs has begun, complete testing and configuration will need to be done to ensure readiness within mission capabilities. This earns the Power Management Sub-assembly a Technology Readiness Level of 3.

Power will be generated through the use of multijunction photovoltaic solar cells. These cells will be included on the Spacecraft in the form of body mounted and fixed arrays. Multijunction solar cells boast multiple positive-negative junctions per solar in comparison to traditional singular junction solar cells, allowing these solar cells to capture a larger spectrum of photon energy. Currently the most efficient solar cell technology, these cells return conversion efficiency rates of over 30 percent, creating a higher power generation to weight ratio. (Fafard). This ratio was a crucial part of the trade studies used to decide the power generation technology, serving to minimize weight while optimizing power generation.

Within this mission the solar cells will be used in a solar panel configuration featuring body mounted rigid solar arrays. These solar arrays will consist of individual solar cells. Layers of multijunction solar cells will consist of top, middle and bottom layers. Each layer will be constructed from a differing substrate material in order to capture varying sections of the spectrum of photons. The top layer will be constructed from Gallium Arsenide, the middle layer of indium gallium phosphide, and a bottom layer of silicon based material. Outside of these layers the construction will be covered in an encapsulation material and anti reflective coating. These serve to protect the solar arrays from damage risks such as regolith, or dust. These will then be placed into mounting frames on the rover body.

Multijunction solar cells have a storied use within the aerospace field. These forms of solar cells were used on the early Mars Exploration Rover mission. Sufficiently supplying Spirit and Opportunity with Electrical Power through the duration of their missions. Multijunction solar cells can also be found in current spacecraft.

Power storage will consist of the use of two lithium batteries. Lithium ion batteries are largely used in a variety of modern applications. Within this subsystem 2 lithium ion batteries will serve as the main power storage capability for the entire Spacecraft.

Lithium ion batteries function through the transfer of lithium ions between anode and cathode during charge and discharge cycles. These batteries have an energy density of up to 330 watt hours per kilogram(“Lithium-Ion Battery). With this mission's usage of two 7 kilograms, this provided a hypothetical max storage of ~ 4260 watt hours. The exact capacity of this storage will need to be explored through further testing.. The batteries are also fast charging, rapidly replenishing spent power. This would prove useful for a long period of power consumption such as driving the rover.

Lithium ion batteries have been used for a variety of planetary exploration missions. Such as the previously mentioned Mars Exploration Rover mission. Within these missions the Lithium ion batteries sufficed as an efficient power storage method. Due to its storied use, the lithium ion batteries were given a Technology Readiness Level of 9. The Batteries have been used in previous aerospace missions and would need no significant changes to be applied within this mission.

2.1.2.3. Power Subsystem Recovery and Redundancy Plans

Due to its importance in regards to the overall rover system the Power subsystem must include several features in order ensure continued functionality after anomalous events that may negatively impact Power subsystem functions. However due to the high cost of specific parts such as the solar panel, redundancy is not a feasible option. As it would be too expensive to include multiple solar cells in addition to the one already planned for. Despite this redundancy will be included in multiple areas within the Power Subsystem, highly concentrated within the PMS.

2.1.2.4. Power Subsystem Manufacturing and Procurement Plans

The Power Subsystem will combine custom manufacturing with the acquisition of tested components. The Power Management System (PMS) will be specifically designed to meet mission-specific requirements using commercially available DC-DC converters, battery management systems, and safety fuses for dependability and cost effectiveness. Lithium-ion batteries with a High Technology Readiness Level will be acquired from reliable aerospace suppliers. Multijunction photovoltaic cells, which have been proven in earlier missions, will be acquired and integrated into rigid solar arrays mounted on the body.

Manufacturing will primarily focus on assembling and testing new combinations, with extensive validation carried out in mission-like environments. Supplier agreements will ensure the timely delivery of necessary components. Testing facilities will assess subsystem integration to ensure compatibility and preparedness for deployment.

2.1.2.5. Power Subsystem Verification Plans

2.1.3. CDH Subsystem Overview

The Command and Data Handling (CDH) subsystem is the central nervous system of the rover. This subsystem is responsible for managing communications, data processing ,subsystem coordination, and command execution. It enables seamless interaction between the rover and the ground station while maintaining internal communication among the various rover subsystems. By leveraging proven technologies with high Technology Readiness Levels (TRLs), the CDH subsystem ensures reliable and efficient operations under the harsh environmental conditions of the lunar surface. Its robust architecture is designed to support the mission’s objectives, including data acquisition, processing, storage, and transmission, while incorporating redundancy and error-handling mechanisms to safeguard critical functions.

The CDH subsystem integrates several subassemblies, including the onboard computer, data storage, data buses, and communication subassembly, each playing a vital role in ensuring mission success. This modular design allows for flexibility in adapting to mission requirements, while the use of space-proven components enhances reliability and operational consistency. With its focus on high-performance data management and robust fault recovery, the CDH subsystem serves as the backbone of the rover's operational framework.

2.1.3.1. CDH Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH-1	Implement Onboard Computer to execute flight software and perform calculations	The brains of the rover will control other subsystems	SYS.5		Inspection	CDH	Met
CDH-1.2	Incorporate storage devices.	This will preserve mission data, and store flight software data, and telemetry information.	CDH-1		Inspection	CDH	Met
CDH-1.3	Enable data interfaces	This will permit information between the CDH Subsystem and other subsystems to be shared.	CDH-1	CDH-1.3.1	Inspection	CDH	Met
CDH-1.3 1	Transfer data between the rover and the ground station.	Allows for command uplink and telemetry downlink	CDH1.3		Analysis	CDH	Met

CDH-1.4:	Implement software error detection and recovery	Ensures that the CDH subsystem can autonomously detect software malfunctions and perform recovery operations	CDH - 1		Inspection	CDH	Met
CDH-1.6	Set power management parameters for CDH operations	Establish power usage limits and conditions for powering down non-essential components to optimize energy uses	SYS.5		Analysis	CDH	Met
CDH - 1.7	Design telemetry data compression protocol	Reduce the size of telemetry data for efficient transmission back to the ground station optimizing bandwidth usage and ensuring all critical data is transmitted back	CDH - 1		Analysis	CDH	Met
CDH 2	Implement a communication latency management system	Manage communication delays between the rover and ground station to ensure commands are executed correctly	SYS.5		Simulation	CDH	Met

The main requirements are implementing an onboard computer responsible for executing flight software and performing critical calculations. This served as the brains for the rover, controlling the subsystems to ensure proper operations. There will be storage devices to hold necessary mission data, flight software, and telemetry information during the mission's course. Once the data has been stored the next stage is to ensure the rover's system is fully functional and to transfer the information. This is where data interfaces enable communication between the CDH system and other critical subsystems. Once the rover's system is functional, data transfer between the rover and the ground station will begin with the transmission of command uplinks and telemetry downlinks.

To ensure the rover's system remains functional, there is software to detect and log any reported errors or diagnostic actions required to carry out the mission. Along with the detection of errors, the power management system is required to ensure energy is disturbed at the right amount and to the correct systems that are required for the duration of the mission. With power management, it is important to compress the telemetry data to prepare to send it back to the ground station without any errors and using the minimum bandwidth required to receive and send data. The second important system is developing a communication latency management system to manage any communication delays and ensure that commands are carried out correctly. The verification methods to test out the systems are through inspection, analysis, and simulation. These will ensure the rover remains fully functional during the mission.

2.1.3.2. CDH Sub-Assembly Overview

The CDH sub-assembly overview is the onboard computer, data storage, data buses, and the communications subassembly. The onboard computer acts as the central processor for the rover. The onboard computer executes flight software, controls the subsystems, and handles data collected from the sensors. The component used as the onboard computer is the *200 MHz 32-bit BAE RAD750* processor. The TRL is given a 7, as the processor has been used in multiple space missions (BAE Systems 2020) and there is an extensive flight history that guarantees its reliability for autonomous operations in space. Its capability to operate within a wide thermal range makes it optimal for the extreme temperatures in the lunar environment.

The data storage is used to store the mission data, telemetry, and flight software securely. The component used is the *Phison 8GB PSS4A111-8G uSSD.* This component scores 7 based on the rigorous environmental testing for Mars applications (Phison Electronics 2024). The uSSD offers low power consumption, essential for energy-limited missions. Additionally, it has been used in space missions like the Mars Perseverance rover, providing sufficient durability and capacity for data collection.

The data buses are used to allow for communication between the CDH and other subsystems in the rover. This provides efficient data transfer between all subsystems. The component used is *MIL-STD-1553* and it scores a TRL 7 as it has been used widely in aerospace and tested under harsh conditions (MIL-STD-1553 Applications 2024). This component receives this score due to the dual-redundancy feature to ensure continuous communication and its long history in aerospace and spacecraft, making it an ideal choice for efficient data transfer.

The communication subassembly is the communication management for both the uplink from Earth and the downlink to the rover. The component used for the communication subassembly is the *X-band High-Gain Antenna.* This component scores a TRL 7 because it has been commonly used in space missions and it has been reliable for data transmission (IQ Technologies for Earth and Space GmbH 2024). This component is being used as it offers robust data transmission, crucial for maintaining communication between the rover and ground station. As well as its capability to perform under deep-space conditions aligns with the requirements for this lunar cave mission.

Overall, the lowest TRL score is a 7 for the *Phison 8GB PSS4A111-8G uSSD.* Each component has been selected for its proven reliability in space-like conditions, but the subsystem's overall TRL is limited by the storage component's slightly lower readiness. However, each component is capable of carrying out the lunar cave mission.

Instrument	Mass	*Dimensions*	*Maximum power consumption*	*Technology Readiness Level*
X-band High-Gain Antenna (Communication)	*20g*	*60 x 40 x 1.8 mm³*	*<2W*	*8*
200 MHz 32-bit BAE RAD750 (OBC)	*9g*	*10.4 mm. by 12.5 mm.*	*5W*	*9*
Phison 8GB PSS4A111-8G uSSD (Data Storage)	*<10g*	*20 mm x 16 mm*	*12mW - 830mW (0.83 W)*	*7*

MIL-STD-1553 (Data Buses)	*50 - 200g*	*50 - 100mm x 20-30mm*	*200-500 mW*	*8*

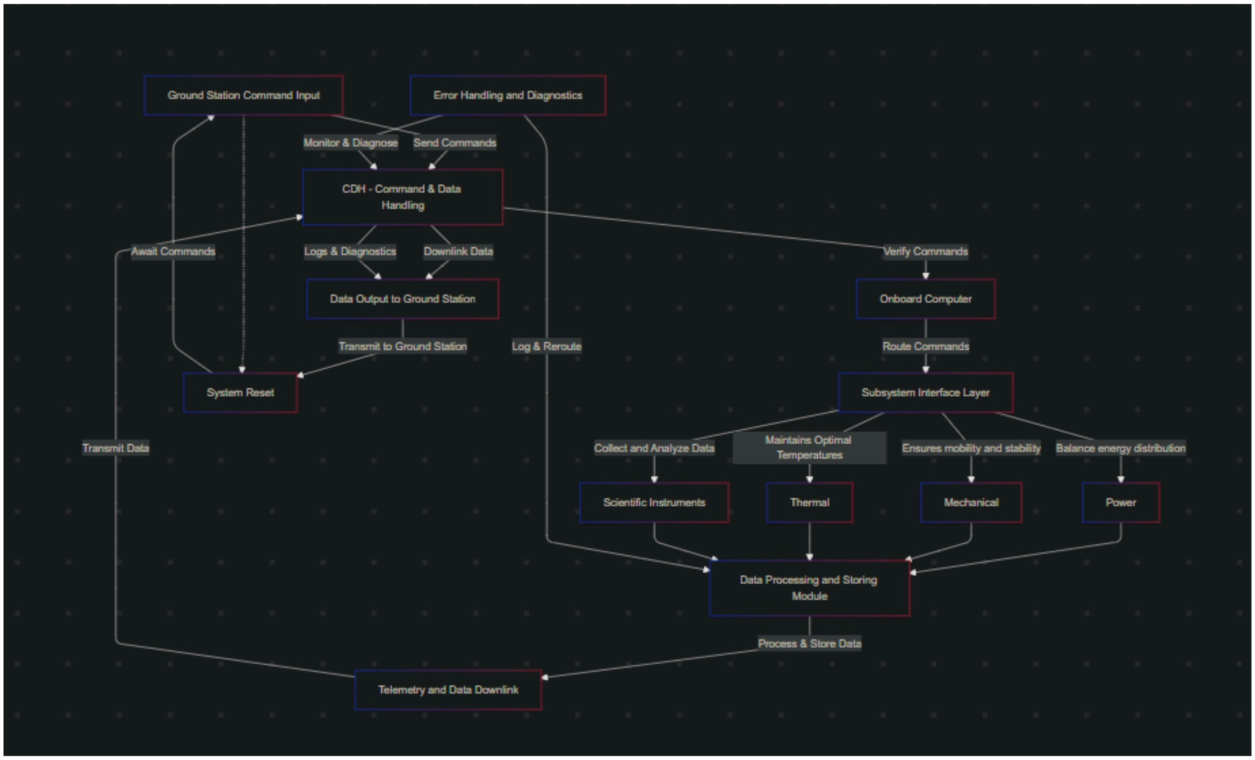


Figure 1.1.1.2.1 - CDH Subassembly Overview

The software architecture for this mission facilitates seamless communication between the ground station and the rover, ensuring data integrity, error handling, and an efficient recovery system. The architecture supports both uplink (commands from the ground station) and downlink (data transmissions from the rover) processes.

1. Ground Station Command Input
    a. The ground station serves as the mission control hub, where operators input commands for the rover.
    b. These commands are transmitted to the rover.
2. CDH
    a. The CDH onboard the rover receives commands from the ground station.
    b. It verifies the integrity of the received commands and routes them to the Onboard Computer.
3. Onboarding computer
    a. Acting as the rover's central hub, the onboard computer verifies commands, logs operational statuses, and determines which subsystems need activation.

    b. The onboard computer logs all commands and system statuses for telemetry and diagnostic purposes.
4. Subsystem interface layer
    a. Commands from the CDH are passed to the subsystem interface layer, which communicates a command to the correct subsystem
    b. Power - Manages energy distribution.
    c. Mechanical - Controls mobility and stability.
    d. Thermal - Maintains optimal temperatures.
    e. CDH - Ensures communication and data handling.
    f. Scientific instruments - Collect and analyze data for the mission.
5. Data Processing and Storing Module
    a. During and after command execution, data collected by the subsystem is routed to the Data Processing and Storing Module.
    b. This module compresses and formats telemetry and mission data for efficient transmission.
    c. Critical mission data and logs are stored for redundancy and retrieval.
6. Telemetry and Data Downlink
    a. Processed data is sent back to the CDH for downlink.
    b. The communication system transmits this data to the ground station.
7. Error Handling and Diagnostics
    a. Parallel to the main operations, an Error Handling and Diagnostics Module monitors the system for anomalies.
    b. If errors are detected, the module performs diagnostic checks, logs issues, and attempts to recover or reroute commands.
    c. Diagnostic data and error logs are sent back to the ground station for troubleshooting and analysis.
8. Data Output to Ground Station
    a. Once all telemetry data, mission logs, and diagnostic information are prepared, they are transmitted to the ground station for analysis.
    b. The system resets and waits for the next command input from the ground station, repeating the operational cycle.

2.1.3.3. CDH Subsystem Recovery and Redundancy Plans

The CDH recovering subsystem is focused on software-based solutions to handle errors, restore normal operations, and ensure the mission is carried out successfully. The onboard computer monitors for faults in processing and memory. If the system detects an error it will attempt a reboot to clear transient faults; if the reboot fails, the software triggers a switch to a redundant backup and powers down the faculty component to avoid further issues. In case of data corruption, the software isolates and bypasses corrupt sectors. If a failure is detected in storage, the data operations shift to a backup unit or utilize redundant data. The data buses provide a built-in recovery through its secondary bus. Software is used to monitor for issues to switch to a backup line in case an error occurs. If temporary disruption happens, the system will pause and retry data transmission, minimizing the amount of data loss. For the communication subassembly, software is used to check the signal quality and strength. If an error occurs, it adjusts transmission power or waits for a stronger signal.

The CDH redundancy plan is designed to ensure critical components have hardware backups and reduce any mission risk in case of hardware failure. The onboard computer may include a backup processor used for low-power standby, ready to take over if the primary system fails. The data storage will have a mirrored backup to allow data recovery. The system is equipped with a primary and backup line for the data buses. The dual-redundancy design ensures a continued data flow between subsystems if the primary fails. For antennas, the mission will consider another antenna in case the first one fails to provide adequate data transfer from the rover to the Lunar Reconnaissance Orbiter.

2.1.3.4. CDH Subsystem Manufacturing and Procurement Plans

The CDH subsystem serves as the central control hub for the rover, ensuring the integration and operation of all subsystems. This manufacturing and procurement plan outlines the components required and the schedule to ensure timely delivery and integration.

The Onboard Computer (OBC) will execute flight software, process scientific data, and control subsystem interactions. The primary manufacturer is BAE Systems (RAB750) and the backup manufacturer is Lockheed Martin. The lead time is estimated to be six months, placing its delivery around June 30, 2025.

The data storage device is used to store mission-critical data, including scientific measurements and rover diagnostics. The primary manufacturer is Phison Technologies (PSS4A111-8GB) and the backup manufacturer will be NASA in-house suppliers. The lead time is estimated to be three months, projecting delivery by April 1, 2025.

The high-gain antenna (HGA) will facilitate communication between the rover and the ground station. The primary manufacturer is NASA Jet

Propulsion Laboratory (JPL) and the backup manufacturer is Northrop Grumman. The lead time is estimated to be four months and is projected to be delivered by May 1, 2025.

The flight software is used for autonomous and manual operations which will be built by mission software engineers. The development will be concurrent with the hardware components and will be ready for integration.

The CDH procurement strategy leverages a mix of Commercial-Off-The-Shelf (COTS) components and custom-developed software. This strategy ensures reliability while optimizing cost and lead times. The COTS components were selected for proven flight heritage to ensure operational reliability in extreme lunar conditions. The custom software and integration will be processed to be tailored to the mission requirements.

The integration and testing timeline aligns with competent delivery dates. Initial inspections and tests for the data storage device will begin upon delivery in April 2025, followed by the integration of the high-gain antenna in May 2025. By June 2025, the onboard computer will be assembled with the integrated subsystem and flight software. Subsystem testing will validate communication, data handling, and overall operational integrity in July 2025, culminating in environmental testing under simulated lunar conditions in August 2025.

Risk	**Mitigation Strategy**
Delays in manufacturing	Place orders early; maintain strong communication with suppliers
Component failure during testing	Procure backup components; implement iterative testing during assembly
Incompatibility with other subsystems	Conduct integration simulations before hardware assembly
Radiation damage to electronics	Select components with proven radiation resistance

Figure - 1.1.1.4.1 CDH Risk Mitigation

The risk mitigation strategies include early order placement to minimize manufacturing delays, procurement of backup components to address potential failures during testing, and rigorous simulations to identify and resolve subsystem compatibility issues.

Component	Estimated Cost ($)	Lead Time	Procurement Source
Onboard Computer	200,000	6 months (June 30, 2025)	BAE Systems / Lockheed Martin
Data Storage Device	50,000	3 months (April 1, 2025)	Phison Technologies / NASA
High-Gain Antenna	120,000	4 months (May 1, 2025)	NASA JPL / Northrop Grumman
Flight Software	300,000	Concurrent	In-house development

Figure - 1.1.1.4.2 CDH Logistics

This plane ensures that all components are inspected, integrated, and tested in advance of the mission's critical milestone, supporting the overarching goal of a successful lunar operation.

2.1.3.5. CDH System Verification Plans

The CDH System Verification Plan will ensure that all subsystems work as intended and meet the mission requirements outlined in the design phase. The verification process will use inspection, analysis, and simulation to validate functionality, reliability, and performance under lunar mission conditions. Below is the detailed verification approach.

1. Confirm the functionality and reliability of the onboard computer, ensuring it can execute flight software, process data, and manage subsystem operations.
2. Validate the performance of the data storage device for secure, efficient mission data storage and retrieval.
3. Test data buses for seamless communication between CDH and other subsystems.
4. Evaluate the high-gain antenna for consistent uplink and downlink communication.
5. Verify the software architecture, focusing on:
    - Command uplink, execution, and subsystem activation.
    - Telemetry data compression and downlink.
    - Error handling and recovery.
6. Test the power management system for energy efficiency and subsystem prioritization.

7. Validate redundancy and fault-tolerant mechanisms to ensure mission-critical operations in case of component failure.

Verification Methods

1. Inspection

- Objective: Ensure physical and logical integrity of CDH components.
- Process:
  - Inspect hardware components (OBC, storage, data buses, antenna) upon delivery.
  - Review software architecture and coding standards for compliance with requirements.
  - Verify physical connections and interfaces between subsystems.
- Output: Documentation certifying component compliance.

2. Analysis

- Objective: Evaluate system design and component performance under expected lunar mission conditions.
- Process:
  - Perform theoretical analysis on data storage capacity, telemetry compression, and power efficiency.
  - Analyze communication latency and its impact on command execution.
  - Conduct system-level integration simulations to identify potential bottlenecks.
- Output: Analytical reports confirming design performance..

3. Simulation

- Objective: Test system performance in a controlled environment that mimics lunar conditions.
- Process:
  - Run simulations to evaluate command execution, subsystem communication, and telemetry transfer.
  - Simulate fault scenarios to test error detection and recovery mechanisms, including reboot and redundant hardware activation.

  - Use environmental simulators to test radiation resistance and thermal stability.
- Output: Simulation logs and performance metrics.

Verification Plan Chronological Schedule

1. Pre-Integration Testing

1.1 Inspect hardware components (OBC, storage, data buses, antenna) upon delivery.

1.2 Test flight software independently for error handling and recovery functionality.

2. Subsystem Integration Testing

2.1 Integrate CDH subsystem components and perform initial system-level tests.

2.2 Test command uplink, data processing, and telemetry downlink in isolation.

3. Environmental Testing

3.1 Simulate lunar conditions (temperature, vacuum, and radiation).

3.2 Perform end-to-end mission simulation with all subsystems.

4. Redundancy and Recovery Testing

4.1 Test backup systems (OBC, storage, data buses) for seamless failover.

4.2 Validate data recovery from redundant storage and communication protocols.

5. Final System Validation

5.1 Conduct a full mission cycle simulation: traverse, data collection, data relay, and error scenarios.

5.2 Ensure the CDH system meets all operational and performance metrics

2.1.4. Thermal Control Subsystem Overview

Within the Thermal Control Subsystem, there are active and passive methods being used to maintain optimal temperature of the rover. Amongst them being multi-layer insulation (MLI), thermal coating, and patch heaters. The multi-layer insulation will be used to prevent excessive heat loss from components and excessive heating from the environment. Patch Heaters will protect components like the Near-Infrared Volatile Spectrometer System (NIRVSS) spectrometer by warming them up to their required operating temperatures of -160°C to +55°C. Furthermore, the rover will have the Neutron Spectrometer (NSS) useful in -25°C to +30°C. The Diviner Lunar Radiometer, Gamma-Ray and Neutron spectrometer, and Raman spectrometer cannot function well between the temperatures -160°C to 120°C. All these scientific instruments will be protected by the thermal control system. The thermal control system will also protect adjacent subsystems such as CDH and power.

$$Q = kA(T_1 - T_2)/L$$

$$Q = \varepsilon\sigma FA(T_1^4 - T_2^4)$$

$$Q = hA(T_1 - T_2)$$

Figure 2.1.4.1.1 - Thermal Equations

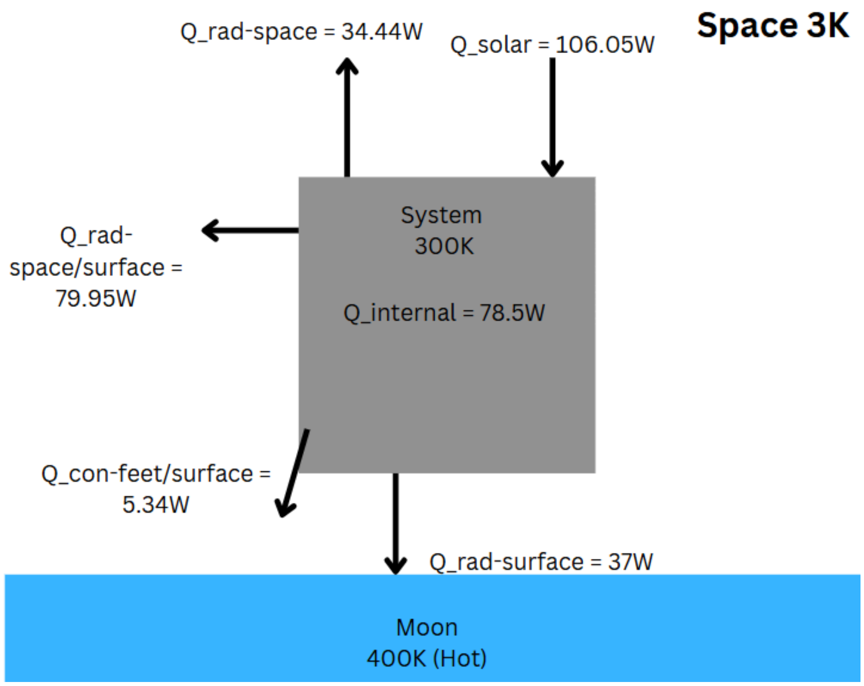


Figure 2.1.4.1.2 - Hot Case

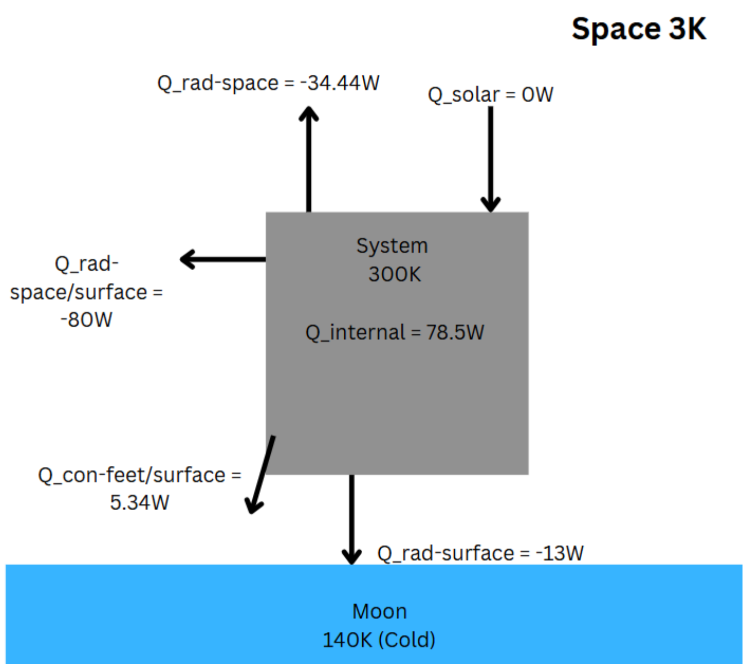


Figure 2.1.4.1.3 - Cold Case

2.1.4.1. Thermal Control Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
TCS-1	Maintain optimal temperature of the rover.	Allows the rover to function properly throughout the mission.	SYS.1, SYS.3, SYS.4, SYS.6		Demonstration	Thermal	Met
TCS-1.2	Incorporate active thermal control systems to maintain temperatures.	Active components will maintain the optimal temperature of the rover.	TCS-1		Demonstration	Thermal	
TCS-1.3	Utilize inherent properties of the rover to maintain temperatures.	Limits power consumption and the amount of active systems needed.	TCS-1		Analysis	Thermal	Met
TCS-1.4	Implement a net load of close to 0W under baseline operations	Ensures that the rover does not deplete its energy reserves.	TCS-1		Analysis	Thermal	Met
TCS-1.5	Minimize outgassing in the environment so total material loss does not exceed 1%	Prevents material from being degraded so it does not lose its durability over the span of the mission.	TCS-1		Test	Thermal	Met
TCS-2.0	Ensure the cost of the thermal subsystem does not exceed the allotted budget.	Ensures the scope of the mission can be within the budget.			Inspection	Thermal	Met

2.1.4.2. Thermal Control Sub-Assembly Overview

Multi-layer Insulation (MLI) will be utilized to provide thermal protection from the lunar environment. The multi-layer insulation weighs about 0.1 - 0.2 kg/m^2 covering the body of the rover in its entirety. MLI is made up of multiple layers of thin, reflective material such as Mylar which are separated by lightweight spacers. By using MLI, it is expected that thermal radiation to the surface will be significantly reduced and electronic components are protected to ensure accurate data collection. Furthermore, MLI has been used in several rovers such as the Mars's Curiosity where it provides sufficient protection to the rover's internal components. MLI has been used in the Apollo 11 moon lander as well so the MLI's technology readiness level (TRL) is quite high at 8.

The rover will utilize white coating as well to regulate temperature and protect important scientific equipment from the lunar environment. The properties of the coating allow for high reflectivity and low absorptivity, keeping the rover's internal components cool during times of sunlight directly overhead. With an emissivity of 0.8 and absorptivity of 0.19 for the rover, the rover will reduce radiation to space and solar flux significantly. Used in spacecrafts and missions, the TRL of thermal coating is a 7.

Once inside a cave, the rover is bound to experience loss in heat due to the absence of sunlight and will begin dealing with the extreme cold. Components that only operate in certain temperatures will cease to operate but the patch heater will provide adequate heating to the scientific instruments. Ranging in various sizes, it can fit the needs of the mission and can range from several centimeters and can draw varying amounts of power depending on the size. Patch heaters have been used in spacecraft and can provide sufficient heating to internal loads thus receive a TRL of 7.

2.1.4.3. Thermal Control Subsystem Recovery and Redundancy Plans

Redundancy:
To maintain the functionality of the rover on the moon, several passive and active management systems will be utilized. Active systems will include patch heaters containing multiple circuits in case one heater circuit fails and to allow for a swift switchover. Passive systems will include Multilayer Insulation to ensure the rover doesn't experience degradation of its material. To detect changes in temperature, sensors will be placed in the rover so swift action can be taken to bring the rover to baseline temperatures during anomalies.

Recovery:
To address fluctuations in temperature, the rover will have systems in place to adapt to changing environmental conditions. There will be software to adjust heating and cooling operations to maintain optimal component temperatures. There will be regular diagnostic tests to ensure components and backup components are in good health.

2.1.4.4. Thermal Control Subsystem Manufacturing and Procurement Plans

The thermal control system will use components such as patch heaters from Northrop Grumman, MLI developed by NASA JPL, thermal white coating from Lockheed Martin, and software developed in-house to run diagnostic and health checks and to activate safe mode during temperature fluctuations.

Component	Estimated Cost ($)	Lead Time	Procurement Source
Patch Heaters	100,000	4 months	Northrop Grumman
Multi-Layer Insulation	200,000	6-12 months	NASA JPL
Thermal White Coating	100,000	2-5 months	Lockheed Martin
Thermal Control Software	300,000	Concurrent	In-house development

2.1.4.5. Thermal Control Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
TCS-1	Maintain optimal temperature of the rover.	Analysis	After conducting all tests for the child requirements it can be concluded whether optimal temperatures can be maintained.	Gather data from the child requirements and determine if they are able to adequately maintain the temperature of the rover.
TCS-1.2	Incorporate active thermal control systems to maintain temperatures.	Inspection	Visually examine for active components such as heaters utilized in the rover.	Note the components used within the subassembly and ensure they happen to be active components such as heaters.
TCS-1.3	Utilize inherent properties of the rover to maintain temperatures.	Inspection	Visually examine for properties of the rover that will be used to maintain temperature.	Note the components used within the subassembly and ensure they happen to be active components such as multi-layer insulation and variable-conductance heat pipes.
TCS-1.4	Implement a net	Analysis	Utilize mathematical formulas	Utilize conduction,

	load of close to 0W under baseline operations		to determine the net load.	convection, and radiation equations to develop a flow chart and to ensure there is a net load of 0 or close to it.
TCS-1.5	Minimize outgassing in the environment so total material loss does not exceed 1%	Test	Conduct a test in the thermal vacuum chamber to ensure total material loss doesn’t exceed 1%>	Conduct in a thermal vacuum chamber. Use equipment such as coldfinger or gas analyzer to measure temperatures. Will ensure total material loss doesn’t exceed 1%.
TCS-2.0	Ensure the cost of the thermal subsystem does not exceed the allotted budget.	Analysis	By using financial data and keeping track of costs, it ensures costs stay well under budget.	Consult with the programmatics team to ensure the cost of the thermal subsystem is well under the mission budget.

2.1.5. Payload Subsystem Overview

The payload subsystem enables the collection of data to address the mission’s objectives. The instruments onboard the rover are selected to align with the goals outlined in the Science Traceability Matrix (STM) in Section 1.2, ensuring that every measurement supports the broader mission of advancing lunar exploration. This subsystem includes 5 core science instruments that are each tailored to perform specialized measurements. They address objectives such as assessing resource availability, structural stability, thermal gradients, radiation shielding, and elemental composition within and around lunar caves. This provides insights into the Moon’s potential for human habitation and resource sustainability. Integrating these instruments into the rover required extensive collaboration across multiple spacecraft subsystems, including power, thermal control, data handling, and structural design. Each instrument operates in a harsh lunar environment characterized by extreme temperature fluctuations, high radiation levels, and pervasive regolith dust. The following provides detailed descriptions of each instrument and how they address the specific mission objectives. This overview also highlights the challenges posed by the lunar environment and how the design of the payload subsystem overcomes them to ensure mission success. The power subsystem ensures that each instrument has sufficient energy to operate at peak performance, particularly during demanding periods of data collection. The thermal control system mitigates the extreme temperature fluctuations that define the lunar environment, safeguarding sensitive components and maintaining operational stability. The data handling subsystem processes the significant volume of data generated by the payload, ensuring that the information is organized, stored, and efficiently transmitted to Earth for analysis. Finally, the structural subsystem provides robust support, shielding the instruments from vibrations, impacts, and pervasive lunar dust.

The Near-Infrared Volatile Spectrometer System (NIRVSS) is designed to detect water, ice, and carbon-rich compounds on the lunar surface and subsurface. It addresses the mission objective of assessing resource availability by providing detailed absorption spectra that indicate the distribution of volatiles, particularly within a 5 km radius of the mission site. Operating across a wide spectral range of 400-4000 nm, NIRVSS can identify ice signatures between 1000-2500 nm and organic compounds along the full spectrum. It has the capability for making accurate compositional maps crucial to assessing the lunar ISRU and long-term sustainability opportunities that will be critical for future human exploration. NIRVSS maps the lunar regolith and subsurface by collecting reflected and emitted near-infrared radiation. The feature of detecting absorption features unique to volatiles help in determining the composition and distribution of resources critical for future exploration missions. It also measures surface brightness and albedo to enhance its data accuracy and characterize the local terrain.

The harsh conditions of the Moon include extreme temperatures, high radiation levels, and pervasive lunar dust that pose significant challenges to NIRVSS's operation. Its optical components are treated with anti-dust coatings to reduce regolith accumulation, which ensures uninterrupted spectral measurements. Active thermal control mechanisms safeguard its functionality during both lunar day and night cycles. Its ability to detect compounds is critical in achieving the mission's science objectives. By complementing data from instruments like the Neutron Spectrometer System (NSS), NIRVSS helps create a comprehensive resource map of the mission area.

The Neutron Spectrometer system (NSS) is designed to detect hydrogen concentrations within the lunar regolith and subsurface. This provides insights into the distribution of water ice. By measuring variations in neutron flux, NSS supports the mission's objective of identifying in-situ resources for sustainable human exploration. This instrument also contributes to understanding the geological processes that influence the presence and distribution of volatiles on the Moon. NSS operates by detecting and analyzing thermal, epithermal, and fast neutrons emitted naturally from the lunar surface. Cosmic rays interact with the lunar soil, producing neutrons that are scattered or absorbed depending on the presence of hydrogen atoms. NSS measures these interactions to determine hydrogen concentrations with high sensitivity. It can analyze depths up to approximately 1 meter, offering a detailed picture of potential water reservoirs in the mission area. To function effectively, NSS relies on several subsystems. The power subsystem provides consistent energy for the neutron detectors and onboard data processing, ensuring uninterrupted operation during measurements. The thermal control system maintains the temperature of the instrument within operational limits, in view of long exposure to extreme temperatures on the lunar surface. The data handling subsystem processes neutron flux data, converts it into hydrogen concentration maps, and stores the results before transmission to Earth. The structural subsystem properly mounts the NSS on the rover for launch and protects it from mechanical vibrations during launch and landing.

The lunar environment is indeed very challenging for neutron spectroscopy. Temperature extremes, along with radiation and pervasive moon dust, might affect the functionality of the NSS. To that end, the instrument is completely enclosed in a radiation-hardened shell to protect its sensitive detectors. A thermally insulated housing prevents operational disruptions brought about by temperature fluctuations. In addition, its exposed surface is treated with anti-dust materials to reduce regolith deposits, allowing for the correct measurement of neutron flux. NSS plays an important role in the mission of meeting the science objectives through the identification and mapping of hydrogen-rich areas, showing water ice. This information is necessary in formulating a plan for future human missions and strategies for the utilization of resources in situ. Subsurface volatile analysis ability supplements the data coming from other instruments, which is important for creating a resource map of the mission site. By pinpointing areas where hydrogen concentration is maximally high, NSS allows an immediate contribution to missions with a highly successful general implication for lunar exploration management, sustainability, and continuous endurance.

The Diviner Lunar Radiometer is designed to measure temperature gradients and thermal properties on the lunar surface within cave structures. It addresses the mission objective of evaluating environmental stability which is crucial for determining the habitability of lunar caves. By mapping temperature variations over time, Diviner gathers data to assess the long-term suitability of potential habitable sites based on their thermal behavior. Diviner detects thermal infrared radiation emitted from the lunar surface, covering a spectral range of 3000–15,000 nm. This allows it to detect subtle temperature variations. The instrument maps diurnal temperature cycles, showing how lunar regolith and cave walls absorb, store, and release heat. This information helps determine how potential habitats might moderate extreme temperature variations on the Moon. The supporting spacecraft subsystems allow for this instrument to assess its full capabilities. The power subsystem provides energy for continuous monitoring and data collection during lunar day and night cycles. The thermal control system shields radiometer sensors against overheating during the lunar day and ensures functionality during sub-zero nighttime temperatures. The data handling subsystem processes thermal data into high-resolution temperature maps and stores it for transmission to Earth. The structural subsystem ensures precise alignment of Diviner's sensors to capture accurate thermal measurements while protecting against vibrations and dust interference.

Extreme temperatures (-160°C to 120°C) and dust can affect the radiometer. Diviner uses refractory materials and active cooling to maintain sensor performance, while anti-dust coatings and protective enclosures safeguard its optical components for reliable operation. Its ability to create detailed thermal maps complements other instruments in the payload.

The Gamma-Ray and Neutron Spectrometer (GRNS) evaluates radiation levels and hydrogen concentrations on the Moon. It analyzes gamma-ray and neutron emissions, which supports the mission's objectives of assessing radiation shielding and identifying hydrogen-rich areas indicative of water ice. GRNS detects high-energy gamma rays and neutrons emitted from the lunar surface, produced by cosmic ray interactions. It quantifies radiation intensity and hydrogen abundance to map resource distribution and assess radiation shielding effectiveness. The supporting spacecraft subsystems include the power subsystem, which provides steady energy for the spectrometer's detectors and onboard data processing unit. The data handling subsystem converts gamma-ray and neutron flux data into actionable insights, storing the results for transmission to Earth. The thermal control system maintains operational temperatures for the sensitive detectors to ensure accurate measurements.

Operating in a radiation-rich environment, GRNS is housed in radiation-hardened enclosures for accuracy. Thermal insulation mitigates temperature fluctuations, ensuring consistent functionality. GRNS provides data on radiation levels and water reserves, which are essential for human mission planning and cave habitability assessments.

The Raman Spectrometer analyzes molecular and elemental compositions of lunar regolith and cave walls. It assesses structural stability by identifying materials that are critical for load-bearing evaluations and habitat construction. The spectrometer uses laser-induced Raman scattering to identify vibrational modes of molecules, enabling precise identification of elements like Fe, Si, Mg, and Ca. This analysis helps evaluate cave wall integrity and provides insights into the geological history of the site. The power subsystem supplies energy for the laser source and detectors, ensuring consistent operation during data collection. The data handling subsystem processes Raman spectra to identify elemental composition, storing results for Earth transmission. The structural subsystem ensures precise alignment of the laser and protective housing for the sensitive optical components.

The lunar regolith's abrasive nature and the potential for dust accumulation could interfere with the spectrometer's optics. To address this, the instrument is equipped with anti-dust coatings and a protective casing. Additionally, its laser is designed to operate efficiently under extreme temperature conditions. The Raman Spectrometer is essential for understanding the composition and structural properties of lunar caves. It assesses load-bearing capacities and identifies critical elements, supporting habitat evaluation and resource goals.

The payload subsystem as a whole is designed to function as an integrated unit. The data from NIRVSS and NSS complement each other by creating a clearer picture of the distribution and abundance of hydrogen and other volatiles on the lunar surface. Diviner improves in thermal mapping when combined with the elemental composition provided by the Raman Spectrometer to bring in properties regarding how different materials affect thermal processes. This is also complemented by GRNS with the addition of vital information on the levels of radiation toward better assessment of resource potential and habitability. The lunar environment poses a host of challenges that must be surmounted for such instruments to function. The pervasive lunar dust, or regolith, is highly abrasive, adhesive, and capable of destroying sensitive components. Each instrument has dust-resistant coatings, protective enclosures, or active cleaning mechanisms to counteract this. Large temperature swings between the lunar day and night, from -160°C to over 120°C, are also highly risky. These are mitigated by advanced thermal insulation, active heating, or cooling systems tailored to each instrument's operational requirements. The highly radiative environment further demands the use of radiation-hardened materials for adequate shielding of electronics for proper measurements. By focusing on resource mapping, structural analysis, thermal stability, radiation assessment, and elemental composition, the payload subsystem shall provide a comprehensive dataset. Together, these instruments constitute a payload subsystem that collectively is much more than their individual contributions to mission success and the next era in lunar exploration.

2.1.5.1. Science Instrumentation Requirements

This section outlines the lower-level requirements for the mission's science instruments, derived from the Science Traceability Matrix (STM). These requirements specify how each instrument will operate in the lunar environment, the performance metrics they must achieve, and the necessary support from spacecraft subsystems to ensure mission success. The payload subsystem relies on the rover's thermal control, power, data handling, and structural systems to ensure optimal performance of its instruments. This integration addresses the extreme environmental conditions on the Moon and ensures that each instrument meets its specific performance goals.

Instrument	Requirement Type	Specific Requirement	Subsystem Dependency
NIRVSS (Near Infrared Volatile Spectrometer System)	Environmental	The spectrometer shall operate in temperatures ranging from -160°C to +55°C, with thermal insulation provided to maintain stability.	Thermal Control Subsystem
	Placement	NIRVSS shall be mounted at a fixed orientation to capture spectral data within a 5 km radius without obstructions.	Structural Subsystem
	Subsystem Dependency	The power subsystem shall supply 20 W continuously for laser operation, detector functionality, and data processing.	Power Subsystem
	Performance	The spectrometer shall detect volatiles at a sensitivity of 0.1% by mass and generate spectral data with 4.8 nm resolution.	Data Handling Subsystem
NSS (Neutron Spectrometer System)	Environmental	The neutron spectrometer shall operate in continuous exposure to radiation and extreme temperatures, with radiation shielding protecting its sensitive components.	Thermal and Structural Subsystems
	Placement	The instrument shall be mounted on the rover in an area with minimal interference from other instruments.	Structural Subsystem
	Performance	NSS shall detect hydrogen concentrations to a depth of 1 meter with a sensitivity of 0.1% by mass.	Data Handling Subsystem
Diviner Lunar Radiometer	Environmental	The radiometer shall use anti-dust coatings and thermal shielding to operate reliably in lunar conditions (-160°C to +120°C).	Thermal Control and Structural Subsystems
	Placement	The instrument shall be positioned to provide an unobstructed view of the lunar surface for thermal gradient mapping.	Structural Subsystem
	Subsystem Dependency	The power subsystem shall supply 25 W for continuous thermal data collection and processing.	Power Subsystem
Gamma Ray and Neutron Spectrometer	Environmental	GRNS shall operate in radiation-hardened enclosures to ensure measurement accuracy in high-radiation environments.	Thermal and Structural Subsystems
	Performance	The instrument shall detect hydrogen concentrations and radiation levels with a resolution of ±5%.	Data Handling Subsystem
	Subsystem Dependency	The power subsystem shall allocate 15 W for spectrometer operation.	Power Subsystem
Raman Spectrometer	Environmental	The spectrometer shall operate in temperatures ranging from -160°C to +55°C, with thermal control provided for laser functionality.	Thermal Control Subsystem

	Placement	The spectrometer shall be mounted with precise alignment to target areas for molecular and elemental analysis.	Structural Subsystem
	Performance	The spectrometer shall identify elemental compositions (e.g., Fe, Si, Mg) with ±0.01% accuracy.	Data Handling Subsystem

Table 2.1.5.1.1. The lower-level requirements for each instrument in the payload subsystem, detailing environmental constraints, placement specifications, performance metrics, and subsystem dependencies.

2.1.5.2. Payload Subsystem Recovery and Redundancy Plans

The payload subsystem comprises several scientific instruments, each vital for the mission's objectives. Ensuring their functionality under extreme environmental conditions, subsystem dependencies, and potential failures is critical. The plan provides recovery and redundancy strategies to safeguard each instrument and minimize data loss or operational downtime.

For the Near infrared volatile spectrometer system recovery measures focus on maintaining operational temperature and data integrity. If the instrument encounters temperature outside its specified range of 160 Celsius to +55 Celsius, backup thermal insulation or heaters will be activated to stabilize the system. In the event of data loss or corruption, a secondary data handling pathway will be utilized to process partial datasets and ensure some levels of continuity. To enhance redundancy, NIRVSS will rely on dual-layer thermal insulation to avoid single point failures and an auxiliary power supply line capable of delivering 20 w continuously if the primary power system encounters a fault. The reinforced mounting brackets ensure that the spectrometer remains in its fixed orientation for capturing spectral data within a 5 km radius, even in the case of physical disruptions. The neutron spectrometer is exposed to continuous radiation and extreme temperatures. Recovery strategies for this instrument include engaging radiation shielding reserves if initial protection degrades. Thermal control systems will monitor exposure levels and adjust the systems configuration to optimize detection accuracy. For redundancy, the NSS will be equipped with enhanced radiation shielding to provide a secondary layer of protection for sensitive components. The structural subsystem will ensure placement in optimal location on the Rover minimizing interference while maintaining operational stability. Power redundancy will include reserve power lines, capable of sustaining operations during unexpected primary power failures. This assures the NSS can detect hydrogen concentrations out to a depth of 1 m with a sensitivity of 0.1% by mass.

The divine lunar radiometer requires anti-dust coatings and thermal sheeting to operate under lunar conditions ranging from -160° to 120°C recovery measures for this instrument focus on maintaining is view of the lunar surface for accurate thermal mapping if the view becomes obstructed by the lunar law or mechanical misalignment and mechanical cleaning or recalibration process will be initiated. For redundancy due, Auntie does recordings will be applied to protect the radio meters optics and thermal sheeting included in active heating and cooling system to meeting. Inform is the temperature fluctuations. A secondary powerline will supply the necessary 25 for uninterrupted, dermal data collection and processing if the primary source fails.. additionally the structural substance was reinforced to ensure a stable position ain't even under external stress.

The Gamma ray and neutron Spectrometer operates in high radiation environments that require robust radiation harder enclosures. Recovery plans include activated, redundant enclosures or deploy adaptive shielding adjustments, and primary protections are compromise.. in the event of operational and accuracy caused by environmental surfaces. The spectrum media will initiate recalibration routines to restore its resolution of +5%. To enhance redundancy Team 22 will make radiation harder enclosures will be used to help provide the back up case of degradation of the primary system.

The recovery and redundancy plans across all instruments will focus on mitigating risk from environmental challenges, operational, anomalies, and subsystem failures. Each instrument leverage is specific thermal, structural, power, and data handling redundancies to ensure mission success. These measures collectively provide resiliency, allowing the payload subsystem to maintain scientific integrity and achieve mission objectives, even under adverse conditions. This comprehensive approach will help reduce the likelihood of total instrument failure and assure the continuity of data collection for team 22 lunar missions..

2.1.5.3. Payload Subsystem Manufacturing and Procurement Plans

The payload subsystem, comprising five core instruments- NIRVSS, NSS, Diviner Lunar radiometer, GRNS, and Raman Spectrometer- is essential for collecting data to meet mission objectives. manufacturing and procurement efforts for this subsystem must ensure precision, quality, and reliability to endure the challenges of the lunar environment. A robust plan is necessary to transition from design to production, procure high-quality components, and mitigate risks to ensure mission success. Manufacturing the payload subsystem begins with a seamless transition from design to production. Collaborative efforts from team 22 will address potential fabrication challenges early, ensuring that instrument designs are optimized for manufacturability. This phase will include prototyping each instrument to validate performance and identify improvements before initiating full-scale production. By iterating on prototypes, the team can confirm compliance with mission requirements and mitigate design risks. Material selection is another step in the manufacturing process. To go against the harsh lunar environment, specific material will be used. Radiation-hardened alloys will protect sensitive sector instruments like GRNS and NSS, while high performance materials will ensure thermal resilience for the instruments like diviner. Optical components for NIRVSS and Raman Spectrometer will be treated with anti-dust coatings to counteract lunar regolith accumulation. Anti dust coating can help Raman Spectrometers by improving signal quality and recreating noise (ResearchGate, 2022). These materials will be fabricated using advanced techniques such as precision CNC machining, additive manufacturing ,and microelectronics assembly in the clean room environments. This ensures that each component meets stringent specifications for durability, performance, and contamination resistance.

Procurement for the payload subsystem requires careful planning and rigorous selection of vendors to source high-quality components. Vendors must strictly qualify standards, including certifications for radiation tolerance, thermal performance, and aerospace-grade material properties. Suppliers with a proven track record of supporting space mission risk and ensuring reliability. To mitigate potential supply chain disruptions, multiple vendors will be identified for critical components, such as detectors and optical systems.

The payload subsystem includes specialized components that require materials from Niche suppliers. Optical components like high-precision lenses and mirrors for NIRVSS and Raman spectrometer will be from vendors specialized in space grade optical systems such as CubeSpace, Tensor Tech , and Veoware. Radiation hardened detectors for GRNS and NSS will be procured from manufacturers experienced in spectrometry-grade semiconductors, while advanced thermal coatings and insulation materials will be for instruments like Diviner to manage the extreme temperature fluctuations of the lunar surface. Lunar regolith stimulants, which mimic the properties of lunar dust, will also be procured to validate the instruments performance conditions realistically.

Procurement timelines are in place to ensure the mission stays on schedule within margin. Custom and highly specialized components will be ordered in advance, accounting for potentially long lead items. For standard or non-critical items, a just in time procurement strategy will be implemented to streamline storage and reduce costs. By coordinating with suppliers and maintaining a robust inventory manage,net system, the team can ensure all components are available for integration and testing without delays.

The integration of manufacturing and procurement is essential for the success of the payload subsystems. During production, regular communication between the engineering and supply chain teams will ensure that any design updates are communicated to the suppliers, preventing discrepancies or delays. Quality control measures, such as inco,inn inspections and component testing wil verify that procured items meet specifications before assembly. This will include tests for optical clarity, thermal resistance, and radiation hardness to confirm performance under lunar conditions.

As the instruments are manufactured and procured, system integration will follow. Each component will be assembled and tested as part of the payload subsystems to verify compatibility with the rovers' powers, thermal controls, data handling, and structural systems. This step ensures that the subsystem operates seamlessly, providing realizable performance through trout the mission. By aligning manufacturing and procurement efforts, they completed on schedule and met the demands of lunar exploration.

The manufacturing and procurement plans for the payload subsystem are designed to ensure precision, reliability and resilience. By leveraging advanced materials, vendor selection, and strategic timelines, the team will deliver a subsystem capable of meeting the mission's objectives in the lunar environment. The integration of manufacturing and procurement processes ensures a streamlined approach, laying the foundation for mission success and advancing the future of lunar exploration.

2.1.5.4. Payload Subsystem Verification Plan

The payload subsystem plays a pivotal role in the success of lunar exploration missions. It integrates scientific instruments to meet mission objectives by collecting critical data on resource availability, structural stability, thermal gradient, radiation, shooting, and elemental composition. Verifying the functionality and reliability of this sub system is essential to ensure mission success under the horse conditions of the lunar environment. This paper outlines a comprehensive verification plan for the pillow social system, focusing on environmental testing performance, validation system integration, and mission simulation. The payload system will operate in extreme lunar conditions, including scientific temperature, fluctuations, higher radiation levels and pervasive revolved dust environmental testing is critical to ensure the sub system's resilience.

Thermal Vacuum Testing

Simulate the temperature screams and vacuum conditions on a lunar surface instrument such as the diviner lunar radiometer and the air and light spectrum system, while underground cycles of heating and cooling to verify their thermal control mechanisms, including active cooling systems and refractory materials.

Radiation Hardness Testing
The gamma ray and neutron spectrometer and neutron spectrum meter system will be exposed to a high energy radiation environment to validate the radiation enclosures. This ensures accuracy and functionality of sensitive detectors in electronics and radiation rich environments.

Dust mitigation Testing
Instruments will be subjected to simulate lunar revolvers to assess the effectiveness of anti-dust coding enclosures and protective mechanisms. Spectrum meter optics and NIRVSS sensors will be tested for performance degradation due to dust accumulation.

Each instrument functionality must be thoroughly tested to confirm its mission requirements. Performance validation focuses when showing data, accuracy, reliability, and alignment with mission objectives. Conduct calibration test using known standards to verify the accuracy of volatile detection across the 400-4000 nm spectral range. Simulating lunar -like terrain with varying compositions of water ice and organic materials to ensure mapping capabilities. Neutron flux detection for NSS will consist of testing NSS ability to measure hydrogen concentrations in simulated regolith and validate its depth analysis capabilities up to 1 meter using controlled environments with varying hydrogen concentrations. Thermal gradient mapping for the diviner validates the diviner's ability to detect subtle temperature radiation in controlled environments with programmed diner temperature cycles. ensure thermal maps align with known surface and subsurface characteristics.

Mission Simulation Field Test
Mission simulation field testing mission simulations are critical to validate the payload subsystems under near operational conditions. Deploy the payload subsystem in a controlled environment mimicking the lunar surface to test overall functionality. evaluating interactions between instruments, such as complementary data from NIRVSS and NSS for resource mapping. Field deployment conducts field tests in terrestrial analog sites, such as volcanic regions or polar deserts to alienate instrument performance in realistic conditions.

Risk Mitigation and Redundancy Testing
Risk mitigation strategies will be validated to address potential failures during the mission. Test backup systems for strategies will be validated to address potential failures during the mission. redundant verification test backup systems for critical components, including power, thermal control, and data handling. Failure mode analysis will simulate potential failures, such as power loss or instrument malfunctions to evaluate recovery

procedures. Ensure the payload subsystems can operate in a degraded mode while meeting primary mission objectives.

The verification plan for the payload subsystems encompasses rigorous testing to ensure it meets the mission's scientific and operational goals. By focusing on environmental testing, performance validation, system integration, mission simulation, and risk mitigation, the payload subsystems can overcome the challenge of the lunar environment. This comprehensive approach ensures the subsystem will provide relatively data, contributing to the next area of lunar exploration and human sustainability on the moon.

2.2. Interface Control

N^2 Table:
The N^2 chart presented in the previous section outlines the direct interactions between subsystems. Each subsystem has its specific input and output needs, which are coordinated with the other subsystems.

Power	Power for thermal management	Power for actuators, motors	Power for communication systems	Power for data handling and onboard processing	Power for motors, mobility systems	Power for sensors, instruments
-	**Thermal**	Thermal data affects mechanical components, actuators	Thermal data may impact communication systems	Thermal monitoring for onboard temperature management	Thermal data affects mobility system components	Temperature impacts instrument operation
Mechanical movements require power for actuators, motors	Mechanical components may generate heat	**Mechanical**	-	-	Mechanical feedback for mobility systems and position	Mechanical components mount payload instruments
Power usage for communication systems	-	-	**Communication**	Communication data and commands are	Commands for rover movement or adjustmen	-

				handled by CDH	ts	
Power usage for CDH operations	Mechanical data for system control	Thermal data for system monitoring and manageme nt	Data to be transmitte d, commands to be executed	**CDH**	Navigation command s for rover movement	Payload data is processed and relayed to Earth
Power usage for motors and actuators used for mobility	Temperatur e data is important for motor and actuator health	Movement feedback to control mobility	Command s for movement or system adjustment s	Navigation commands and feedback for autonomy	**Navigatio n**	-
Power usage for sensor operation and instrument ation	Payload instruments are affected by temperatur e	Mounting of sensors and instruments	Payload data needs to be communic ated to Earth or other systems	Payload data is processed and relayed	-	**Payload**

Instrumentation and Payload Interface

The payload in this mission plays a critical role in scientific data collection, including sensors to measure surface composition, temperature, and other key environmental factors. The payload requires specific interfaces that are crucial to its operation:

1. **Mechanical Mounting**: The payload will be mounted securely onto the rover's frame. This mounting system must be robust enough to handle the dynamic loads generated during rover movement. It will also be strategically placed to avoid interference with other systems, ensuring clear lines of sight for sensors.
2. **Thermal Isolation**: Since the payload will operate in an environment with extreme temperature fluctuations, it must be thermally isolated to prevent the heat from other components (such as the rover's motors or power systems) from interfering with its sensors. A dedicated thermal control system will be used to maintain the payload within the required temperature range.

3. **Data Handling**: The payload will generate significant amounts of data, which must be processed and transmitted back to Earth. The **CDH** subsystem will handle this data, ensuring that the payload's outputs are properly processed and sent through the communication systems.
4. **Robotic Arm**: Depending on the specific requirements of the payload, it may need a **robotic arm** for orientation control, allowing the payload to target specific locations on the lunar surface. This ensures the sensors are directed at the proper sites for data collection. The **Mechanical** subsystem will control the gimbal or arm movements based on commands from the **Navigation** subsystem.
5. **Communication**: The payload's data will be transmitted back to Earth via the **Communication** subsystem. This involves careful integration to ensure that the payload can send data in real-time and receive commands for any adjustments during the mission. The payload may also need to communicate with other subsystems to receive operational updates and system status.

System Integration and Coordination

The interaction between subsystems is vital for ensuring that the spacecraft meets its objectives efficiently. The **Navigation** system will direct the rover to target locations on the lunar surface, where the **Payload** subsystem will perform its measurements. These systems must work together to navigate the terrain, avoid obstacles, and collect valuable data.

The **Mechanical** system will support both the rover’s movement and the payload’s sensor mounts, ensuring they remain stable during travel. The **Thermal** system will monitor temperature levels and regulate them across subsystems to avoid overheating or damage to sensitive components. Finally, the **Power** system will ensure that all subsystems, including the payload, are provided with the energy they need to operate.

3. Science Mission Plan

3.1. Science Objectives

The mission’s primary science objectives are centered on advancing lunar exploration goals by investigating the habitability potential of lunar caves and pits. These objectives are closely aligned with NASA's Science Mission Directorate (SMD) goal to “develop precursor lunar robotic missions and define those scientific activities that astronauts will conduct on the Moon” (Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032). Additionally, the mission supports the Exploration Systems Development Mission Directorate (ESDMD) goal of enabling “safe and enduring habitation systems”. The focus on lunar caves and pits is driven by their potential to shield future astronauts from extreme surface conditions, such as temperature swings, micrometeorite impacts, and radiation. By characterizing the terrain, thermal properties, and structural stability of these caves, the mission aims to identify sites that could provide natural protection and reduce the need for extensive engineering interventions. These efforts directly contribute to the objective of providing safe habitats for long-term exploration.

The investigation into vital resources such as water ice and carbon-rich compounds is crucial for supporting in-situ resource utilization, which reduces reliance on Earth-based resupplies. Understanding regolith composition within a 5 km radius will help map resource distribution and inform the design of extraction technologies. Peer-reviewed studies highlight the importance of water ice in lunar polar regions for producing oxygen and hydrogen for life support and fuel production, making this data critical for sustainable lunar missions (Colaprete et al. 2010). Additionally, assessing depth, terrain variations, and temperature gradients within these pits will provide data essential for evaluating their suitability as safe habitation zones. Measuring radiation levels will inform habitat shielding requirements, while determining rock density and elemental composition will evaluate the structural integrity of cave walls for long-term use. Studies in planetary geology have demonstrated that such analyses are foundational for understanding the mechanical properties of subsurface environments and ensuring their stability under human activities (H. Jay Melosh 2011).

The Near Infrared Volatile Spectrometer System (NIRVSS) will detect the presence and distribution of water and ice by analyzing their unique absorption characteristics. The Neutron Spectrometer System (NSS) will aid in identifying and mapping the distribution of organic materials, which are essential for understanding resource availability. Additionally, the Diviner Lunar Radiometer will measure temperature gradients, capturing variations across the day-night cycle to assess thermal stability. These instruments work in tandem to provide critical data on resource distribution, environmental conditions, and structural properties, enabling a comprehensive evaluation of the habitability potential of lunar caves and pits.

3.2. Experimental Logic, Approach, and Method of Investigation

The primary mission goal is to advance lunar exploration by investigating the potential habitability of lunar caves and pits. This mission aligns with NASA's Science Mission Directorate (SMD) goal to develop precursor lunar robotic missions, particularly those that will define scientific activities astronauts will conduct on the Moon. Additionally, the mission supports the Exploration Systems Development Mission Directorate

(ESDMD) goal of enabling safe and sustainable habitation systems for future lunar exploration. The scientific objectives are focused on characterizing lunar terrain, assessing resource availability, and evaluating the thermal and structural conditions of lunar caves, which will be crucial for long-term human habitation.

Integrated Payload Approach and Components:
To achieve the scientific objectives, the mission payload integrates four key instruments that complement each other, each designed to collect specific data essential for understanding the habitability of lunar caves and pits.

- NIRVSS Spectrometer (Near Infrared Volatile Spectrometer System) - This will detect and map the presence of water ice and organic compounds within a 5 km radius from the landing site. It will operate within the spectral range of 1000–4000 nm, which is ideal for identifying these volatiles based on their unique absorption characteristics. The minimum success threshold is detecting water at a concentration of 0.1% by mass and organic compounds at a concentration of 0.1%. The optimum success involves mapping the distribution of water ice and organics across the full operational area, with a spectral resolution of 5nm. A stretch goal is to analyze isotopic compositions, such as hydrogen and oxygen isotopes, which will offer insights into the Moon's formation and potential lunar water resources for future exploration.

- Neutron Spectrometer System (NSS) - This will detect the presence of hydrogen in the lunar regolith, which serves as an indirect indicator of water ice deposits. The minimum success criterion is detecting hydrogen at a concentration of 0.1%, with a sensitivity of 0.08%. The optimum success will be to create detailed maps of hydrogen distribution over a 5 km radius, which could highlight areas with concentrated water ice deposits. Stretch goals include identifying hydrogen anomalies, which could indicate regions rich in water ice, thereby aiding in future resource extraction planning. This data is essential for understanding the availability of water, a crucial resource for sustaining human life and fuel production.

- Diviner Lunar Radiometer - This will collect continuous temperature data across a day-night cycle, both inside and outside the lunar caves. The minimum success involves collecting thermal data over a single day-night cycle with a spatial resolution of 200 meters. Optimum success would involve continuous thermal mapping across multiple cycles, capturing the variations in temperature within the cave environment and identifying stable thermal zones. The stretch goal is to detect microthermal anomalies, which could indicate regions with stable temperatures ideal for lunar habitation. Thermal stability is crucial for the safety and comfort of future astronauts, and this instrument will provide critical data to identify zones where temperature fluctuations do not exceed tolerable limits for human activity.

- Raman Spectrometer - This will analyze the elemental and mineral composition of the lunar regolith and cave walls, focusing on key elements like iron, silicon, calcium, and other minerals that contribute to the mechanical properties of the terrain. The minimum success is to measure the composition of at least one regolith sample with 0.03% sensitivity. The optimum success would involve mapping the load-bearing capacity and structural integrity of cave walls, providing critical information about their suitability for long-term human habitation. The stretch goal is to detect rare minerals, such as those that could have economic or scientific value, contributing to the broader understanding of lunar geology and the potential for resource utilization.

Experimental Plan and Data Collection Procedure:

1. Pre-Landing Phase:
    - Site Selection: Using high-resolution imagery from previous lunar missions (such as the Lunar Reconnaissance Orbiter and data from JMARS), potential landing sites are selected based on key features like terrain variability, cave formations, and potential for resource availability. Sites are prioritized based on their scientific interest, access to resources like water ice, and accessibility for rover operations.
    - Mission Planning: The mission is planned to maximize data collection while minimizing risks. The instruments will operate sequentially and collaboratively to ensure data consistency and avoid interference between them. Data collection procedures will be refined based on the local terrain and scientific objectives of each target area.

2. Landing and Initial Survey:
    - Upon landing, the NSS and Diviner Radiometer will begin initial surveys of the surroundings, focusing on detecting hydrogen concentrations and thermal variations. The thermal data will provide insights into the environmental conditions inside and outside the lunar caves, while the hydrogen data will inform further exploration, guiding the deployment of NIRVSS and the Raman Spectrometer.
    - These initial readings will be used to refine the exploration path for the rover and prioritize areas for further investigation.

3. Data Collection:
   - NIRVSS Operation: The NIRVSS will be operated throughout the mission to conduct spectral scans of the lunar surface and caves. It will focus on detecting water ice and organic compounds at varying depths and distances from the landing site, with regular updates sent back to Earth for analysis.
   - Continuous Thermal Monitoring: The Diviner Radiometer will continuously monitor temperature variations over the course of multiple day-night cycles. It will prioritize regions inside the cave to assess thermal stability and identify any microthermal anomalies that could signal zones with more favorable conditions for human habitation.
   - Regolith and Cave Wall Analysis: The Raman Spectrometer will collect regolith samples and analyze the mineral composition of cave walls, assessing the load-bearing capacity and structural integrity of the cave environment. The data will help identify whether certain areas are structurally sound for the construction of long-term habitation systems.

4. Iterative Analysis:
   - Data from each instrument will be processed and transmitted back to Earth for ongoing analysis. Findings from one instrument will inform the operations of the other instruments, ensuring a holistic and efficient data collection process.
   - Regions with overlapping indicators of resource richness, structural stability, and thermal suitability will be prioritized for deeper investigation.

Subsystem Design and Integration:
The instruments on board the rover are integrated into a cohesive payload system. Each instrument shares power and data subsystems to ensure efficient operation and reliable data transmission. The instruments are designed to complement each other, allowing for cross-validation of data. For instance, the NSS's hydrogen data will guide NIRVSS operations by identifying potential ice-rich areas, and thermal data from Diviner will inform the positioning and timing of Raman Spectrometer analyses. This integrated approach maximizes the scientific yield while minimizing operational risks.

Mission Development and Justification:
The experimental logic and methodology behind this mission are based on peer-reviewed studies that underscore the importance of resource identification, thermal stability, and structural integrity for future lunar

exploration. The data collected by the instruments will fill critical knowledge gaps in our understanding of lunar cave environments and their potential for supporting human missions. By integrating results from multiple scientific subsystems, the mission will provide a comprehensive evaluation of lunar caves' suitability for habitation and resource utilization.

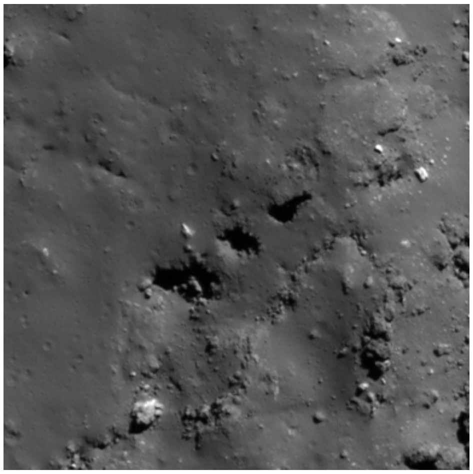


Figure 3.2.a Tycho 29b lunar pit cave (Wagner & Robinson 2021)

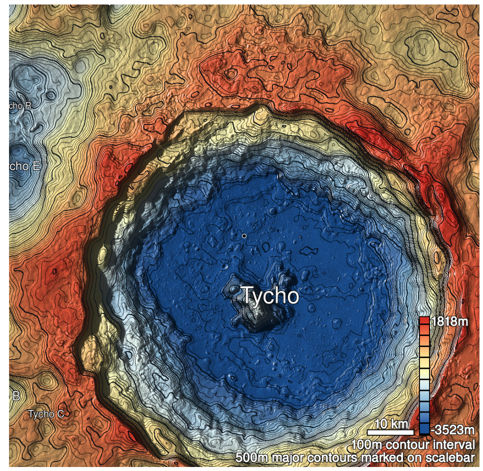


Figure 3.2.b Tycho 29b structural heatmap (Wagner & Robinson 2021)

3.3. Payload Success Criteria

Category	Minimum Success	Optimum Success	Stretch Goal
NIRVSS Spectrometer System	Detects water ice presence within a 1-meter depth and organic compounds at 0.1% concentration.	Maps water ice and organic compounds across a 5 km radius with 95% accuracy and spectral resolution of 5nm.	Identifies isotopic compositions of water or unexpected volatiles, revealing insights into lunar formation.
NSS (Neutron Spectrometer System)	Detects hydrogen at concentrations as low as 0.1% within the lunar regolith at one site.	Maps hydrogen and potential ice deposits over a 5 km radius, achieving a sensitivity of 0.08%.	Identifies hydrogen-rich anomalies, providing detailed subsurface maps of potential resource-rich regions for extraction.
Diviner Lunar Radiometer	Collects thermal data for one day-night cycle outside and inside the lunar caves at 200 m spatial resolution.	Provides continuous temperature mapping inside and outside the pit over multiple cycles with accurate thermal variations.	Detect micro thermal anomalies and stable temperature zones ideal for future lunar habitation.
Raman Spectrometer	Measures the elemental composition of regolith at 0.03% sensitivity for at least one sample.	Maps load-bearing capacity and structural integrity of cave walls, detecting all key minerals	Identifies rare minerals including those with economic or scientific value, contributing to

		(iron, silicon, etc).	planetary science and human missions.

The NIRVSS Spectrometer will detect and measure ice and organic compounds within a 5-kilometer radius of the rover's location. The success threshold for this instrument is to detect water at a concentration of 0.1% by mass and identify organic compounds in the spectral range of 1000-4000 nm. Minimum success would be detecting volatiles at a single site, while optimal success would involve mapping the spatial distribution of volatiles across the full operational range. A stretch goal includes identifying isotopic compositions of water and carbon-rich compounds, which would provide insights into lunar formation. The NIRVSS Spectrometer is vital for understanding the distribution of volatile resources on the moon to support future human exploration and contribute to understanding the Moon's geological and atmospheric history.

The Neutron Spectrometer System (NSS) is tasked with detecting hydrogen concentrations in the lunar regolith, a key indicator of water presence. The minimum success threshold is detecting hydrogen at 0.1% concentration within the regolith. Optimum success involves producing a detailed map of hydrogen distribution over a 5-kilometer radius, with a sensitivity of 0.08%. A stretch goal includes detecting hydrogen-rich anomalies that may indicate concentrated water ice deposits for resource extraction. The NSS provides critical data on subsurface volatiles, essential for advancing the understanding of lunar geology. Identifying hydrogen deposits will directly impact mission planning for sustainable human exploration and settlement.

The Diviner Lunar Radiometer will measure thermal variations within and outside the lunar cave over a full day-night cycle. Minimum success is collecting temperature data for a single day-night cycle with 200-meter spatial resolution. Optimum success involves continuous thermal mapping across multiple cycles, identifying stable temperature zones. A stretch goal includes detecting microthermal anomalies that can guide the design for future lunar habitations. The Diviner Lunar Radiometer is critical to provide insight into the thermal environment of lunar caves, aiding in the identification of stable zones for human habitation.

The Raman Spectrometer will analyze the elemental and mineral composition of lunar regolith and cave walls. The minimum success threshold is identifying key elements like iron, silicon, and calcium with 0.03% sensitivity in a single sample. Optimum success involves mapping the structural integrity and load-bearing capacity of the cave walls. A stretch goal is the discovery of rare or economically valuable minerals, contributing to planetary science. The Raman Spectrometer is essential for assessing the structural integrity of potential human habitats in lunar caves and insights into the Moon's geological processes and history.

3.4. Testing and Calibration Measurements

Once the rover reaches the lunar surface, preliminary testing will be conducted to ensure that all scientific instruments are functional. These tests will involve controlled data collection, comparisons to baseline performance, and calibration adjustments as needed to account for the lunar environment.

The NIRVSS Spectrometer will undergo a calibration routine using onboard spectral calibration targets. These targets are designed to replicate known materials, allowing for a direct comparison to validate instrument sensitivity and wavelength accuracy. The instrument will collect initial spectra of the lunar regolith at the landing site to compare against terrestrial testing data, ensuring consistent operation under lunar temperature and radiation conditions. The NIRVSS Spectrometer will periodically calibrate during the mission using its internal calibration targets to account for potential drift caused by extreme temperate variations. Calibration targets with known spectral properties will be used, ensuring accurate comparison for absorption spectra of water and organic compounds. The lunar surface temperature, lighting conditions, and dust interference will be monitored as control variables. The collected data will be cross-checked against expected absorption peaks for water and organics within the 1000 - 4000 nm range to confirm instrument functionality.

The Neutron Spectrometer System (NSS) will be tested for hydrogen detection sensitivity by taking baseline neutron flux measurements at the landing site. These measurements will be compared to terrestrial calibration performed in controlled lab conditions. Anomalies in detected hydrogen concentrations will indicate possible errors in calibration or shielding interference. The system's thermal shielding and detector sensitivity will be validated using onboard reference sources to ensure that neutron flux measurements are not affected by radiation or temperature fluctuations. The baseline neutron levels in the lunar regolith and shielding effectiveness will serve as control variables. Regular monitoring will account for environmental interference like cosmic rays. The instrument's data will be validated by comparing measured hydrogen concentrations with expected values based on lunar geological models.

The Diviner Lunar Radiometer will measure surface thermal radiation at the landing site during the first lunar day-night cycle. Initial measurements will be compared with historical lunar surface temperature data from previous missions to verify accuracy. The radiometer will use its internal thermal references to periodically calibrate during operation. These references will allow it to adjust for any environmentally induced drift. The known thermal profiles of regolith and shadowed areas will act as the control variables. The surrounding ambient temperature, instrument alignment, and exposure duration will be monitored. The data will be validated by checking for consistency in thermal gradient patterns and alignment with pre-existing temperature models of the lunar surface.

The Raman Spectrometer will collect spectra from the lunar regolith at the landing site. These spectra will be compared to preloaded references of common lunar minerals to ensure proper detection and vibrational mode identification. The Raman Spectrometer will use an onboard calibration laser to verify its wavelength accuracy and resolution. Calibration will be repeated periodically to maintain precision. The known mineralogical compositions from past lunar missions will serve as the control variables. Environmental factors like dust accumulation and vibration will be monitored to ensure reliable data collection. The detected vibrational modes will be cross-referenced with terrestrial Raman spectra for key minerals to confirm the accuracy and sensitivity of the instrument.

3.5. Precision and Accuracy of Instrumentation

NIRVSS Spectrometer System

The Near Infrared Volatile Spectrometer (NIRVSS) is designed to measure surface and subsurface water, carbon dioxide, and methane. Furthermore, it can map the surface temperature of and changes that occur at the landing site or the immediate area. The primary objectives are to characterize lunar surface composition, morphology and thermo-physical properties. Particularly, the composition, morphology and thermo-physical properties of water ice, which is critical for permanent settlement for the lunar surface, and rocket fuels that can lead the mission to Mars and celestial bodies within the solar system.

In addition, the instrument consists of two parts, a bracket assembly and a spectrometer box. The total mass of the instrument is 3.57 kg. It draws a nominal power of 30 W. The spectrometer box has one short-wave (1200-2400 nm) and one long-wave (2300-4000 nm) spectrometer. The short-wave spectrometer holds a spectral resolution of <20 nm, and the long-wave <50 nm. Both spectrometers are fiber-optic fed.

What makes the NIRVSS precision and accuracy LEDs set to 410 nm, 740 nm and/or 940 nm.

The Neutron Spectrometer System (NSS)

The Neutron Spectrometer System (NSS) is designed to measure the amount of hydrogen-bearing materials near the surface at the landing site to determine the potential for water ice. Or in the immediate area It also measures the composition of water ice in the bulk of the regolith. Also the instrument works by making measurements to determine the local thermal (<0.3 eV) and epithermal (0.3 eV to 1 keV) neutron flux, which can be used to determine the local hydrogen content.

The instrument comprises two gas-proportional counter (GPC) sensors. Both are filled with helium-3 at 15 atmospheres pressure, one is bare, so it is sensitive to both thermal and epithermal neutrons. The other GPC is wrapped in a 0.63 mm thick layer of cadmium, which absorbs neutrons with energy under 0.3 eV, so that it measures only epithermal neutrons.

This measurement, when subtracted from the first GPC reading, gives the thermal neutron flux. The sensors, mounted on the electronics unit, make up the sensor module, including a high-voltage power supply and pre-amplifiers. A separate data processing module controls the sensors and data processing. The instrument has a mass of 1.6 kg and uses 1.5 W power. The sensor module is 21.3 x 32.1 x 6.8 cm, the data processing module is 13.9 x 18.0 x 3.0 cm.

NASA's Neutron Spectrometer System (NSS) precision and accuracy works by passively surveys the subsurface to identify locations of enhanced hydrogen content at concentrations as low as 0.5 wt% water-equivalent hydrogen (WEH). WEH reports the hydrogen concentration as if it is found entirely in water molecules

Diviner Lunar Radiometer

This instrument flying aboard NASA's Lunar Reconnaissance Orbiter, the Diviner Lunar Radiometer Experiment is designed to measure surface temperatures on the moon, providing key information for future lunar surface operations and exploration.

The Diviner will precision and accuracy measure reflected solar and emitted infrared radiation in nine spectral channels with wavelengths ranging from 0.3 to 400 microns. The resulting measurements will enable characterization of the lunar thermal environment, mapping surface properties such as thermal inertia, rock abundance and silicate mineralogy, and determination of the locations and temperatures of volatile cold traps in the lunar polar regions.

Raman Spectrometer

Raman Spectroscopy is a non-destructive chemical analysis technique which provides detailed information about chemical structure, phase and polymorphy, crystallinity and molecular interactions. It is based upon the interaction of light with the chemical bonds within a material.

NASA-supported researchers have released the first set of spectra made available in the NASA Raman Spectroscopic Database (Ramdb). This database was developed to provide a publicly accessible, user-friendly resource of spectra relevant to planetary science research.

The Raman Spectroscopy has precision and accuracy rates ranging from 85% to 98%.

3.6. Expected Data & Analysis

NIRVSS Spectrometer System

Figure 3.6.1 - NIRVSS

The Near Infrared Volatiles Spectrometer System (NIRVSS) is an instrument package designed to acquire imaging and spectral data of targets within the lunar permanently shaded regions (PSRs). At its core, the instrument consists of a monochromatic imager and a spectrometer that covers the wavelength range of 1.3 μm to 4 μm at a spectral resolution of 15 to 30 nm. The imager uses a set of color LEDs to illuminate the target at different wavelengths, whereas a tungsten lamp illuminates the target for the spectrometer.

The Neutron Spectrometer System (NSS)

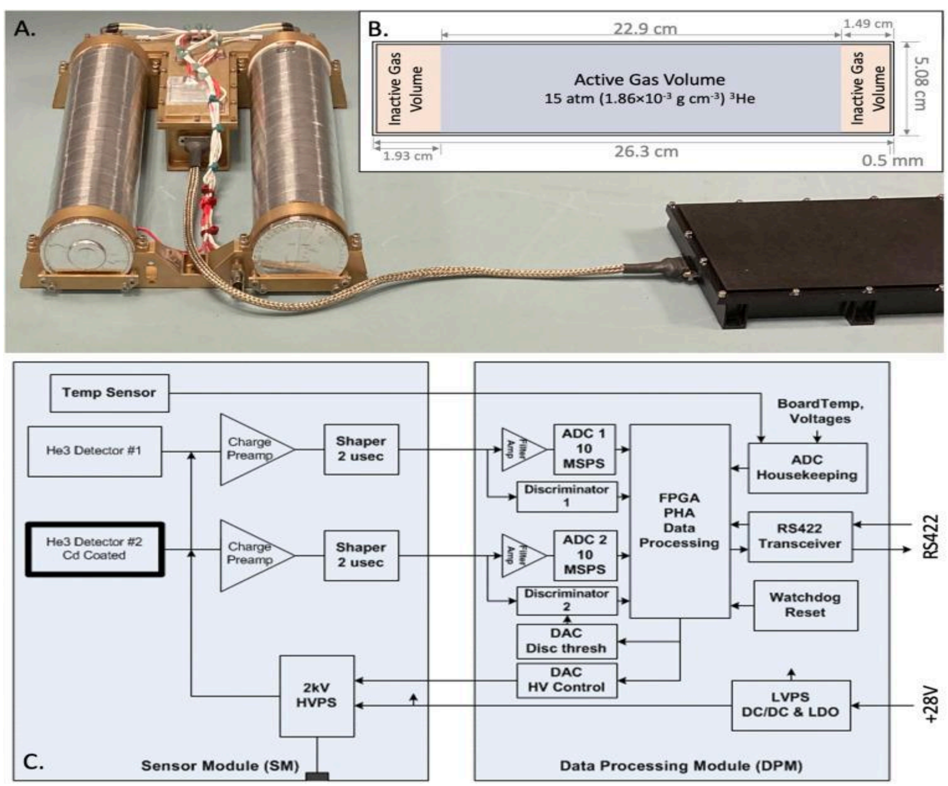


Figure 3.6.2 - NSS

NASA's Neutron Spectrometer System (NSS) is a compact, low-resource instrument that passively surveys the subsurface to identify locations of enhanced hydrogen content at concentrations as low as 0.5 wt% water-equivalent hydrogen (WEH). WEH reports the hydrogen concentration as if it is found entirely in water molecules. NSS measures neutrons resulting from cosmic-ray-induced spallation reactions within the lunar subsurface to estimate WEH concentrations. Orbital neutron spectroscopy is a proven technique to identify and quantify subsurface hydrogen from lunar orbit (e.g. [1], [2]) at the 10+ km spatial scale. Surface-based investigations facilitate measurements at spatial scales as small as tens of cm, a three order-of-magnitude improvement over current orbital measurements.

Diviner Lunar Radiometer

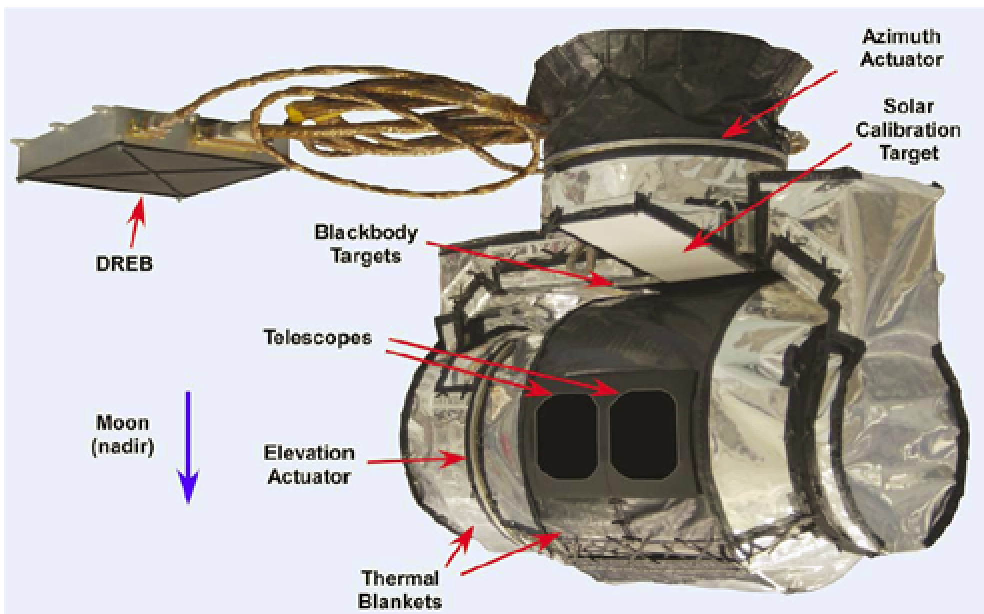


Figure 3.6.3 - Diviner Lunar Radiometer

An approach is presented to efficiently produce high quality gridded data records from the large, global point-based dataset returned by the Diviner Lunar Radiometer Experiment aboard NASA's Lunar Reconnaissance Orbiter. The need to minimize data volume and processing time in production of science-ready map products is increasingly important with the growth in data volume of planetary datasets. Diviner makes on average >1400 observations per second of radiance that is reflected and emitted from the lunar surface, using 189 detectors divided into 9 spectral channels. Data management and processing bottlenecks are amplified by modeling every observation as a probability distribution function over the field of view, which can increase the required processing time by 2–3 orders of magnitude.

Raman Spectrometer

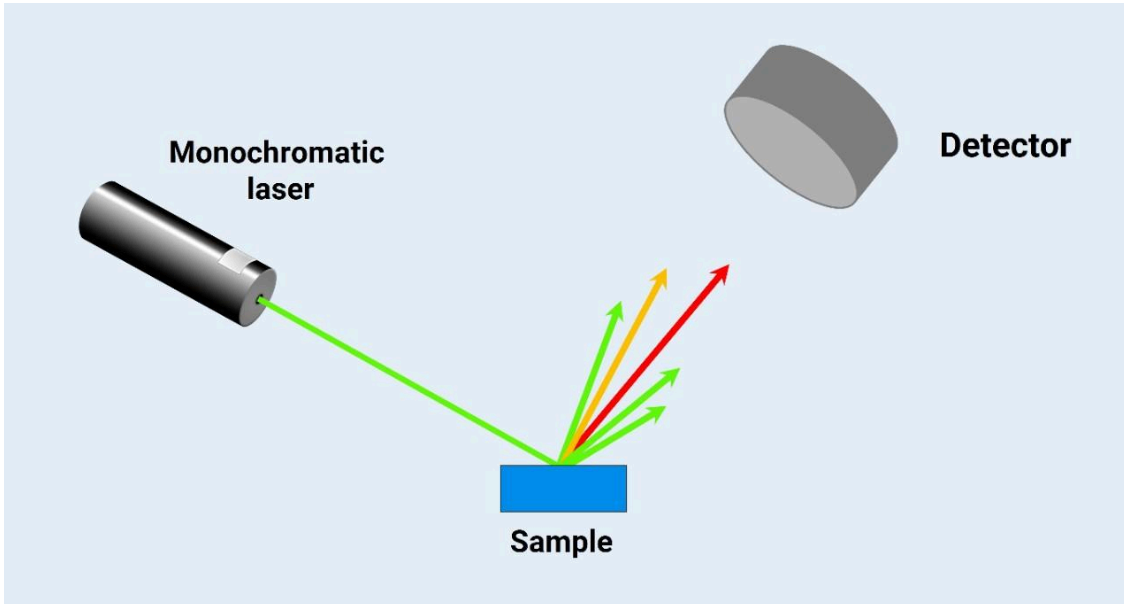


Figure 3.6.4 - Raman Spectra from Raman Spectrometer

We graphically display the results of our Raman spectroscopy measurements as Raman spectra. The y-axis represents the intensity of the scattered light, while the x-axis represents the energy (frequency) of light. We are interested in the shift in frequency of the Raman-scattered light, so we plot the x-axis frequencies relative to that of the laser. We label the x-axis as the Raman shift (shown by the units cm-1).
The frequencies of vibration depend on the masses of the atoms involved and the strength of the bonds between them. Heavy atoms and weak bonds have low Raman shifts. Light atoms and strong bonds have high Raman shifts.

In the polystyrene spectrum, we see the high frequency carbon-hydrogen (C-H) vibrations at about 3000 cm-1. The low frequency carbon-carbon (C-C) vibrations are at around 800 cm-1. The C-H vibrations have a higher frequency than the C-C vibrations because hydrogen is lighter than carbon.
Similarly, we see the vibrations of two carbon atoms linked by strong double bonds (C=C) at around 1600 cm-1. This is at a higher frequency than two carbon atoms linked by a weaker single bond (C-C, 800 cm-1). You can use these simple rules to explain many of the features of Raman spectra.

4. Mission Risk Management

4.1. Safety and Hazard Overview

Mission safety and risk minimization are fundamental to achieving success and form the backbone of every phase of the mission lifecycle. The comprehensive identification of risks and the implementation of corresponding mitigation strategies influence every aspect of design, development, and operational execution. This approach ensures that potential risks are detected early and addressed effectively using proper mitigation strategies, safeguarding critical mission objectives and increasing the likelihood of success.

A holistic and structured approach is employed to identify, analyze, and manage risks. This process begins with a detailed breakdown of subsystems and their components to identify potential failure modes. Each failure mode is then analyzed for its likelihood and impact on the mission. By understanding how risks propagate through the system, the team is better equipped to design targeted mitigation strategies that address vulnerabilities while maintaining the mission's operational and financial constraints. While lower-cost missions may carry higher risks due to the demonstration of new technologies, it is important that risks related to critical areas are mitigated effectively to avoid mission failure.

Methods such as Risk-Informed Decision Making (RIDM) and Critical Risk Management (CRM) are utilized to ensure that decisions are based on a thorough understanding of risk factors. RIDM enables the team to make well-informed judgments about the mission's design by evaluating the strengths and trade-offs between candidate components, considering potential risks, and determining how these risks can be mitigated within the available resources. This approach ensures that all options are assessed carefully, allowing for decisions that optimize mission success. CRM, on the other hand, focuses on identifying and managing the most critical risks that could jeopardize the mission's success. It ensures that these high-priority risks are addressed with appropriate resources and attention. By applying both of these approaches, the team ensures that critical risks are effectively identified, prioritized, and managed in line with mission objectives

The team uses tools such as Failure Mode and Effects Analysis (FMEA) to assess the potential consequences of identified risks and develop appropriate strategies to reduce or eliminate them. FMEA enables the systematic evaluation of the consequences of identified risks, prioritizing them based on their severity, and formulating effective mitigation plans. This approach ensures that risk management is not static, but rather dynamic, with continuous updates throughout the mission lifecycle to adapt to evolving challenges and technologies. Regular risk reviews are conducted and updates are made to existing risk assessments to better suit the evolving nature of risks. This adaptability allows the mission to remain robust against uncertainties and unforeseen circumstances. Residual risks are continuously monitored to ensure they align with the mission's overall risk tolerance, maintaining a controlled and predictable risk posture throughout the lifecycle.

While the Moon falls under Category II of the Committee on Space Research (COSPAR) planetary protection guidelines, indicating a low potential for biological contamination, the mission does not involve activities that present specific planetary protection concerns. Nonetheless, the team adheres to international standards for planetary protection to demonstrate responsibility in space exploration. These considerations include ensuring compliance with guidelines that support the integrity of future missions and preserve the Moon's environment for scientific study.

By integrating safety and risk minimization into every aspect of the mission, the team ensures a robust, reliable design that can adapt to challenges and maintain alignment with mission objectives. This comprehensive approach strengthens confidence in the mission's outcomes, minimizes the potential for failure, and upholds the principles of responsible exploration.

4.2. Risk Analysis

Mission safety and risk minimization are essential to achieving success and they are carefully incorporated into each phase of the mission lifecycle. Through a methodical approach, the team identifies, analyzes, and mitigates risks, ensuring that potential challenges are addressed proactively. This strategy not only protects the mission's objectives but also establishes a strong foundation for both design integrity and operational reliability.

A key methodology guiding the risk management process is Risk-Informed Decision Making (RIDM). This approach incorporates risk considerations into decision-making processes, particularly during the mission design and planning phases. By evaluating potential outcomes and their associated uncertainties, RIDM enables the team to prioritize risks based on their impact and likelihood, ensuring that resources are allocated efficiently to mitigate critical risks. For instance, trade studies were conducted to compare design options by weighing their risks, costs, and benefits. This process ensured that subsystems and components offering the best balance of reliability and innovation were selected. With the incorporation of this approach, all design and operational decisions were informed by a thorough understanding of the risks involved, enabling the selection of reliable choices that are aligned with the mission objectives.

Continuous Risk Management (CRM) is another methodology that is employed for the purposes of efficient risk management. It provides an iterative framework for managing risks throughout the mission lifecycle. CRM emphasizes ongoing monitoring and reassessment of risks as new information emerges or the mission progresses through different phases. The team utilized a variety of tools and methodologies to support the comprehensive risk analysis process. Tools such as Failure Mode and Effects Analysis (FMEA) were employed to understand the severity and potential consequences of each risk. TRL assessments pinpointed technology gaps, informing decisions about additional testing or development. Historical data from heritage systems and analogous missions provided valuable insights into known risks and effective mitigation strategies. Another important tool used to identify and manage risk was the Risk Matrix. Trigger questions were asked to identify risks and upon their identification, they were categorized on how likely they were to occur and their consequences. Proactive strategies, including micrometeoroid shielding, active thermal management systems, and radiation-hardened components, were developed to mitigate environmental hazards. Risks were continuously monitored, classified as increasing, decreasing, or stable, and reviewed regularly to ensure residual risks remained within acceptable levels. This iterative nature of CRM aids in the adaptability of the mission during adverse situations as the team can adapt to emerging challenges and refine mitigation strategies dynamically.

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Mechanical	2	5	↓	M	Since micrometeoroid strikes could impact the rover, there is a possibility of micrometeoroid strikes impacting the rover, which can lead to failures in the critical systems. This can lead to system failure and jeopardize the mission's success.	**Active**
2	Mechanical	4	4	↓	M	Since there are extreme temperatures on the lunar surface, this can lead to continuous thermal expansion and contradiction affecting the structural and joint integrity. This can lead to mechanical stress and degradation over time, thus resulting in possible structural failure and impairing the rover's function.	**Active**
3	Power	3	5	↓	M	Bearing in mind there are extreme temperatures on the lunar surface, there is a chance that these temperatures may fall outside the operational range for lithium-ion batteries, which can result in reduced energy storage efficiency and potential battery damage. This failure can lead to a loss of	**Active**

						reliable power for critical rover systems.	
4	Power	3	4	↓	M	Given the abundance of lunar regolith, it can accumulate on the rover, obstructing solar panels from receiving sunlight, reducing the effectiveness of the power generation system and limiting the available power for the rover's operations and possibly causing mission interruptions.	**Active**
5	CDH	3	3	↓	M	Taking into account the moon has no atmosphere, which allows for high levels of solar and cosmic radiation, radio signals may be disrupted. This could result in communication blackouts with the Lunar Reconnaissance Orbiter, which would fail to send back scientific data to Earth.	**Active**
6	CDH	2	5	↓	M	Since the rover’s CDH subsystem lacks failback protocols, the rover may be unable to revert to safe modes during critical system failures, preventing the CDH subsystem from maintaining operational integrity. This will compromise the rover’s safety and risk mission failure.	**Active**
7	Thermal	2	5	↓	M	Given the moon's extreme temperature on the lunar surface, it is a possibility that the thermal system may fail to maintain a stable internal temperature, leading to critical components experiencing temperatures beyond their operational range, leading to total system failure.	**Active**
8	Thermal	3	5	↓	M	Due to the moon's lack of an atmosphere, heat dissipation may occur, leading to a severe decrease in the internal subsystem's temperature in regions of no light and overheating when in direct sunlight. This can ultimately lead to total system failure and the mission's failure.	**Active**
9	Instrumentation	3	3	↓	M	Considering that the rover will be maneuvering through caves on the lunar surface, signals may be obstructed as the antennas are not in a clear line of sight of the base. This could lead to communication blackouts, which would prevent the transfer of scientific data to the home base and the conduct of proper scientific goals.	**Active**

10	Instrumentation	2	4	↓	M	Given the structure of the lunar regolith comes with the possibility that sensitive components like lenses and other exposed parts may be damaged over time, leading to degradation in instrumentation functionality, this will impact the quality and longevity of the collected data and sensor performance.	**Active**
11	Programmatics	3	4	↓	M	Given the complex and interdependent nature of testing and integration activities, there may be delays in meeting critical milestones, which could potentially impact the overall mission timeline and lead to missed launch windows and increased costs.	**Active**
12	Programmatics	2	3	→	M	In case of the stringent planetary protection policies to prevent biological contamination, inadequacies in early integration of compliance requirements may later on result in non-compliance leading to regulatory delays or restrictions on mission execution.	**Active**
13	Programmatics	3	4	↑	M	Reliance on a global supply chain for mission-critical materials may cause disruptions due to unforeseen circumstances such as geopolitical issues, material shortages, or logistical delays, disrupting the proper flow of the mission schedule due to shortage of necessary materials.	**Active**
14	Programmatics	2	2	↓	M	Given the high demand for skilled professionals in engineering and related fields, there may be skill gaps, high turnover, or insufficient workforce that could impact project continuity and knowledge retention, delaying in meeting technical and operational goals.	**Active**

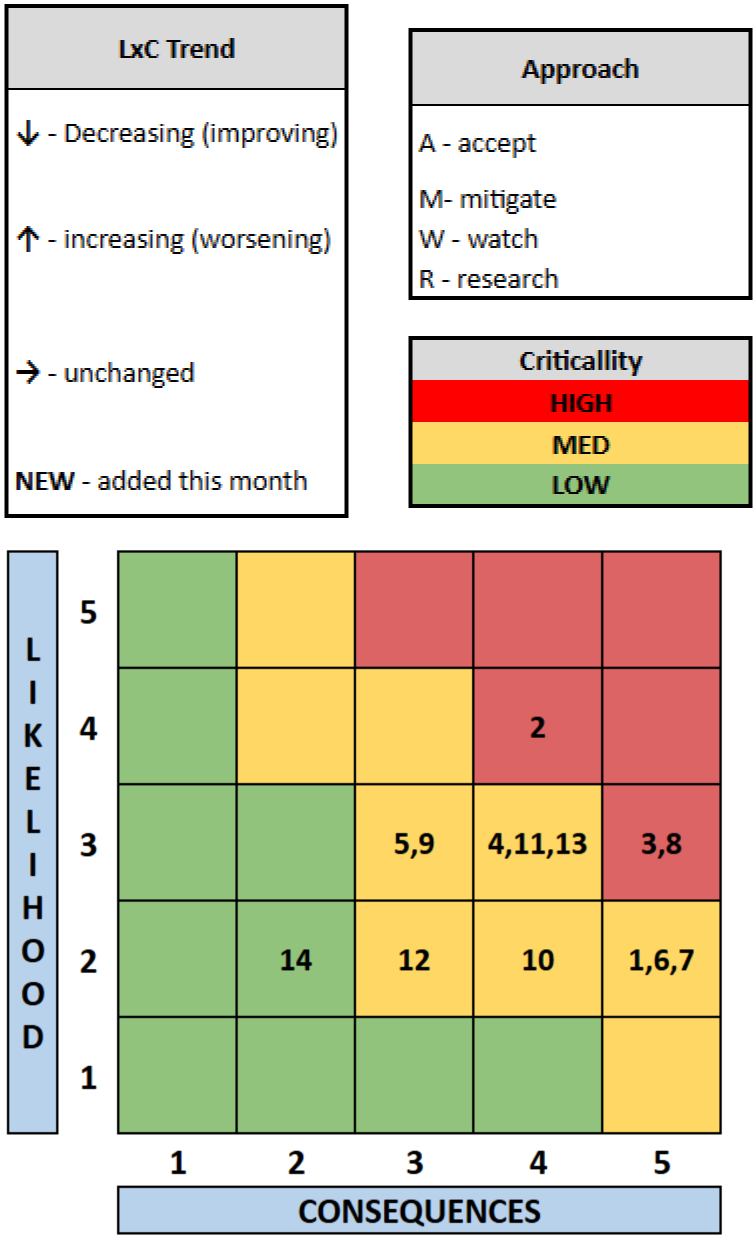


Figure 4.1 Risk Matrix

One vital aspect that the team observed was that the moon's atmosphere posed a hazard to several subsystems of the rover which the team directed their focus on. The lack of an atmosphere results in extreme temperature fluctuations with intense heat in sunlight and freezing conditions in the shadows, this poses a significant challenge to the rover's operations. Additionally, the absence of an atmosphere leaves the rover vulnerable to micrometeoroid impacts, which threaten its structural integrity and overall mission success. Finally, exposure to high levels of solar and cosmic radiation presents a persistent risk potentially disrupting operations and affecting sensitive systems. These environmental hazards remain a central focus.

For the mechanical subsystems, a risk is that micrometeoroid strikes could impact the rover, there is a possibility of micrometeoroid strikes impacting the rover, which can lead to failures in the critical systems. This can lead to system failure and jeopardize the mission's success. To address this risk, the team has incorporated micrometeoroid shielding into the rover's design. Ongoing testing is being conducted to evaluate the effectiveness of these protective measures. Another risk is since there are extreme temperatures on the lunar surface, this can lead to continuous thermal expansion and contradiction affecting the structural and joint integrity. This can lead to mechanical stress and degradation over time, thus resulting in possible structural failure and impairing the rover's function. To mitigate this, the team is exploring the use of materials with high thermal tolerance and flexible joint designs.

For the power subsystems, since there are extreme temperatures on the lunar surface, there is a chance that these temperatures may fall outside the operational range for lithium-ion batteries, which can result in reduced energy storage efficiency and potential battery damage. This failure can lead to a loss of reliable power for critical rover systems. To address this, the team has researched the use of thermal insulation and active thermal management systems to stabilize lithium-ion batteries under extreme lunar conditions. Additionally, the abundance of lunar regolith can lead to dust accumulation obstructing solar panels from receiving sunlight. This reduces the effectiveness of the power generation system, limiting the available power for the rover's operations and possibly causing mission interruptions. To mitigate this, the team has researched resistant coatings using electrostatic technologies to repel lunar dust from solar panel surfaces.

For the thermal subsystems, a lack of an atmosphere indicates that heat dissipation may occur, leading to a severe decrease in the internal subsystem's temperature in regions of no light and overheating when in direct sunlight. This can ultimately lead to total system failure and the mission's failure. Additionally, the extreme temperatures on the lunar surface can lead to a possibility that the thermal system may fail to maintain a stable internal temperature, leading to critical components experiencing temperatures beyond their operational range. This can lead to total system failure due to the extreme temperatures on the lunar surface. To address these risks, the team has researched active thermal management systems to dissipate heat effectively in sunlight and maintain internal temperatures in cold regions. These systems include phase-change materials which absorb and release heat to stabilize the rover's internal environment.

For the CDH subsystem, given that the moon has no atmosphere, which allows for high levels of solar and cosmic radiation, radio signals may be disrupted. This could result in communication blackouts with the Lunar Reconnaissance Orbiter, which would fail to send back scientific data to Earth. To mitigate this, the team has conducted research exploring the use of radiation-hardened components, which protect electronic systems from radiation effects and improve operational resilience. In addition, since the rover's CDH subsystem lacks failback protocols, the rover may be unable to revert to safe modes during critical system failures, preventing the CH subsystem from maintaining operational integrity. This will compromise the rover's safety and risk mission failure. To address this, robust fail-safe software designs and testing procedures are being implemented to ensure the system can maintain operational integrity.

For the instrumentation, given that the rover will be maneuvering through caves on the lunar surface, signals may be obstructed as the antennas are not in a clear line of sight of the base. This could lead to communication blackouts, which would prevent the transfer of scientific data to the home base and the conduct of proper scientific goals. To mitigate this, solutions like omnidirectional antennas and signal relay stations have been explored to maintain consistent communication throughout the mission. Furthermore, the structure of the lunar regolith comes with the possibility that sensitive components like lenses and other exposed parts may be damaged over time, leading to degradation in instrumentation functionality, this will impact the quality and longevity of the collected data and sensor performance. Protective measures like dust-repellent technologies, have been developed to shield instrumentation from lunar regolith exposure and maintain operational efficiency.

The success of the lunar mission depends on several programmatic aspects including schedule delays, budget overruns, supply chain interruptions, compliance with planetary protection policies, personnel risks as well as operational readiness issues. Given the complex and interdependent nature of testing and integration activities, there may be delays in meeting critical milestones, which could potentially impact the overall mission timeline. This might also lead to missed launch windows and increased costs. This risk can be mitigated by efficiently utilizing schedule management tools and contingency plans to create a robust schedule that takes into account reasonable marginal periods, ensuring the conformance to the tight schedule. In case of the stringent planetary protection policies to prevent biological contamination, inadequacies in early integration of compliance requirements may later on result in non-compliance leading to regulatory delays or restrictions on mission execution. Integrating planetary protection requirements at the project's outset, documenting compliance efforts thoroughly, and performing regular audits can be helpful in mitigating this risk. The uncertainty in cost estimation for lunar mission components may cause a risk of exceeding the allocated budget, and could potentially require scoping down or additional funding to maintain mission goals. Utilizing advanced cost modeling tools, establishing a reserve budget for unforeseen expenses, and conducting periodic financial reviews to ensure alignment with projections are ways this risk can be minimized. Reliance on a global supply chain for mission-critical materials may cause disruptions due to unforeseen circumstances such as geopolitical issues, material shortages, or logistical delays. This could disrupt the proper flow of the mission schedule due to shortage of necessary materials. A mitigation strategy that can be employed to counter this risk is to establish supplier redundancies, and closely monitor the real-time status of the supply chain. Given the high demand for skilled professionals in engineering and related fields, there may be skill gaps, high turnover, or insufficient workforce, that could impact project continuity and knowledge retention. This might cause delays in meeting technical and operational goals. Actively recruiting skilled candidates and implementing comprehensive training programs and cross-training to ensure role redundancy are ways to minimize the impact of turnover. The cutting-edge nature of technologies employed in the lunar mission, might suffer from inadequate readiness or there are chances that unproven systems may fail in critical environments. This could compromise mission components' functionality and jeopardize mission success and safety. This risk can be mitigated by conducting thorough testing in simulated and operational environments to validate all systems, employing iterative design improvements based on test outcomes, and engaging with experts to identify potential failure points early in development.

4.3. Failure Mode and Effect Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) is a systematic, structured approach that is used to identify, assess, and prioritize potential risks throughout the mission. It enables the team to evaluate the impact of possible failures within each subsystem, understand their potential consequences, and establish mitigation strategies. This analysis not only helps identify risks but also quantifies their severity, likelihood of occurrence, and detectability, providing a clear framework for prioritizing resources and efforts based on the most critical risks. The FMEA process begins by breaking down each subsystem involved in the mission, including power, communication, thermal, mechanical, and instrumentation systems. Potential failure modes are identified in each subsystem, such as hardware malfunctions, environmental stresses, or operational errors. After identifying the failure modes, factors such as the severity (Sev), the likelihood of their occurrence (Occ), and how easily they can be detected (Det) are evaluated. These three factors are combined to calculate the Risk Priority Number (RPN), which is used to prioritize risks according to their potential impact. The value of FMEA is not limited to identifying failure modes, but also lies in understanding how each failure could potentially impact the entire mission. FMEA allows the team to anticipate these kinds of failure scenarios and implement appropriate safeguards early on. This proactive approach helps ensure that weaknesses in the system are addressed before they can manifest as problems during the mission. By focusing on failure modes with high RPN values, resources can be allocated efficiently. By addressing high-priority risks in advance, the overall resilience of the mission and the reliability of subsystems can be improved.

FMEA is an iterative process that evolves throughout the mission's lifecycle. As new data is gathered through testing, or if mission parameters change, the FMEA analysis is revisited to reassess risks and adjust mitigation strategies. This iterative nature ensures that risks are continuously managed and that mitigation strategies are up-to-date. New failure modes or emerging risks can be incorporated into the analysis to prevent any surprises as the mission progresses. Throughout the mission, FMEA acts as a critical tool of risk management, guiding decisions about which failure modes need the most attention. It drives the development of solutions that address the highest risks first, ensuring that the mission remains safe and functional even in the face of uncertainties. This organized and iterative approach strengthens confidence in the design by continuously identifying and addressing associated risks through mitigation strategies, thereby ensuring the overall safety and success of the mission.

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
	Dust Accumulation on solar panels	Reduced power generation, limiting rover operations potentially causing mission failure	85	Lunar regolith dust buildup blocking sunlight	70	Use dust-resistant coatings	40	238000	Develop redundancy with backup power sources

Power subsystem

	Extreme lunar temperature variation	Battery damage or reduced efficiency, risking power loss to critical systems	90	Temperature extremes beyond lithium-ion battery capabilities	65	Implement thermal management systems; use temperature-resistant battery materials	50	292500	Employ additional thermal protection and battery insulation
	Disruption in communication signals	Communication blackout, loss of data transfer, compromising mission objectives	80	High levels of solar and cosmic radiation on the lunar surface	70	Use radiation-hardened components and establish redundant communication pathways	50	280000	Develop autonomous fallback data storage protocols
CDH subsystem	Lack of failback protocols for critical systems	Inability to revert to safe modes during system failure, risking full system blackout	90	There are no failback protocols in the software design	50	Design robust failback protocols and conduct testing	40	180000	Include redundant systems and safe mode activation procedures
	Overheating in direct sunlight	Components exceed operational temperature limits, causing system shutdown or permanent damage	85	Lack of an atmosphere for heat dissipation	60	Use active thermal management systems, reflective coatings, and heat shields	40	204000	Add heat-resistant materials and emergency cooling systems

Thermal subsystem

	Freezing in shadowed areas	Internal subsystems freeze, reducing functionality and risking total mission failure	90	Prolonged exposure to extreme cold on the dark side of the moon	70	Insulate critical components, including heaters for low-temperature conditions	50	315000	Develop redundancy in thermal systems and pre-program fail-safes
	The thermal system fails to stabilize the internal temperature	Components fail to operate potentially leading to mission failure	95	Extreme temperature fluctuations on the lunar surface	50	Design systems with high thermal tolerance, conduct rigorous environmental testing	45	213750	Include backup thermal regulation mechanisms and alarms
	Structural failure due to micrometeoroid strikes	Damage to structural integrity, risking rover mobility and mission-critical components	85	Micrometeoroid impacts damaging critical structures	70	Use micrometeoroid shielding and redundant structural supports	40	238000	Develop self-repair mechanisms or contingency plans for mobility failures
Mechanical Subsystem	Degradation from thermal expansion and contraction	Joint and structural weakening over time, impairing mobility or mechanical function	90	Exposure to extreme lunar temperature fluctuations	60	Use materials with high thermal tolerance and flexible joint designs	50	270000	Include regular diagnostics for wear and tear, design replaceable joints
	Signal obstruction in lunar caves	Loss of communication with the base, preventing data transfer	80	Antennas not in the clear light of sight to the base	70	Use omnidirectional antennas or signal relay stations	50	280000	Develop autonomous data storage and delayed transfer protocols

Instrumentation

	Damage to sensitive components from lunar regolith	Degradation in sensor functionality, lowering data quality and lifespan	85	Abrasive lunar regolith damaging lenses and exposed parts	65	Use protective covers and robust materials	45	248625	Enhance protective casing

4.4. Personnel Hazards and Mitigations

Machining hazards include risks including injuries from handling sharp tools, eye injuries from debris during some stages of manufacturing such as cutting, drilling or grinding materials as well as those caused by improper handling of machinery. Additionally burns can occur from contact with heated tools or equipment, and component malfunctions such as overheating can pose further risks to personnel. Mitigating such risks would include steps such as providing proper training on machine operation, regular safety inspections on machinery, and enforcing the use of personal protective equipment such as safety goggles and gloves. Adherence to OSHA standards will be maintained to ensure a safe working environment, including the provision of proper machine safeguards and compliance with OSHA's General Industry Standards (29 CFR 1910).

Electrical hazards include risks such as electric shocks, burns, or electrocution caused by contact with live circuits, faulty wiring, or improperly grounded equipment. Short circuits or equipment failures can lead to sparks, fires, or explosions, while static discharge in sensitive environments may damage components or injure personnel. To mitigate these risks, it is important to ensure proper grounding and insulation of electrical systems, enforce lockout/tagout (LOTO) procedures during maintenance, and provide training on safe handling of electrical equipment. Regular inspections, the use of insulated tools, and compliance with electrical safety standards, including those established by OSHA (such as 29 CFR 1910.303 for electrical systems), will further minimize the risk of injury or equipment damage.

Chemical hazards consist of risks from exposure to hazardous substances such as solvents, adhesives, cleaning agents, or other chemicals used in the manufacturing processes of mission components. These can cause skin irritation, burns, respiratory issues, or long-term health effects if inhaled, ingested, or absorbed. Improper storage or handling of chemicals can also lead to spills, leaks, or cause reactions that pose threats to safety of personnel. To mitigate these hazards, proper storage of all chemicals should be ensured where every chemical is labeled, provide access to Material Safety Data Sheets (MSDS), and enforce the use of personal protective equipment such as gloves, goggles, and respirators. Regular training on safe chemical handling, spill response protocols, and the use of ventilation systems to reduce fume exposure are essential to maintaining a safe environment. Compliance with OSHA standards for hazardous chemicals (29 CFR 1910.1200, Hazard Communication) will also be enforced.

Biological hazards consist of risks due to exposure to harmful biological agents, harmful microorganisms, or allergens that can cause infections, allergic reactions, or other health issues. In shared workspaces, the spread of illnesses and contagious diseases can occur at a fast rate and thereby threaten the safety of the rest of the personnel. Poor hygiene practices, improper sanitation and inadequate ventilation are some factors that increase biological risks. Minimizing these biological hazards would include taking proper steps to ensure high workplace hygiene standards, supplying sufficient sanitation equipment, and imposing strict protocols for proper handling of biological materials. Adherence to OSHA regulations for workplace sanitation and cleanliness (29 CFR 1910.141) will be prioritized.

Testing hazards involve risks associated with the operation of equipment or systems under extreme conditions during the testing phase. These include exposure to high pressures, extreme temperatures, electrical malfunctions, or the release of hazardous gasses or fluids from equipment failures. For instance, testing pressurized systems can lead to explosions or leaks, while high-temperature tests may cause burns or heat exhaustion. Additionally, electrical testing could result in shocks or fires, and malfunctioning components can cause physical injuries. To mitigate these risks, testing should be conducted in controlled environments with proper safety protocols in place, such as pressure relief valves, protective barriers, and emergency shutdown systems. Personnel should wear appropriate personal protective equipment such as flame-resistant clothing, gloves, and goggles. Regular maintenance and pre-test checks of equipment are also very important, along with setting clear communication of hazards and emergency response procedures to all involved personnel. Compliance with OSHA standards related to industrial safety (29 CFR 1910.147, Control of Hazardous Energy) will be enforced during testing operations.

Fire hazards include the risk of fires or explosions from handling flammable materials, faulty electrical systems, or overheating equipment. Flammable substances like solvents and oils can ignite easily, and electrical malfunctions may spark fires. To mitigate these risks, flammable materials should be stored properly, equipment checks should be conducted regularly, and fire safety protocols should be prioritized. Ensuring proper supply of fire extinguishers and suppression systems at considerable distances across facilities, setting clear evacuation routes, and conducting fire drills to prepare personnel for emergencies are also steps to handle sudden explosions. OSHA guidelines for fire safety (29 CFR 1910.38, Emergency Plans) will be followed, and personnel will be trained in fire prevention and response.

Noise hazards occur when employees are exposed to loud machinery or equipment, which can lead to hearing loss or damage over time. Prolonged exposure to high noise levels can also cause stress and fatigue, impacting overall well-being. To mitigate these risks, it is important to provide hearing protection such as earplugs or earmuffs, and implement noise-reducing measures like soundproofing or barriers around noisy equipment. Regular monitoring of noise levels and limiting exposure times can also be helpful ways to protect personnel against potential hearing damages. OSHA noise regulations (29 CFR 1910.95, Occupational Noise Exposure) will be adhered to, including monitoring noise levels and providing hearing protection where necessary.

Lab hazards are a combination of the above mentioned risks such as exposure to hazardous chemicals, electrical accidents, fires, or injuries from equipment like centrifuges, lasers, or high-pressure systems. There is also a risk of contamination from biological agents or improper disposal of hazardous waste. Some ways to mitigate these risks include ensuring proper lab safety protocols, strictly using personal protective equipment before performing any operation or experiment in the lab, and constructing appropriate ventilation systems. Regular safety inspections and maintaining clean and organized lab spaces further reduce potential lab hazards. Compliance with OSHA lab safety standards (29 CFR 1910.1450, Occupational Safety and Health Administration for Laboratories) will be ensured.

Ergonomic Hazards involve risks arising from poorly designed workstations, repetitive tasks, or improper posture, leading to musculoskeletal disorders such as back or joint pain. These hazards can also cause long-term injuries from continuous physical strain. To mitigate these risks, it is important to conduct ergonomic assessments of workspaces to ensure they are designed for maximum comfort and safety. Personnel should receive training on proper posture and lifting techniques Workstations are needed to be adjusted to suit individual personnel needs. Breaks in between tasks are also instrumental in reducing physical strain, and tasks will be rotated to prevent repetitive motion injuries. Compliance with OSHA ergonomic standards (29 CFR 1910.900, Ergonomics) will be ensured to reduce the risk of musculoskeletal disorders.

Psychosocial Hazards include risks associated with work-related stress, team dynamics, long working hours, or high-pressure environments that can negatively affect mental health, job satisfaction, and overall performance of personnel. These factors can lead to burnout, anxiety, or depression, which can affect both individual and team performance. To mitigate these hazards, it is crucial to maintain a supportive work environment with open channels of communication between personnel and management. Implementing workload management practices and conducting regular assessments of stress levels are also helpful in supporting the mental health of personnel. Additionally, stress management programs, counseling services, and team-building activities should be offered to promote mental well-being and maintain a healthy work-life balance. Compliance with OSHA standards related to workplace stress and mental health (29 CFR 1910.1000, Occupational Health) will be followed to ensure the psychosocial safety of employees.

5. Activity Plan

5.1. Project Management Approach

Aside from the Academy team, around 40-50 personnel will be needed in order to accomplish the full scope of the mission. These personnel will be divided into sub-teams, which includes the science personnel, engineering personnel, technicians, operations personnel, and project management personnel. By adding in these additional team members beyond the direct Academy team, the mission will have a robust set of team members that is capable of covering the entire scope of the mission's tasks and goals.

The science personnel sub-team, composed of both scientists and researchers, will be responsible for the mission's science objectives. Science personnel will play a role in conducting the scientific research that drives the vehicle design for the mission, defining and refining the instrumentation requirements, and analyzing the mission data once data collection has begun. Due to the foundational nature of the work that the science team completes, science personnel are required to be skillful in research, design, and any specialized subject matter that is relevant to the mission. This subject matter can include lunar geology, mineralogy, astrobiology, and expertise on in-situ resources. Within this sub-team, each of the four science instruments will have two designated scientists that will act as instrument specialists and are responsible for the research, design, and implementation of said instrument. While these scientist pairs have autonomy over decision making regarding their instrument, these decisions must ultimately be analyzed and approved by the science team lead in order to ensure accuracy and accountability. All science personnel must be willing to collaborate closely with the engineering personnel sub-team in order to ensure that the rover's design is optimized for lunar environmental conditions and that the design is on track to complete the proposed science objectives.

The engineering personnel sub-team will be responsible for the technical implementation of the lunar rover and its systems. Engineering personnel will be responsible for designing the rover's subsystems, ensuring that each subsystem is integrated seamlessly into the vehicle while meeting performance criteria and mission constraints. All engineers are required to possess skills in subsystem design, development, and integration in order to ensure that all subsystems are correctly meeting the requirements established by the mission task. Individuals on the engineering sub-team will be further divided into groups based on these subsystems, which includes mechanical, electrical, thermal, power, and CDH subsystems. The total number of individuals divided into each subsystem group will be determined by their level of experience with each subsystem, and the proper individuals will be allocated into the correct group that properly aligns with their skill level. Each subsystem group will have substantial autonomy over the design and implementation of their subsystem, but they will be responsible to report these decisions to the engineering team leader and must apply any feedback or decisional changes at the discretion of this team leader.

The technician sub-team will be responsible for testing and maintaining the lunar rover that is completing the mission's tasks Technicians play a crucial role in analyzing the work of both the science and engineering sub-teams by troubleshooting any issues that arise with the equipment and ensuring that each subsystem functions properly while adhering to the mission's requirements and constraints. Technician tasks may include subsystem assembly, instrument calibration, rigorous testing, quality assurance, launch support, documentation, and troubleshooting. Each technician will have an instrument or subsystem that they will specialize in as a way to assure that all aspects of the vehicle are compliant and adhere to the mission's tasks, goals, requirements, and constraints. All technicians will report their work to the technician team lead in order to ensure that all instruments and systems are accounted for and functioning properly. Technicians will also report to the scientists and engineers that worked on the instruments and systems so that the relevant sub-teams can either have a confirmation of the successful design or description of any issues that arose during task completion, that the sub-teams can then address and solve.

The administration sub-team is responsible for creating the cost and schedule estimates for the mission based on the designs provided by the science and engineering sub-teams. This team will be responsible for analyzing the subsystems and instruments created by these teams and create budget estimates from these designs. If any item goes over budget, the corresponding sub-team will be notified. It will be up to the sub-teams discretion if they would like to redesign the system or request a budget increase. If a budget increase is requested, the programmatics sub-team will approve the request if it is possible to reallocate funds within each team, and deny the request if reallocation is not possible. This team will also be responsible for creating a timeline for the mission based on the mission's tasks and goals. These estimates will ultimately be approved by the project management team. Additional administrative sub-team tasks include administrative tasks and human resources.

The project management team, composed of five people, is responsible for overseeing the mission and managing each sub-team to ensure that all teams are completing work that aligns with the mission's objectives. This team will also be responsible for ensuring that all programmatic requirements are being met, such as ensuring schedule and cost estimates provided by the programmatics sub-team follow the mission's constraints. The project managers will play a role in overseeing cross-team collaboration, ensuring that key points in the mission timeline are being met, allocating team members to the most suitable roles, allocating budget, and mission reporting and analyzing.

All instrument specialists and subsystem experts from the science and engineering sub-teams have autonomy over design and implementation. However, the budget will be controlled and analyzed by the programmatics sub-team that will be responsible for properly allocating funds to each sub-team in order to meet cost constraints while giving each sub-team the resources necessary in order to accomplish their tasks. Each sub-team team leader will be responsible for working with these budget analysts in order to ensure that the systems being designed adhere to these budgets, and advocating for the team if a budget change is necessary within that subteam.

All sub-teams will report to a corresponding team lead. This group of sub-team leads will then ultimately report to the project management team. The project management team holds the highest level of responsibility and approves the decisions of the entire mission team. Each team will have the autonomy to control their designs and decisions, but all decisions will be ultimately approved by the project management team. The following visual displays the organization chart that indicates the flow of reports:

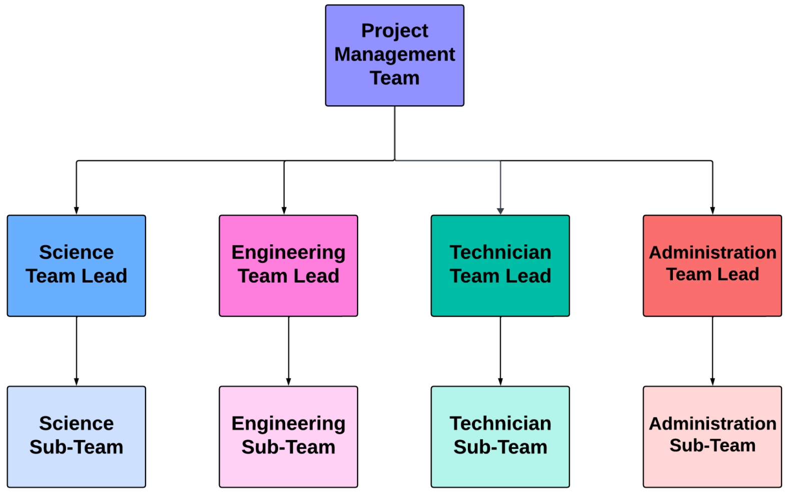


Figure 5.1.1 - Personnel Organization Chart

All sub-teams have a responsibility to communicate between other sub-teams in order to understand the ongoing tasks of the mission. In addition to this regular cross-team communication, the project management team will provide regular updates to the entire team in regards to the mission's progress. This team will make important announcements to the team in order to keep the team aware of major situations, problems, or circumstances.

5.2. Mission Schedule

5.2.1. Schedule Basis of Estimate

Factors determining schedule began primarily with the mission task and constraints listed within the mission task document. Scientific objectives, goals, and areas to be explored on the moon also went into the schedule making process. Each part of the mission requires detailed planning and execution leading to longer time within phases.

This is largely due to the inherent complexity of lunar rover missions, which require in depth testing through the integration of each subsystem. Due to the extreme environments found on the moon and the extreme conditions that our subsystems will need to operate in, extensive testing, in numerous locations, significantly impacts our schedule estimate as testing each individual subsystem across varying test sites is a timely process and one that must be taken into account. Testing includes simulated experiences, such as testing the rover as whole at field sites. Complexity also extends towards personnel, due to the large scope of any NASA mission, multiple differing departments and kinds of personnel may be required to complete a mission. The collaboration between these personnel requires high level coordination between teams. An example of this is the coordination with the launch vehicle as this mission is not the main goal of the launch vehicle that will be sending the rover to the moon. The official launch of the rover must align with that of the launch vehicle, adding another level of complexity. Therefore ensuring that each team is able to accomplish their respective milestones at each juncture is of extreme importance and ensures that the schedule continues to move along as planned. Accounting for all departments and people adds additional time to the schedule in each individual juncture.

Key drivers of schedule estimates also include the adherence to NASA review cycles. In which the mission must continue through Critical Design Review and Mission Readiness review after the Preliminary Design Review. The status of these phases will determine a large part of the overall mission timeline, particularly in the events of failure. Adhering to the NASA review cycles in conjunction with ensuring that each subsystem and department is ready for a review at the scheduled time further drives the schedule estimate.

Current estimates are largely based on previous rover missions, including those on mars and the lunar surface. Specifically Chang'e 4, Mars Explorations Rovers, and Perseverance missions These missions represent successful rover based exploration missions in which operation of the rover on the planetary surface pursued relevant science goals. The schedules of these missions allow us to have a strong basis off where to start and ensure that the provided schedule is both reasonable to the team working on the project and the client.

5.2.2. Mission Schedule

The critical path of the mission schedule includes several phases. Including Preliminary Design review, Critical Design Review, and beginning phases of engineering design and testing. This phase will last approximately 24 months, beginning in January of 2025.

The next phase included further testing of system integration, integrity through launch vibration testing, testing of the rover navigational system, and preparations for launch. This phase will last approximately 12 months.

In phase three, further testing will be conducted on the rover and payload to ensure proper integration. This phase will largely consist of launch preparation and testing. Within this time span a launch window will be selected.The next phase will include the trip to the moon, in which checks will be done on the system throughout travel. The final predetermined phase includes landing and the rover's lunar surface activities.

After the rover has completed all predetermined tasks, it will enter its post mission lifecycle. Further scientific data could be collected within this phase if the rover still maintains capabilities until this point.

This schedule estimate part provides a high-level timeline for the lunar rover mission, covering Phases C through F of the NASA project life cycle. Dates are based on estimates drawn from NASA's project management standards, historical mission timelines, and references from the NASA Space Flight Program and Project Management Handbook. This timeline offers a structured schedule, detailing major milestones from Critical Design Review to mission closeout.

Mission Life Cycle Phases and Milestones

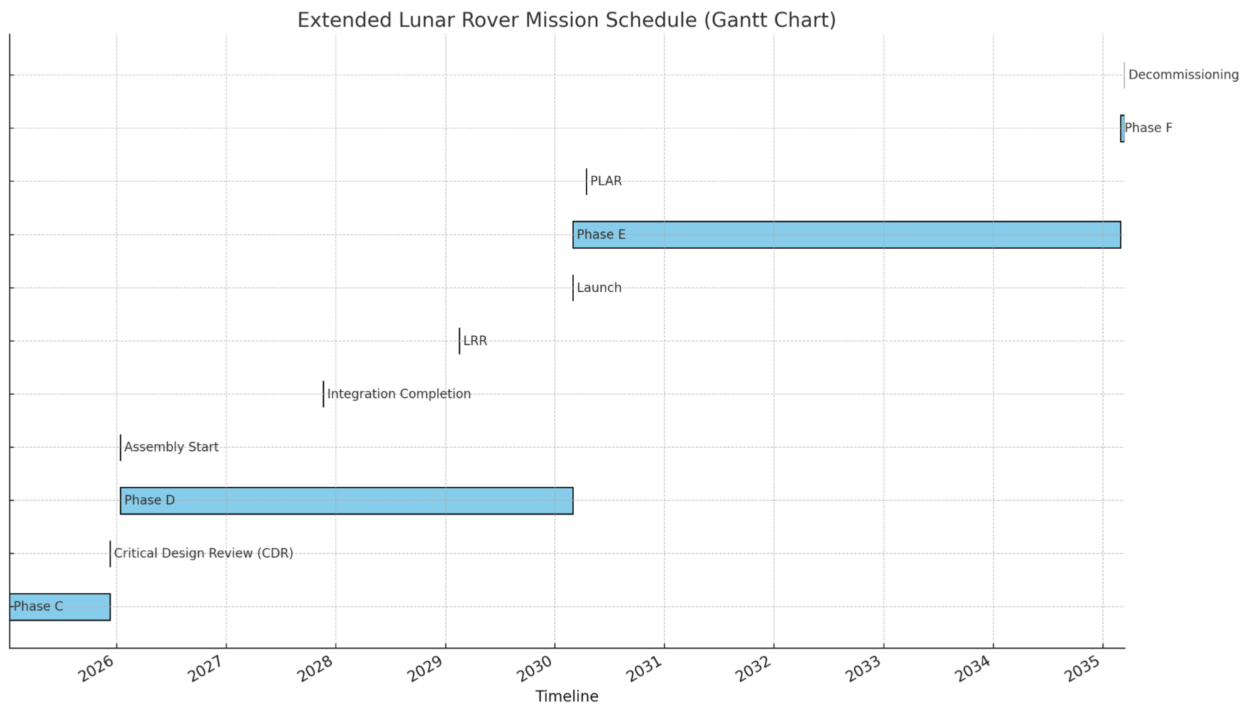
1. **Phase C (Final Design and Fabrication):**
    - **Dates:** January 8, 2025 – December 9, 2025
    - **Source and Reasoning:** *Curiosity* and *Perseverance* had the equivalent of year-long final design periods before moving into assembly to make necessary design refinements. NASA typically holds major design milestones at the end of a calendar year, and the final date for CDR is slated for December 9, 2025.
2. **Phase D (System Assembly, Integration, Testing, and Launch):**
    - **Dates:** January 12, 2026 – March 1, 2030
    - **Source and Reasoning:** System assembly, integration, and testing are based on extended timelines observed in Mars rover missions. *Curiosity* required approximately three years, and *Perseverance* required around three and a half years from assembly start to launch. Here, assembly starts on January 12, 2026, with integration completing by November 20, 2027. The Launch Readiness Review (LRR) occurs on February 15, 2029, aligning with

typical launch readiness timelines. The actual launch date is scheduled for March 1, 2030, allowing for final checks.

3. **Phase E (Operations and Sustainment):**
    - **Dates:** March 1, 2030 (Launch) – March 1, 2035 (Estimated End)
    - **Source and Reasoning:** The operational timeline of the mission is pegged on the operational phases developed for the Lunar Reconnaissance Orbiter and the Mars rovers, each envisioned around five years in length with assessments of performance every six months. Launch will be on March 1, 2030, while landing is expected to be on March 29, 2030. This shall be followed by the Post-Launch Assessment Review, PLAR, on April 15, 2030, to ensure that systems are fully functional. The operational phase is planned to conclude on approximately March 1, 2035, but may be extended depending on the performance of the rover.
4. **Phase F (Closeout):**
    - **Dates:** March 1, 2035 – March 15, 2035
    - **Source and Reasoning:** Assuming from the operation phase, it is estimated that closeout activities, including data archival and decommissioning, will take approximately two weeks. Decommissioning is scheduled on 15th March 2035, following the final system shutdown procedures after the receipt of DRR.

Phase	**Milestone**	**Date**
Phase C	Final Design Start	January 8, 2025
	Critical Design Review (CDR)	December 9, 2025
Phase D	Assembly Start	January 12, 2026
	Integration Complete	November 20, 2027
	Launch Readiness Review (LRR)	February 15, 2029
	Launch	March 1, 2030

Phase E	Lunar Arrival	March 28, 2030
	Entry, Descent, & Landing (EDL)	March 29, 2030
	Post-Launch Assessment Review (PLAR)	April 15, 2030
Phase F	Start of Closeout	March 1, 2035
	Decommissioning Readiness Review (DRR)	March 15, 2035



Sources and Timeline Justification

1. **NASA Cost Estimating Handbook (CEH)** and **NASA Systems Engineering Handbook (2007)** guided the duration for Phases C and D, ensuring adequate time for design finalization, assembly, and rigorous testing.
2. **Historical Mission Data** from Mars rover projects (*Curiosity* and *Perseverance*) provided benchmarks for final design and integration timelines, adapted here for lunar mission requirements.

3. **NASA Space Flight Program and Project Management Handbook** emphasized key reviews like CDR, LRR, and DRR to ensure quality control and mission readiness before each phase transition.

Each phase's timeline reflects best practices and established NASA standards, with planned reviews to monitor and adjust mission progress. This structure ensures the lunar rover mission advances effectively within budget and meets scientific objectives.

5.3. Budget

5.3.1. Budget Basis of Estimate

The budget formulation for this mission was based on structured ground rules, assumptions, and drivers. Federal standards, historical data, and mission-specific requirements were integrated to establish estimates for transportation, personnel, outreach, and direct costs both accurately and comprehensively. Refinements contained projected inflation rates(The mission budget incorporated a fixed inflation rate of **154.44%** for direct costs, with projected annual rates of **2.6% to 13.0%** over fiscal years 2023–2027, ensuring all estimates account for economic trends and maintain financial stability for manufacturing, testing, transportation, personnel, and outreach activities.) Standardized NASA budgeting models such as the Budget Template, the Mission Concept Cost Estimation Tool (MCCET), and industry benchmarks, aligning the estimates with the mission's goals described in the Mission Task Document.

Transportation

The Transportation budget was developed to support essential mission travel based on GSA and City Pair Program rates. Flights were based on transportation from Newark Liberty International Airport (EWR) to the Cape Canaveral area in Florida, where most of the mission activities occur. Flights from Newark Liberty International Airport (EWR) to Cape Canaveral, Florida, were chosen because of proximity to major NASA facilities supporting the mission. These are in line with the operational and logistical requirements of the mission. Hotel reservations like Homewood Suites by Hilton Cape Canaveral-Cocoa Beach will be grounded on proximity and cost-effectiveness. GSA and City Pair Program standards guided airfare, per diem, and rental transportation estimates. The location supports pre-launch, mission reviews, and critical operational milestones. Hotel reservations were projected based on current rates, utilizing Homewood Suites by Hilton Cape Canaveral-Cocoa Beach for five-day reservations that ensure pre- and post-launch activity coverage. In contrast, per diem rates for meals were estimated to follow GSA guidelines. Local transportation- including estimated Uber or rental services between the airport, hotel, and mission facilities - was calculated based on average area rates to cover all mission-critical travel comprehensively. This structured approach ensures estimates are realistic and compliant with standards and aligned with the mission logistics and operations needs.

Personnel

The personnel costs were estimated based on assumptions regarding competitive industry salaries, benefits, and other employees' related expenses. Based on historical data and projections captured in the NASA Cost Estimating Handbook, this budget used only direct costs with a fixed inflation rate of 154.44%. Other functions required for mission success, such as engineering, science, and project management, were market-priced and inflated over the life of the mission. Additional allowances included overtime when periods of intensity were expected, along with training and morale support; market rate adjustments were projected to be competitive to ensure qualified personnel in key positions were attracted and retained.

Outreach

The Lunar Resource Exploration Festival budget was planned in a structured and research-oriented way that reflects the mission objectives of Team 22: to improve public awareness, STEM education, and diversity for space exploration. The outreach budget of $8 million was distributed based on previous NASA outreach efforts to effectively utilize the resources with consideration for logistics, materials, and technology at each event. Costs associated with hands-on activities such as the Lunar Habitat Design Challenge and mining simulations were estimated based on consultation with mission experts and the integration of educator feedback to ensure alignment with Next-Generation Science Standards. Partnerships with local schools, universities, and underrepresented communities were prioritized to maximize inclusivity and impact. A portion of the budget was used for travel related to guest speakers, teacher training, and virtual streaming platforms to extend the event's reach. The estimated cost of $600,000–$1,300,000 is based on a detailed breakdown of materials, scholarships, and logistical support, using NASA's cost model and tailored adjustments for contingencies. This strategic approach ensures the festival remains engaging, educational, and financially sustainable while achieving the mission outreach goals.

Direct Costs
The direct costs involve mission-critical hardware, software, and test facilities. Estimates were made against establishing reliable frameworks through the MCCET and NASA Instrument Cost Model (NICM), guided by historical data and industry benchmarks. A constant inflation rate of 154.44% was imposed, with forecasted inflation rates of 2.6% to 13.0% for future fiscal years, maintaining financial stability. Primary components, like the power systems of the rover and the GNC subsystems, were estimated with facilities, enhancements, and performance criteria incorporated. Testing and integration processes were prioritized based upon critical mission milestones, where functionality and reliability under lunar environmental stresses—such as extreme temperatures, dust, and radiation—were essential.

Critical assumptions about subsystem mass, power draw, and operational design were developed to create estimates via the MCCET tool. Historical mission data guided these assumptions, refined through iterative research of comparable components. For instance, mass assumptions for the mechanical and thermal systems of the rover considered the specific materials and design tolerances for lunar operations. Power draw estimates were based on anticipated operational loads, considering redundancy and peak usage during high-demand mission phases. Where exact data was unavailable, conservative estimates were applied to account for uncertainties and ensure adequate budget allocation.

"High-priority basis" relates to ensuring that the subsystems are functioning through thorough testing and validation processes. The testing included TVAC, vibration analysis, EMItests, and functional integration trials to simulate the lunar environment and mission conditions. Testing was scheduled early in the development cycle so that emerging issues could be identified and resolved with minimal risk to mission success. Additional emphasis was placed on redundant testing for critical subsystems, such as power and communication systems, to ensure resilience and operability under extreme conditions. These measures underpin the mission's adherence to robustness and operational readiness.

Contingency Additional Assumptions and Planning
In conjunction with the budget categories, fiscal stability, and inflation assumptions were employed to determine and mold the budget planning accordingly. Stabilizing the projected rates across

fiscal years complemented the fixed rate of inflation in this regard toward long-term cost planning. The cost estimates for travel were set according to GSA standards, and each category had integrated contingency buffers to account for uncertainties, thus insulating against unforeseen expenses that would impact mission success.

Budget Reduction and Prioritization
This additional prioritization was needed because the original $425 million budget had to be reduced to $300 million. Outreach activities in this process were aligned and reduced to only the necessary ones, the redundant testing phases were removed, and funding for all core mission elements within direct costs was secured to retain scientific rigor and operations readiness.

5.3.2. Total Mission Cost

Additional Information

	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5	FY 6
Science Personnel:	10	10	10	10	10	10
Engineering Personnel:	20	20	20	20	20	20
Technicians:	8	8	8	8	8	8
Administration Personnel:	5	5	5	5	5	5
Management Personnel:	5	5	5	5	5	5

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Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative Total**
PERSONNEL							
Science Personnel	$ 800,000	$ 820,800	$ 841,600	$ 862,400	$ 883,200	$ 904,000	$ 5,112,000
Engineering Personnel	$ 1,600,000	$ 1,641,600	$ 1,683,200	$ 1,724,800	$ 1,766,400	$ 1,808,000	$ 10,224,000
Technicians	$ 480,000	$ 492,480	$ 504,960	$ 517,440	$ 529,920	$ 542,400	$ 3,067,200
Administration Personnel	$ 300,000	$ 307,800	$ 315,600	$ 323,400	$ 331,200	$ 339,000	$ 1,917,000
Project Management	$ 600,000	$ 615,600	$ 631,200	$ 646,800	$ 662,400	$ 678,000	$ 3,834,000
Total Salaries	$ 3,780,000	$ 3,878,280	$ 3,976,560	$ 4,074,840	$ 4,173,120	$ 4,271,400	**$ 24,154,200**
Total ERE	$ 1,054,998	$ 1,082,428	$ 1,109,858	$ 1,137,288	$ 1,164,718	$ 1,192,148	**$ 6,741,437**
Personnel Margin							$ -
TOTAL PERSONNEL	$ 4,834,998	$ 5,089,686	$ 5,350,912	$ 5,618,674	$ 5,892,973	$ 6,173,809	$ 32,961,052
TRAVEL							
Total Flights Cost	$ 47,196	$ 48,346	$ 16,170	$ 16,530	$ 13,560	$ 14,680	**$ 156,482**
Total Hotel Cost	$ 44,378	$ 45,467	$ 17,787	$ 18,183	$ 9,322	$ 9,798	**$ 144,935**
Total Transportation Cost	$ 4,617	$ 4,729	$ 2,156	$ 2,204	$ 2,712	$ 2,877	**$ 19,295**
Total Per Diem Cost	$ 15,944	$ 16,332	$ 5,950	$ 6,084	$ 5,932	$ 6,328	**$ 56,570**
Travel Margin	$ 8,000	$ 8,500	$ 2,500	$ 2,500	$ 2,000	$ 2,000	**$ 25,500**
Total Travel Costs	$ 120,135	$ 126,582	$ 46,880	$ 49,050	$ 37,013	$ 40,322	**$ 419,982**
OUTREACH							
Total Outreach Materials	$ 41,040	$ 47,475	$ 54,000	$ 60,500	$ 67,500	$ 73,450	**$ 343,965**
Total Outreach Venue Costs	$ 35,910	$ 39,055	$ 43,200	$ 46,200	$ 50,625	$ 53,100	**$ 268,090**
Total Outreach Travel Costs	$ 20,520	$ 23,210	$ 25,920	$ 28,600	$ 31,500	$ 34,050	**$ 163,800**
Total Outreach Services Costs	$ 30,780	$ 33,760	$ 36,720	$ 39,600	$ 42,750	$ 45,200	**$ 228,810**
Total Outreach Personnel Costs	$ 25,650	$ 28,485	$ 31,320	$ 34,100	$ 37,125	$ 39,550	**$ 196,230**
Outreach Margin	$ 5,130	$ 5,805	$ 6,480	$ 6,960	$ 7,875	$ 8,475	**$ 40,725**
Total Outreach Costs	$ 159,030	$ 182,413	$ 207,917	$ 232,805	$ 262,062	$ 286,822	**$ 1,331,049**
DIRECT COSTS							
Mechanical Subsystem	$ 3,060,000	$ 12,400,000	$ 14,960,000	$ 18,750,000	$ 10,880,000	$ 8,110,000	**$ 68,160,000**
Power Subsystem	$ 359,000	$ 1,160,000	$ 1,867,000	$ 2,670,000	$ 1,005,000	$ 347,000	**$ 7,408,000**
Thermal Control Subsystem	$ 2,565,000	$ 2,625,000	$ 2,808,000	$ 2,983,500	$ 3,164,000	$ 2,975,400	**$ 17,120,900**
Comms & Data Handling Subsystem	$ 307,800	$ 315,000	$ 345,600	$ 375,700	$ 395,500	$ 359,100	**$ 2,098,700**
Guidance, Nav, & Control Subsystem	$ 200,000	$ 600,000	$ 1,000,000	$ 1,200,000	$ 650,000	$ 186,000	**$ 3,836,000**
Science Instrumentation	$ 8,000,000	$ 26,400,000	$ 50,400,000	$ 45,600,000	$ 20,000,000	$ 9,600,000	**$ 160,000,000**
Spacecraft Cost Margin	$ 48,000	$ 50,000	$ 520,200	$ 202,040	$ 20,200	$ 202,020	**$ 1,042,460**
Total Spacecraft Direct Costs	$ 14,539,800	$ 44,682,300	$ 75,639,642	$ 77,380,177	$ 39,870,629	$ 24,610,858	**$ 276,723,405**
Manufacturing Facility Cost	$ 360,000	$ 1,710,000	$ 1,710,000	$ 1,710,000	$ 1,750,000	$ 1,755,000	**$ 8,995,000**
Test Facility Cost	$ 480,000	$ 2,280,000	$ 2,285,000	$ 2,180,020	$ 2,340,000	$ 2,405,000	**$ 11,970,020**
Facility Cost Margin	$ 48,000	$ 228,000	$ 230,000	$ 230,400	$ 234,000	$ 245,000	**$ 1,215,400**
Total Facilities Costs	$ 888,000	$ 4,327,668	$ 4,444,700	$ 4,441,813	$ 4,773,696	$ 4,977,650	**$ 23,853,527**
Total Direct Costs	$ 15,427,800	$ 49,009,968	$ 80,084,342	$ 81,821,989	$ 44,644,325	$ 29,588,508	**$ 300,576,931**
Total MTDC	$ 14,539,800	$ 44,682,300	$ 75,639,642	$ 77,380,177	$ 39,870,629	$ 24,610,858	**$ 276,723,405**
FINAL COST CALCULATIONS							
Total F&A	$ 1,449,180	$ 4,463,230	$ 7,511,944	$ 7,717,814	$ 3,985,043	$ 2,440,884	**$ 27,568,094**
Total Projected Cost	$ 21,991,143	$ 58,871,879	$ 93,201,995	$ 95,440,332	$ 54,821,415	$ 38,530,344	**$ 362,857,108**
Total Cost Margin	$ 109,130	$ 292,305	$ 759,180	$ 441,900	$ 264,075	$ 457,495	**$ 2,324,085**
	0.5%	0.5%	0.8%	0.5%	0.5%	1.2%	
Total Project Cost	$ 21,991,143	$ 58,871,879	$ 93,201,995	$ 95,440,332	$ 54,821,415	$ 38,530,344	**$ 362,857,108**

Figure 5.3.2.1 - Total Mission Cost Table

The comprehensive budget for this mission has been diligently developed using standard industry methodologies in keeping with federal cost-estimating guidelines and mission-specific requirements to realize a robust and actionable financial plan. Key resources drawn upon include the NASA Cost Estimating Handbook (2015), the Mission Concept Cost Estimation Tool (MCCET), and the NASA Budget Template, which all provide detailed frameworks to determine cost allocations across personnel, outreach, and direct mission components. Additional insights were derived from NASA Systems Engineering Handbook 2007 and NASA Financial Management Manual 2022, which helped shape the procedural guidelines and follow the standards.

This budget represents a carefully crafted financial strategy encompassing all direct and indirect costs necessary to achieve mission objectives. The cost estimates incorporate historical data, federal standards, and advanced financial modeling to ensure precision and accountability. Each subsystem, personnel expense, travel requirement, and outreach activity has been thoroughly analyzed to reflect a realistic and comprehensive financial plan.

The total mission cost is $362,857,108, covering all phases and ensuring adequate allowance for personnel, travel, outreach, direct costs, and contingency margins. This financial framework balances technological needs against fiscal discipline, providing operational flexibility and ensuring the mission's success. The detailed breakdown shows the allocation for personnel, outreach, spacecraft subsystems, manufacturing, testing, and infrastructure, thus creating a sound basis for the proposed mission.

5.3.3. Personnel Budget

Additional Information

	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5	FY 6
Science Personnel:	10	10	10	10	10	10
Engineering Personnel:	20	20	20	20	20	20
Technicians:	8	8	8	8	8	8
Administration Personnel:	5	5	5	5	5	5
Management Personnel:	5	5	5	5	5	5

NASA L'SPACE Mission Concept Academy Budget - *Team 22*

Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative Total**
PERSONNEL							
Science Personnel	$ 800,000	$ 820,800	$ 841,600	$ 862,400	$ 883,200	$ 904,000	$ 5,112,000
Engineering Personnel	$ 1,600,000	$ 1,641,600	$ 1,683,200	$ 1,724,800	$ 1,766,400	$ 1,808,000	$ 10,224,000
Technicians	$ 480,000	$ 492,480	$ 504,960	$ 517,440	$ 529,920	$ 542,400	$ 3,067,200
Administration Personnel	$ 300,000	$ 307,800	$ 315,600	$ 323,400	$ 331,200	$ 339,000	$ 1,917,000
Project Management	$ 600,000	$ 615,600	$ 631,200	$ 646,800	$ 662,400	$ 678,000	$ 3,834,000
Total Salaries	$ 3,780,000	$ 3,878,280	$ 3,976,560	$ 4,074,840	$ 4,173,120	$ 4,271,400	**$ 24,154,200**
Total ERE	$ 1,054,998	$ 1,082,428	$ 1,109,858	$ 1,137,288	$ 1,164,718	$ 1,192,148	**$ 6,741,437**
Personnel Margin							**$ -**
TOTAL PERSONNEL	$ 4,834,998	$ 5,089,686	$ 5,350,912	$ 5,618,674	$ 5,892,973	$ 6,173,809	$ 32,961,052

Figure 5.3.3.1 - Personnel Budget Table

Based on the detailed role, responsibilities, and duration of each mission phase, the personnel costs for this mission have been worked out in fair detail with a given budget template. This template should summarize personnel expenses covering Science, Engineering, Technicians, Administration, and Project Management personnel. The composition is such that the team remains the same across all years to ensure continuity and stability in these mission-critical roles, reflecting the operational demands at each project phase.

The team in Year 1 consists of 10 Science, 20 Engineering, 8 Technicians, 5 Administration, and 5 Project Managers. This staffing profile is consistent with the initial demands of Phase An era of preparation, design, and early-stage testing of mission components. The personnel in each role are allocated based on expertise and the particular needs outlined in the Project Management Approach section to ensure that each Phase is sufficiently supported for its objectives to be realized. Science and Engineering personnel are the two largest groups because of the technical nature of the mission, which calls for continuous research, analysis, and engineering solutions.

The budget template contains detailed personnel costs: salary, EREs, and a personnel margin. In estimating the salaries, EREs, and personnel margin, allowance for inflation and any compensatory increase over time is included. Salaries increase every year by a few tenths of one percent to account for increases in the cost of living. The same fixed inflation rate is used at 154.44% for all employees. EREs are estimated, as in general industry practice and as instructed by NASA, at a standard rate of 28% for all personnel categories. This perhaps owes to the fact that a 10% personnel margin acts as a buffer in the case of unexpected hiring costs, overtime, or fluctuations in personnel needs, especially in periods of highest intensity or during critical testing phases.

The science personnel are kept constant to ensure research and data analysis continuity throughout the mission. Similarly, engineering personnel constantly manage the design, testing, and troubleshooting necessary for mission success. Technicians provide the hands-on skills required for the assembly and maintenance efforts, while administrative support staff attend to the logistical and operational tasks. Project Management personnel oversee the coordination of each Phase by ensuring it aligns with project milestones, budget constraints, and mission objectives.

This structured budget template has allowed us to project expenses accurately across six years and is designed to match the phases of each mission. This way, we can continue a staff of skilled professionals in each vital position while maintaining fiscal responsibility. This detailed budget template format has enabled us to balance technical and operational mission requirements against financial constraints, ensuring each Phase is appropriately matched with the qualified team required for mission success. Such systematic forecasting of personnel costs supports the adaptability and responsiveness of the mission within the framework established in terms of budgeting for the project.

5.3.4. Travel Budget

TRAVEL							
Total Flights Cost	$ 47,196	$ 48,346	$ 16,170	$ 16,530	$ 13,560	$ 14,680	$ 156,482
Total Hotel Cost	$ 44,378	$ 45,467	$ 17,787	$ 18,183	$ 9,322	$ 9,798	$ 144,935
Total Transportation Cost	$ 4,617	$ 4,729	$ 2,156	$ 2,204	$ 2,712	$ 2,877	$ 19,295
Total Per Diem Cost	$ 15,944	$ 16,332	$ 5,950	$ 6,084	$ 5,932	$ 6,328	$ 56,570
Travel Margin	$ 8,000	$ 8,500	$ 2,500	$ 2,500	$ 2,000	$ 2,000	$ 25,500
Total Travel Costs	$ 120,135	$ 126,582	$ 46,880	$ 49,050	$ 37,013	$ 40,322	$ 419,982

Figure 5.3.4.1 - Travel Budget Table

The travel budget, estimated at roughly $420,000 over six fiscal years, is essential to the mission-supporting system testing, Key Decision Points (KDP), and mission launch. Following GSA guidelines, this estimate was developed using the Budget Basis of Estimate and overall budget chart, including projected inflation between 2.6% and 13.0% per year. This ensures comprehensive financial planning for all mission-critical travel activities.

System testing will require four trips, with half of the team traveling each trip, comprising eight personnel per trip, to review the rover and its subsystems. Two of these trips will be to NASA Glenn Research Center in Cleveland, Ohio, for environmental and subsystem testing. The other two will be conducted at a remote location that is yet to be determined, simulating the lunar environment. These trips are essential for rover performance validation and associated travel, including flights, lodging, and per diem; the costs are estimated at approximately $120,135 and $126,582 for FY1 and FY2, respectively.

Five KDPs are to be expected along the path of the mission. This is a requirement for NASA Category 2 projects in excess of $250 million. These meetings will be held at NASA Headquarters in Washington D.C. and include flights for the entire team of 15 personnel per trip. The trips are four days long, with estimated costs for flights, lodging, meals, and transport of $46,880 and $49,050, respectively, in FY3 and FY4.

The mission launch will require the entire team to travel to Cape Canaveral, Florida, for five days to complete pre-launch preparations and attend the launch event. Accommodations at Homewood Suites by Hilton Cape Canaveral-Cocoa Beach were selected for their proximity to the launch site and cost-effectiveness. The travel budget for this phase, including flights, lodging, meals, and local transportation, is estimated at $40,322 for FY6.

The total travel budget consists of $156,482 for flights, $144,935 for lodging, $19,295 for transportation, and $56,570 for per diem costs, while an additional $25,500 has been added as the travel margin. These projections will fully support system testing, decision-making milestones, and mission launch with financial stability and unity with the mission objectives.

5.3.5. Outreach Budget

OUTREACH							
Total Outreach Materials	$ 41,040	$ 47,475	$ 54,000	$ 60,500	$ 67,500	$ 73,450	**$ 343,965**
Total Outreach Venue Costs	$ 35,910	$ 39,055	$ 43,200	$ 46,200	$ 50,625	$ 53,100	**$ 268,090**
Total Outreach Travel Costs	$ 20,520	$ 23,210	$ 25,920	$ 28,600	$ 31,500	$ 34,050	**$ 163,800**
Total Outreach Services Costs	$ 30,780	$ 33,760	$ 36,720	$ 39,600	$ 42,750	$ 45,200	**$ 228,810**
Total Outreach Personnel Costs	$ 25,650	$ 28,485	$ 31,320	$ 34,100	$ 37,125	$ 39,550	**$ 196,230**
Outreach Margin	$ 5,130	$ 5,805	$ 6,480	$ 6,960	$ 7,875	$ 8,475	**$ 40,725**
Total Outreach Costs	$ 159,030	$ 182,413	$ 207,917	$ 232,805	$ 262,062	$ 286,822	**$ 1,331,049**

Figure 5.3.5.1 - Outreach Budget Table

The Outreach Plan for the Lunar Resource Exploration Festival is an indispensable part of the mission objective to enable public engagement in understanding lunar exploration. Given the approximate budget for this plan, $1,331,049 over six years, the focus is placed on cost-effectiveness with maximum impact in engaging diverse audiences from K-12 students through undergraduates and underrepresented groups.

Outreach Budget Breakdown and Activities:
Total Outreach Materials
This allocation for outreach materials has graduated across the fiscal years, from $41,040 in FY1 to $73,450 in FY6, for a six-year total of $343,965. Outreach materials include AR models of lunar craters to explore, mining simulation kits, and educational resources aligned with NGSS standards.

Total Outreach Venue Costs:
The festival requires large venues for hosting interactive exhibits, workshops, and audiences. Venue costs start at $35,910 in FY1 and grow to $53,100 in FY6, for $268,090. This includes the cost of renting the space, setting it up, and utilities to make the experience for attendees seamless.

Total Outreach Travel Costs:
Travel costs include accommodations and per diem for visiting scientists, engineers, and astronauts. Inflating annually to account for inflation, the budget is $20,520 in FY1 and $34,050 in FY6, for a total of $163,800.

Total Outreach Services Costs:

To broadcast the event and offer virtual participation, outreach services include IT support and camera setups, which are budgeted at $30,780 in FY1 and grow to $45,200 in FY6, for $228,810. This ensures accessibility worldwide for those who cannot be present in person.

Total Outreach Personnel Costs:
Personnel costs involve staffing the event, providing volunteer support, and organizing honorariums for expert speakers. Starting at $25,650 in FY1, this increases to $39,550 in FY6, for $196,230.

Outreach Margin:
This allows for flexibility and financial sustainability in the program. The outreach margin is from $5,130 in FY1 to $8,475 in FY6, up to $40,725. This reserve accounts for unexpected expenses or additional funding needed for mission-critical activities.

Total Outreach Costs:
The total annual cost of outreach captures the mission's commitment to education and inclusion, scaling from $159,030 in FY1 to $286,822 in FY6 for a cumulative total of $1,331,049.

Strategic Goals and Impact:
STEM-based activities in the outreach plan include the Lunar Habitat Design Challenge and AR lunar crater exploration, which introduce and provide opportunities for problem-solving and innovation. The budget allows the inclusion of underrepresented communities through scholarships, mentorships, and marketing initiatives, with $200,000 slated for this group. Streaming capabilities further widen this reach to ensure no one misses the event, inclusive of the rest of the world.

This detailed outreach strategy aligns with the mission's goal of promoting the importance of lunar resource exploration while maintaining fiscal responsibility and adaptability. The budget allocated has been well-placed toward education, inclusivity, and public engagement to create a long-lasting effect.

5.3.6. Direct Costs

DIRECT COSTS							
Mechanical Subsystem	$ 3,060,000	$ 12,400,000	$ 14,960,000	$ 18,750,000	$ 10,880,000	$ 8,110,000	**$ 68,160,000**
Power Subsystem	$ 359,000	$ 1,160,000	$ 1,867,000	$ 2,670,000	$ 1,005,000	$ 347,000	**$ 7,408,000**
Thermal Control Subsystem	$ 2,565,000	$ 2,625,000	$ 2,808,000	$ 2,983,500	$ 3,164,000	$ 2,975,400	**$ 17,120,900**
Comms & Data Handling Subsystem	$ 307,800	$ 315,000	$ 345,600	$ 375,700	$ 395,500	$ 359,100	**$ 2,098,700**
Guidance, Nav, & Control Subsystem	$ 200,000	$ 600,000	$ 1,000,000	$ 1,200,000	$ 650,000	$ 186,000	**$ 3,836,000**
Science Instrumentation	$ 8,000,000	$ 26,400,000	$ 50,400,000	$ 45,600,000	$ 20,000,000	$ 9,600,000	**$ 160,000,000**
Spacecraft Cost Margin	$ 48,000	$ 50,000	$ 520,200	$ 202,040	$ 20,200	$ 202,020	**$ 1,042,460**
Total Spacecraft Direct Costs	$ 14,539,800	$ 44,682,300	$ 75,639,642	$ 77,380,177	$ 39,870,629	$ 24,610,858	**$ 276,723,405**
Manufacturing Facility Cost	$ 360,000	$ 1,710,000	$ 1,710,000	$ 1,710,000	$ 1,750,000	$ 1,755,000	**$ 8,995,000**
Test Facility Cost	$ 480,000	$ 2,280,000	$ 2,285,000	$ 2,180,020	$ 2,340,000	$ 2,405,000	**$ 11,970,020**
Facility Cost Margin	$ 48,000	$ 228,000	$ 230,000	$ 230,400	$ 234,000	$ 245,000	**$ 1,215,400**
Total Facilities Costs	$ 888,000	$ 4,327,668	$ 4,444,700	$ 4,441,813	$ 4,773,696	$ 4,977,650	**$ 23,853,527**
Total Direct Costs	$ 15,427,800	$ 49,009,968	$ 80,084,342	$ 81,821,989	$ 44,644,325	$ 29,588,508	**$ 300,576,931**
Total MTDC	$ 14,539,800	$ 44,682,300	$ 75,639,642	$ 77,380,177	$ 39,870,629	$ 24,610,858	**$ 276,723,405**

Figure 5.3.6.1 - Direct Costs Table

Direct Mission Costs: Detailed Estimate and Justification
This mission will be successful because of a well-thought-out budget that will ensure the inclusion of all direct costs without sacrificing operational integrity. The direct mission costs include spacecraft-related, instrumentation, and associated systems costs. These estimates were formulated using a multi-pronged approach that integrated historical data, federal cost-estimating standards, and advanced financial modeling techniques to produce realistic and actionable estimates. This section goes deep into the financial planning and justifications for each subsystem, evidencing the precision and foresight that went into crafting this budget

Science Instrumentation: Enabling Groundbreaking Lunar Research

Overview and Role

These will be the linchpin for this mission, which was specifically designed to accomplish main goals related to data collection, surface, and environmental assessment. Together, these tools represent the most critical components for the research milestones to be achieved on the surface of the Moon. Estimated to cost $160 million altogether, the instrumentation includes:

1. NIRVSS Spectrometer System

   Purpose: Perform remote sensing and identify mineralogical and chemical compositions.
   Design Challenges: High precision in optical components, sensitivity in the near-infrared range, and robust housing for lunar conditions.
   Cost Justification: Costs were derived using MCCET, factoring in material quality, calibration needs, and optical sensitivity.

2. Neutron Spectrometer System (NSS)

   Purpose: Detect hydrogen atoms to identify water molecules or hydrogen-rich deposits.
   Design Challenges: High neutron-detection sensitivity and specialized shielding to avoid environmental interference.
   Cost Justification: Cost Estimating Relationships (CER) were used to evaluate costs, considering power demands and construction complexity.

3. Diviner Lunar Radiometer

   Purpose: Create detailed maps of thermal variations across the lunar surface.
   Design Challenges: Accurate thermal calibration and resistance to extreme temperature fluctuations.
   Cost Justification: MCCET and NICM were utilized to refine estimates, emphasizing accuracy and resilience.

4. Raman Spectrometer

   Purpose: Identify molecular compositions through vibrational spectroscopy.
   Design Challenges: Precision optical alignment, calibration, and dust resistance.
   Cost Justification: Costs represent high-resolution optical systems that must be lunar dust resistant and capable of withstanding extreme thermal fluctuations.

   Every instrument was handpicked with a specific emphasis on complementary functionality to study the lunar environment in multiple dimensions. Cost estimates were drawn on the MCCET, NICM, and CERs databases for accuracy in historical and recent trends.

Mechanical Subsystem: Engineering Mobility and Stability

Overview and Role

The mechanical subsystem provides the spacecraft mobility, stability, and the ability to navigate the challenging lunar terrain. Estimated at $68 million, this subsystem is made of several components designed for durability and precision:

1. Rocker Bogie Suspension System

Purpose: Provides stability and enables obstacle negotiation.
Cost Justification: MCCET estimated costs based on material strength, pivot joint complexity, and vibration absorption.

2. IMUs

   Purpose: Assist in navigation and balance with highly accurate gyroscopes and accelerometers.
   Cost Justification: CERs considered radiation shielding and long life for high accuracy in missions, and thus, the cost estimate for items was evaluated accordingly.

3. Rover Chassis

   Purpose: Protection of subsystems and ability to bear thermal stress.
   Cost Justification: MCCET and NICM provided advanced structural estimates, optimizing lightweight, high-strength materials.

4. Geared Cleated Wheels

   Purpose: Cleated designs for increased traction on rough surfaces with independent actuators.
   Cost Justification: Costs are based on the complexity of the actuators and terrain capability compared to previous missions.

5. Robotic Arms and Camera Systems

   Purpose: Sample collection, instrument placement with precision, and navigation imaging.
   Cost Justification: NICM cost baselines, adjusted by articulation complexity and optical sensor durability.

The cost for the mechanical subsystem was estimated while allowing a balance between the performance's ruggedness and the operation's flexibility. Cost assumptions have been justified by MCCET and NICM data, maintaining consistency with historical missions.

Thermal Subsystem: Optimal Operating Conditions Maintenance

Overview and Role

Thermal control protects the spacecraft's sensitive electronics and mechanical components. The estimated $17 million thermal subsystem incorporates active and passive technologies in managing the extreme temperature fluctuations on the lunar surface.

1. Active Thermal Control

Components: Heaters, thermoelectric coolers, and pumped fluid loops.
Cost Justification: MCCET estimates accounted for power efficiency, heat dissipation, and long-term reliability.

2. Passive Thermal Control

   Components: Thermal coatings, insulation materials, and radiators.
   Cost Justification: NICM data-informed costs for advanced materials with high thermal resistance, ensuring durability in extreme conditions.

This subsystem is focused on efficiency and resilience, balancing cost-effectiveness with the need for robust thermal management.

Command and Data Handling (CDH): Ensuring Seamless Operations

Overview and Role

The CDH subsystem processes, stores, and transmits mission-essential data. Although it is a relatively inexpensive subsystem at a mere $2.1 million, it is vital in ensuring mission success.

1. Radio and Communication Systems

   Purpose: Maintain high-frequency transmission between the spacecraft and mission control.
   Cost Justification: NICM benchmarks and MCCET adjustments were considered for radiation resistance and data transmission reliability.

2. Onboard Computer (OBC)

   Purpose: Process data and manage mission operations.
   Cost Justification: Costs reflect the need for robust processing power, error correction, and resistance to lunar conditions.

3. Data Storage and Buses

   Purpose: Store and transfer data between subsystems.
   Cost Justification: CERs provided cost estimates for storage capacity and transfer speed, adjusted for lunar-specific demands.

CDH costs were carefully optimized to balance reliability, efficiency, and durability.

Spacecraft Cost Margin

The spacecraft cost margin was set at $1.04 million to accommodate unexpected expenses or modifications during development. This margin ensures the project remains financially agile, adapting to unforeseen challenges without compromising the mission timeline or objectives.

Facilities Costs: Manufacturing, Testing, and Integration

Manufacturing Facility Costs

Estimated at $9 million, these costs cover the production of spacecraft components, leveraging state-of-the-art facilities and experienced personnel.

Test Facility Costs

Budgeted at $11.97 million, testing will involve thermal vacuum tests, electromagnetic interference assessments, and vibration tests that will simulate conditions on the Moon.

Facility Contingency

Appropriated $1.21 million margin for facility-related contingencies.

5.4. Scope Management

5.4.1. Change Control Management

Any major changes to the team's mission will be requested using the L'SPACE Change Request Form (L'SPACE Mission Concept Academy). A change request form will be submitted in the event that the team has identified a necessary change to the mission after that item has been baselined, and will require a Change Control Board (CCB) to approve or deny the request (L'SPACE Mission Concept Academy). These requests will be sent through the Student Success Advisor and L'SPACE through an email sent by the Program Manager. The PM and any relevant team leaders or members involved with the change request will be required to attend a CCB.

If the CCB approves the change request, then the team will document the change in a Change Log Document which is described in detail at the end of this section. This change will then be reflected in all future deliverables and will become the new baseline for that specific item for the remainder of the mission. If the CCB denies the change request, then the team will proceed with the pre-existing item for the remainder of the mission. The denied change request will still be documented in the Change Log

Document in order to maintain an accurate record of all changes that have been requested.

Any Request for Action (RFA) or Advisory (ADV) changes that are provided by stakeholders will be monitored and implemented by the entire team. The PM will host an internal meeting with the entire team in order to discuss all RFAs, and team leaders for each relevant sub-team will be responsible for ensuring the full competition of these changes for the next deliverable. RFAs are high priority change items and will receive a high priority in terms of competition. When an RFA is made by the stakeholders, it is required that the item is completed by submission of the next deliverable.

ADVs shall also be discussed during the meeting, but the full completion of these items will have a lower priority in comparison to that of the RFAs. When all RFAs are addressed and completed, then the team may begin to address the concerns mentioned in the ADVs. While it is the team's goal to address all ADVs, the completion of all RFAs will remain as the higher priority action item.

Any and all changes–whether that be a Change Request Form, an RFA, or an ADV–will be tracked in a Change Log Document that will reside in the Team 22 Shared Google Drive. A sample image of the document can be seen as follows:

Team22_ChangeLog

Change ID	Change Type	Affected Document/ Section	Document/ Section To be Updated	Description	Status	Priority	Area of Impact
MCR-RFA-1	RFA	MCR - Section 1.1	SRR - Section 1.1	Discuss how the mission objective will be achieved	Completed	High	Entire Team
MCR-RFA-2	RFA	MCR - Section 1.3	SRR - Section 1.3	Conduct a trade study with top three sites to down-select the final site based on quantified reasoning. Include this trade study in section 1.3.	Completed	High	Science
MCR-RFA-3	RFA	MCR - Section 1.5	SRR - Section 1.6	The team needs to address Planetary Protection Concerns.	Completed	High	Science, Programmatics
MCR-RFA-4	RFA	MCR - Section 1.5	SRR - Section 1.6	The team didn't address much risk associated to their sites but focused towards their rover components risk. The team should have focused on lunar surface, lunar pits, and risk associated to manned missions. Mitigation or solutions were not needed or implmented into the section that wasn't consice.	Completed	High	Science, Programmatics

Figure 1.7.4.1 - Team 22 Change Log Document

This document will ensure that all changes are fully documented in order to be presented in the final Preliminary Design Review (PDR), along with full awareness regarding any changes amongst the entire team. Any team member that is involved in a change is responsible for updating the information regarding their specific change. The Deputy Project Manager of resources will be responsible for ensuring that the entirety of the Change Log Document is properly maintained. They will be responsible for conducting any follow-up communications or updates regarding a change when necessary. The full change log that has implemented all RFAs, ADVs, and Change Requests can be found in the Appendix section of this document.

5.4.2. Scope Control Management

Effective scope control is an important contributing factor in mission success, In order to effectively manage changes to scope the team must consider a variety of influencing factors. Namely mission requirements, core objectives, budget and manufacturing limitations and unforeseen circumstances.

In terms of downscoping, the management plan for decrease in budget or resources consists of the following. The team must consider the critical objectives and paths for the mission and ensure the requirements and goals are still being met. Once these are identified, unnecessary or non - critical elements of the mission can be delayed or removed entirely in order to preserve the core components of the mission. In addition to this removal and simplification of engineering devices may be implemented in order to further reduce on spent budget. Amounts of personnel required for each subteam may be redefined as well in order to further streamline and better allocate resources to more critical aspects of the mission.

Manufacturing represents another unforeseen risk in the form of product and procurement delays. In this case current manufacturing suppliers will need to be negotiated to ensure possession of most critical components, whereas other subsystem elements may have to be replaced by currently existing parts that can be easily sourced. In the case of extreme descope in which a large portion of the budget and or resources are cut, it may facilitate the need for removal of scientific instrumentation. This however is an absolute last resort, only to be used after the follow through of all previous resources. As a mission the gathering of scientific data must be prioritized above all else, and if removal is necessary comparison between scientific instruments will be conducted to maintain mission integrity from a scientific standpoint.

Currently total mission expenditure is estimated to be 313 million, in comparison to the established mission budget of 320 million, leaving a gap of 7 million. Additional funding would be firstly considered in the context of increased scientific capability.

5.5. Outreach Summary

An outreach plan that Team 22 will implement to create public awareness for the mission is an event called the Lunar Resource Exploration Festival**.** The purpose for this event is to help the public understand why it is important to conduct this mission in the first place, which is to the moon for resources.The team's mission is to focus the community on how the use of scientific research to find resources on the moon is beneficial for life on Earth and the progress of lunar exploration. This event would combine hands-on activities, live demo stations, and interactive learning opportunities to engage participants of all ages. Event highlights are listed as: Lunar crater exploration stations, lunar mining simulations, Scientist and engineer workshop stations, Lunar habitat design challenge for our K-12 audience, and a community engagement and outreach (Q&A) at the end of the event and also have it live streamed for internet viewers.

Figure 6.5.1 - Lunar Resource Exploration Festival Poster

Activities that will be hosted during the event include the following:

- A **lunar crater exploration station** will be a set up model of the moon's surface, highlighting the craters our team chose to conduct research that we believe contains ice, water etc. This station would allow participants to virtually explore these areas using augmented reality or 3D models, with a focus on how these resources can support long-term lunar habituation and earth applications.
- **Lunar mining simulations** will create a simulation where students can simulate mining activities using small models or simulations if

digging for lunar resources like our rover would do during this mission.

- **Scientist and engineer stations** will have scientists, engineers, and astronauts working on this mission give talks and host a workshop on the significance of the lunar mission.
- **Lunar Habitat Design Challenge** will be a station for students to participate in an activity where they design a lunar habitat using resources from the craters, such as building structures or water filtration. This will help with problem solving and understating the science and engineering applied to the mission. (K-12 mainly)
- **Community engagement/ Livestream** will be hosted by NASS experts that could answer questions the public has for this particular mission . This could also be helpful for those who didn't have a chance to make out the event and streaming virtually to get more facts about that mission objectives and purpose.

The Lunar Resource Exploration Festival would engage the public, universities, and K-12 students in science, technology, engineering, and mathematics fields especially related to space exploration. This could also spark an interest in a space science career and promote a deeper understanding on Team 22's goals of this mission.

Team 22 will reach out to community centers, universities, and K-12 schools in the area for this event. We will collaborate with K-12 students, universities students, and communities by designing these activities to keep them engaged and gain knowledge on this Lunar mission. K-12 students will gain a deeper understanding with hands-on activities such as the Lunar Habitat design challenge where the students will work to design habitats using lunar resources like water ice and regolith. These activities will align with specific next-generation science standards, ensuring that lessons learned are not only fun but also educational. Also the mining activity will keep them engaged with materials which will be available to teachers also to help support classroom discussions on the importance of the moon for both space exploration and its potential contributions to addressing the challenges. For the universities and college level, we will collaborate with space and engineering departments to offer lectures and specialized workshops for a deeper understanding of technologies and lunar resources. Team 22 will also promote the creation of internships and research opportunities for students in the areas of sustainable energy, engineering and resource management to give a practical hands-on experience for this level of audience.

Ensuring that the outreach reaches under-presented communities is essential to the success of our mission. Team 22 recognizes that space exploration has often lacked diversity, but the team will make an effort to involve underserved communities by collaborating with community centers, local libraries, and youth organizations to host learning events that could explain how lunar exploration has an impact on earth and human life. It would be great to reach out to historically black colleges and universities, tribal colleges and universities to help increase that underrepresented groups in STEM fields. These institutions will be invited to participate in research partnerships, mentorships, and outreach programs for students directly engaged in research related to lunar resource utilization.

The budget allocation for outreach planning is $8 Million which would include cost of materials, event logistics, technology platforms, teacher training, community partnerships, and student scholarships. A portion will also go towards the travel costs for guest speakers and workshops for universities and community organizations. The original budget cap of $8 million will not be fully used after an analysis of the required costs to host this event. In total, the Lunar Resource Exploration Festival and other forms of outreach will total $1.3 million. A detailed analysis of the outreach costs can be found in section 6.3.5, which includes a cost table and narrative breakdown for all aspects of the outreach plans.

Team 22 outreach plan will focus on increasing public awareness and appreciation for the lunar mission by engaging K-12 students, university and colleges students, and underrepresented communities through these targeted actualities, workshops, and collaborative opportunities. The focus will be on making the lunar mission relatable by highlighting the implications of lunar resource utilization and its potential to provide solutions to global challenges. This outreach strategy aligns directly with the goals of Team 22 mission and is designed to make space exploration more inclusive, educational, and impactful for everyone involved.

6. Conclusion

Team 22’s Preliminary Design Review evaluated the mission’s overall preliminary design in regards to the lunar rover and its capabilities for completing the mission goals and objectives on the Moon. The rover is designed to explore lunar volcanic tubes in order to determine the viability of establishing a settlement that will protect future lunar exploration team.The mission concept, vehicle systems, cost, schedule, and risks were thoroughly discussed and analyzed, ensuring the continued success of mission planning in order to begin Phase C, which is the final design and fabrication of the mission.

The next milestone that the team is working towards is beginning the work tasks of Phase C, which assumes that the cost and schedule are adequate enough for ensuring mission success. The team will undergo a review of the final PDR in the form of an oral presentation, which is to be presented in December of 2024. After the review, the team will have an understanding of the mission’s success level and would be able to begin the final design and fabrication. If given more time to work on the PDR, the team would focus on implementing any outstanding ADVs provided by reviewers from the Mission

Concept Academy in order to strengthen this body of work.

The lessons learned, skills gained, and connections made throughout the previous four months have enhanced the members of Team 22 academically, professionally, and individually. Upon successful completion of this PDR, Team 22 has completed the scope of the NASA L'SPACE Mission Concept Academy.

Bibliography

BAE Systems. *RAD750® 3U CompactPCI Single-Board Computer*. BAE Systems, 2020. Accessed October 27, 2024. https://www.baesystems.com/en-media/uploadFile/20210404070637/1434555679066.pdf&sa=D&source=docs&ust=1730075071106457&usg=AOvVaw0s6_ubpipvLNTCvG-lY7zq.

BAE Systems. "Radiation-Hardened Electronics." *BAE Systems*, www.baesystems.com/en-us/product/radiation-hardened-electronics. Accessed 29 Oct. 2024.

Budget Template. Google Sheets. Accessed November 18, 2024. https://docs.google.com/spreadsheets/d/1A3QuEN-kgxmddUtTIpW2MRDp50Ltti4VUJlc3gD0UhY/edit?gid=25101628#gid=25101628.

Burcin, A. *Technical Overview of RAD750™ Microprocessor*. BAE Systems, 2002. Accessed October 27, 2024. https://web.archive.org/web/20090326020946/http://www.aero.org/conferences/mrqw/2002-papers/A_Burcin.pdf.

"Calibration of NASA's Neutron Spectrometer System (NSS) for Landed Measurements of Hydrogen Content of the Lunar Subsurface." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, January 20, 2023. https://www.sciencedirect.com/science/article/pii/S0168900223000530.

Colaprete, A., P. Schultz, J. Heldmann, D. Wooden, M. Shirley, K. Ennico, B. Hermalyn, et al. 2010. "Detection of Water in the LCROSS Ejecta Plume." Science 330 (6003): 463–68. https://doi.org/10.1126/science.1186986.

Coughlin, Thomas. "Storage In Outer Space." *Forbes*, December 27, 2022. Accessed October 27, 2024. https://www.forbes.com/sites/tomcoughlin/2022/12/27/storage-in-outer-space/.

CPU Shack. "Computers and CPUs in Space." *CPU Shack*, www.cpushack.com/space-craft-cpu.html. Accessed 29 Oct. 2024.

"Diviner Lunar Radiometer Gridded Brightness Temperatures from Geodesic Binning of Modeled Fields of View." Icarus, April 12, 2017. https://www.sciencedirect.com/science/article/abs/pii/S0019103517302737..

“Diviner - Moon Instruments - NASA Jet Propulsion Laboratory.” NASA. Accessed December 9, 2024. https://www.jpl.nasa.gov/missions/diviner-lunar-radiometer-experiment-dlre/.

Fafard, Simon. “Multijunction Solar Cell.” Multijunction Solar Cell - an overview | ScienceDirect Topics, 2021. https://www.sciencedirect.com/topics/engineering/multijunction-solar-cell.

Gilmore, David. *Spacecraft Thermal Control Handbook, volume I: Fundamental technologies David Gilmore*. Washington, DC: American Institute of Aeronautics and Astronautics, 2002.

“Guide to Raman Spectroscopy.” Bruker. Accessed December 9, 2024. https://www.bruker.com/en/products-and-solutions/infrared-and-raman/raman-spectrometers/what-is-raman-spectroscopy.html.

H. Jay Melosh. 2011. Planetary Surface Processes. Cambridge University Press.

IQ Technologies for Earth and Space GmbH. *X Band Antenna Datasheet*. IQ Technologies for Earth and Space GmbH, May 2024. Accessed October 27, 2024. https://www.iq-spacecom.com/images/Datasheets/IQspacecom_X_Band_Antenna_datasheet_05.2024.pdf.

“Jean-Pierre Williams.” Jean-Pierre Williams - Research. Accessed December 9, 2024. https://luna1.diviner.ucla.edu/~jpierre/research_missions.html.

“Lithium-Ion Battery.” Clean Energy Institute, June 20, 2024. https://www.cei.washington.edu/research/energy-storage/lithium-ion-battery/.

L’SPACE Mission Concept Academy. “MCA Team Organization Guide - Fall 2024.” Google Docs. Accessed October 24, 2024. https://docs.google.com/document/d/1I8x0KmdqNCit1YXEaDq07xG-xCjCJqSSaqFJ_CK5aH8/edit.

L’SPACE Mission Concept Academy. “Mission Concept Cost Estimate Tool (MCCET) - Instructions.” Google Docs. Accessed November 18, 2024.

MIL-STD-1553 Applications. "MIL-STD-1553 Applications." Accessed October 30, 2024. https://www.milstd1553.com/applications/.

NASA Cost Estimating Handbook. *Version 4.0*. NASA, 2015. Accessed November 18, 2024. https://www.nasa.gov/pdf/420297main_NASA-SP-2010-3403.pdf.

NASA Failure Modes and Effects Analysis (FMEA) A Bibliography. NASA, 2000. Accessed November 15, 2024.

https://ntrs.nasa.gov/api/citations/20000070720/downloads/20000070720.pdf

NASA Instrument Cost Model (NICM). *NASA*, 2015. Accessed November 18, 2024. https://www.nasa.gov/sites/default/files/atoms/files/nasa_cost_model_2015.pdf.

NASA Risk-Informed Decision Making Handbook. *Version 1.0*. NASA, 2010. Accessed December 8, 2024.

https://ntrs.nasa.gov/api/citations/20100021361/downloads/20100021361.pdf

Neutron Spectrometer System (NSS) - the NSSDCA. Accessed December 10, 2024. https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=PEREGRN-1-02.

Phison Electronics. "Phison's uSSD is Now on Mars: A Key Component in NASA's Perseverance Rover." *Phison Blog*, May 2024. Accessed October 27, 2024. https://phisonblog.com/phisons-ussd-is-now-on-mars-a-key-component-in-nasas-perseverance-rover-2/.

Renishawplc. "What Raman Can Tell You." Renishaw. Accessed December 9, 2024. https://www.renishaw.com/en/what-raman-spectroscopy-can-tell-you--25800#:~:text=Interpretation%20of%20the%20Raman%20spectrum,all%20in%20the%20same%20configuration.

"Supporting NIRVSS Development and Operations." Planetary Science Institute, November 27, 2024. https://www.psi.edu/blog/project/supporting-nirvss-development-and-operations/.

tech bytes - NASA. Accessed December 10, 2024. https://www.nasa.gov/wp-content/uploads/2023/06/techbytes-winter2015.pdf.

The near--infrared volasle spectrometer system (NIRVSS ... - NASA. Accessed December 10, 2024. https://lunarscience.nasa.gov/wp-content/uploads/LSF13P/ennico_nirvss_nlsf2013_poster_final_40x36.pptx.pdf.

"What Is Raman Spectroscopy?" HORIBA. Accessed December 9, 2024. https://www.horiba.com/usa/scientific/technologies/raman-imaging-and-spectroscopy/raman-spectroscopy/.

Declaration of Generative AI and AI-Assisted Technologies in the writing process

During the preparation of this body of work, the team used ChatGPT 4o to create concise sentence structure, clean up any grammatical errors, and ensure sources are in

Chicago format. After using ChatGPT, the team reviewed and edited the content. Team 22 takes full responsibility for the contents of this deliverable.

Appendix

Change Log

SRR-CR-1	Change Request Form	SRR	MDR, PDR	The team request a budget request due to the budget descope from \$450M to \$300M. After analysis, the team calculated a new budget of \$320M, which requires an additional funding request of \$20M.	Approved	High	Entire Team, Programmatics

Known and Assumptions	
n radiating to space	1
n radiating to space/surface	4
n radiating to surface	1
space node temp, k	3
surface temp hot, k	400
surface temp cold, k	140
q_solar flux, W/m^2	1440
SA faces, m^2	0.25
emissivity base, e	0.3
absorptivity base, a	0.3
system temp, k	300
Stephan Boltzman Constant	0.0000000567

	Hot Case	
Q_solar = q_solarflux*A*α	1414*.25*.3	106.05W
Q_internal_load	78.5W	20W
Q_rad-space	(.3)(5.67*10^-8)(1)(.25)(300^4-3^4)	34.44W
Q_rad-space/Surface	4*[(0.3)(5.67*10^-8)(1)(.25/2)(300^4-3^4)+(.3)(5.67*10^-8)(1)(.25/2)(300^4-400^4)]	79.95W

Q_rad-surface	(0.3)(5.67*10^-8)(1)(.25/2)(300^4-400^4)	37W
Q_in	106.05+78.5+34.44+37+1.24	257.23W
Q_out	37W	37W
Excess	257-37	220W

MLI		
Q_rad-space/surface		1.33W
Q_rad-surface		0.62W
White Paint		
Emissivity	0.8	
Absorptivity	0.19	
Q_rad-space	(.8)(5.67*10^-8)(1)(.25)(300^4-3^4)	91.85W
Q_solar	1414*.25*.19	67.165W
Q_in	67.165+78.5+1.33+0.62	147.615W
Q_out	91.85W	
Total	147.615-91.85	55.77W