Preliminary Design Review (PDR)

Mission Concept Academy

L’SPACE Team 19

9 December 2024



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A. Abbreviation

I. DoF - Degree of Freedom
II. GPR - Ground-Penetrating Radar
III. ISRU - In-Situ Resource Utilization
IV. KDP- Key Decision Point
V. LADEE - Lunar Atmosphere and Dust Environment Explorer
VI. LIDAR - Light Detection and Ranging
VII. LRO - Lunar Reconnaissance Orbiter
VIII. MCR - Mission Concept Review
IX. MTP - Mare Tranquillitatis Pit
X. NASA - National Aeronautics and Space Administration
XI. RTG - Radioisotope Thermoelectric Generator
XII. SRR - System Requirements Review
XIII. TRL - Technology Readiness Level
XIV. SSR - Solid State Recorder
XV. CLUPI - Close-UP Imager
XVI. TIRS - Thermal Infrared Sensor
XVII. APXS - Alpha-particle X-ray Spectrometer

1. Mission Overview

1.1. Mission Statement

This mission aims to assess the potential habitability and analyze the geophysical characteristics of the Mare Tranquillitatis Pit on the lunar surface. The mission will be conducted by a rover equipped with scientific instruments to gather crucial information about the thermal environment, structural integrity, radiation levels, resource availability, and subsurface composition of the pit. Instruments such as radiometers and thermal sensors will characterize the thermal environment by measuring temperature fluctuations and stable zones. Structural integrity will be evaluated using LiDAR and ground-penetrating radar (GPR) to identify cracks or weaknesses in the pit walls and overhangs. Radiation levels will be assessed using a radiation detector to quantify potential exposure risks. A spectrometer will be utilized to analyze resource availability, such as the presence of volatiles like water and hydrogen, while subsurface composition will be studied using GPR and imaging tools. This data will directly contribute to evaluating the pit's ability to serve as a habitat, with minimal need for artificial environmental regulation. Understanding radiation shielding capabilities and stable temperature zones will also be crucial for assessing the site's suitability for human protection. This approach directly addresses customer-defined goals by aligning the mission's focus with the need to evaluate environmental and structural parameters critical for long-term lunar habitation.

An autonomous all-terrain rover designed for extreme conditions on the Moon's surface will deliver continuous measurements. The rover will transmit the gathered data when the satellite is in the overhead vicinity of the pit location. These observations will provide insight into the long-term feasibility of establishing a sustainable human colony. The gathered data will add knowledge of lunar geology and resource availability while addressing fundamental questions about origin and development. This mission will enhance the planning of further manned missions by providing crucial data to ensure astronaut safety and mission success and, most importantly, lay the foundation for possible lunar habitation.

1.2. Science Traceability Matrix

<u>Science Objectives:</u>

This mission aims to find a place where humans and technology can exist on the lunar surface for prolonged periods of time in the hopes of utilizing the moon as a gateway to the outer parts of the solar system. In addition, the Moon is one of the few locations in the solar system with perfectly preserved records of early solar system formation

(Origins, Worlds, and Life… 2023). Uncovering this evidence may provide new insights into the formation of the planetary and extrasolar systems. An aim that stems from this goal is to identify where these records are located and how NASA might gain access to them. Based on the team's LRO image analysis, Lunar Pit Tranquillitatis is an exceptional candidate for exploration. With this in mind, a discovery class mission must provide baseline characteristics of as many variables as possible to secure this location as a hub for future explorers. Such variables include temperature, chemical composition, structural integrity, and radiation hazard. These variables are the foundations of the science objectives listed in the Science Traceability Matrix (STM).

Stakeholder Science Goals:

As per the stakeholder's mission task, the science goals of this mission are divided into two parts. The first objective is to characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves to determine the viability of human habitation, which stems from the Exploration Systems Development Mission Directorate (ESDMD) goal: "*Provide safe and enduring habitation systems to protect individuals, equipment, and associated infrastructure" (*Lunar Exploration Analysis Group (LEAG) Habitation: HAB-SAT Report, Priority Objectives). The second science goal is derived from Science Theme 3 of Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032: "*Reveal the inner solar system's volatile origin and delivery processes*."

Each science objective has been derived to meet the following vital constraints:

- Safety and Stability: Identify stable regions within the pit that can support infrastructure.
- Resource Availability: Determine the presence of volatiles and other in-situ resources.
- Environmental Suitability: Evaluate the thermal and radiation environment to ensure the safety of future human missions.
- Surface Operations**:** Identify the quality of the terrain in an area within the landing zone and inside the pit

In summary, the science objectives:

- Characterize the thermal environment of the Mare Tranquillitatis pit to evaluate the stability of temperatures within potential habitat zones.
- Assess the structural integrity of the pit walls and overhang using high-resolution imaging and seismic sensors.

- Investigate the presence of subsurface voids and lava tubes, which could serve as natural shelters or storage areas.
- Quantify the radiation environment at various depths within the pit to identify optimal locations for habitats.
- Map the distribution of volatiles and hydrogen concentrations to evaluate the feasibility of in-situ resource utilization (ISRU).

Further detail can be found in the STM below, or in section 3.1 which outlines the science objectives in greater detail.

Science Traceability Matrix:

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
The moon is one of the few places in the Solar System capable of preserving centuries of geological transformations, including pits, caves, and lava tubes. Do habitable conditions exist within these features, and do they contain resthe team'sces for future explorers to use in situ? *(Lunar Exploration Analysis Group (LEAG) Habitation: HAB-SAT Report, Priority Objectives)*	Characterize the thermal environment of Mare Tranquillitatis Pit (MTP)	Identify temperature fluctuations throughout mission lifespan on the lunar surface and MTP floor	Observe stable floor and wall temperatures around 290 K (17°C)	Temperature Sensitivity:	150-300 K	6–35 µm & 14.5-15.5 µm	Thermal IR Sensor aboard Mars Environmental Dynamics Analyzer (MEDA)	Rover will land within a 5km radius of Mare Tranqulitatis Pit
				Spatial Resolution:	< 10 sq. m	~ 10 sq. m		
				Measurement stability:	± 1 K	< 1 µm		
	Assess the structural integrity of the walls and overhangs of MTP	Conduct nondestructive testing to identify signs of structural instability through imaging	Image cracks, fractures, deformations, and debris piles near MTP entryway, walls, floor, and overhang	Spectral Range:	Visible	400-700 nm	Close-Up Imager (CLUPI)	Vehicle shall maintain at most a 100 cm distance from the imaging target
				Resolution	< 2.5 mm/pixel	79 µm/pixel at 10 cm		
				Field of View:	< 100°	14 +/- 2°		
	Investigate and characterize potential cave networks and terrain in and around MTP, respectively	Identify hidden cave network(s) and other features using ground penetrating radar and map their terrain	Collect strong reflective radar signatures of MTP subsurface cavities	Spatial Resolution:	< 1 sq. m	< 0.5 sq m	Under-Rover Ultra-Wide Band Non-Contact Ground Penetrating Radar Antenna	Vehicle shall collect temperature samples daily for thermal mapping
				Depth:	≤ 50 m	> 5 m		
				Central Frequency:	~ 100 MHz	~1000 MHz		
				Frequency Range:	> 100 Mhz	120 MHz to 2000 MHz		
	Quantify the radiation environment in and around MTP to understand its effect on humans and instrumentation	Identify radiation dose rate and total ionizing dose in areas surrounding MTP and within MTP.	Collect telemetry on total ionizing dose (TID) rate, displacement damage dose (DDD) rate, and cosmic ray flux	Energy Coverage:	100 keV - 10 MeV	5 MeV - 100 MeV	Radiation Assessment Detector (RAD)	
				Exposure Time:	< 1 hr	< 15 min		
				Sensitivity:	< 10^4 erg/s	~ 100 keV		
	Map the distribution of volatiles and hydrogen concentrations found in and around MTP	Identify abundances of H, CH4, SiO2, N2, NH3	Collect relative abundance of H, CH4, SiO2, N2, NH3 in MTP regolith	Infrared Wavelength Range:	780 nm - 4 µm	1–25 keV	Alpha Particle X-Ray Spectrometer (APXS)	Vehicle shall identify terrain characteristics and ease of access into MTP
				Optical/UV Range:	100 - 700 nm			
				Resolution:	~1-2 nm	~ 200 eV		

1.3. Summary of Mission Location

Located approximately 400 kilometers away from the Apollo 11 landing site on the moon's northeastern quadrant is the Mare Tranquillitatis lunar pit, a caved-in structure that is speculated to be an entryway to a type of lunar cave network called a lava tube. Lava tubes, which are hollowed-out geologic structures on the moon, are remnants of volcanic activity. They are of interest to the scientific community due to their potential for lunar habitation, as they experience less extreme temperature fluctuations and radiation exposure compared to the lunar surface, these being two of the biggest obstacles to a sustainable lunar presence. While many such lunar pits are known, the Mare Tranquillitatis pit offers landing and research conditions that make it favorable for this mission.

Firstly, the mission is constrained by landing site requirements, which dictate that the landing site slope must be no more than 10 degrees. Additionally, the spacecraft must be able to maneuver itself to the cave after landing. Between these two requirements, a pit with navigable terrain was a mission critical consideration, making the pit's smooth surrounding surface a good option. Additionally, the team desired a location selection that would have a consistent line-of-sight for orbiter communications and data downlinking, which would allow mission data and science objectives to be analyzed. This eliminated lunar pits on the far side of the moon, and the Mare Tranquillitatis pit's location on the near side further contributed to its selection.

Furthermore, the pit's size and speculated connection to a lava tube network were taken into consideration when selecting a pit location. The pit has an inner diameter of approximately (100 x 88) meters with a funnel diameter of approximately (146 x 140) meters. Having large enough dimensions that the pit would be eligible for long-term infrastructural development factored into Mare Tranquillitatis' selection. Along with these dimensions, the pit's estimated 100-meter depth and 15-20 meters of overhang on the east, west, and north sides gave the team reason to believe that Mare Tranquillitatis would offer an acceptable amount of protection from cosmic and solar radiation. Mare Tranquillitatis' depth likely provides protection from the lunar surface's extreme thermal and radiative environment sufficient to achieve the team's scientific goal of studying lunar habitability options. Additionally, the suspected presence of lava tubes makes Mare Tranquillitatis a favorable option for completing the planetary science Decadal Survey's Science Theme 2: "Understand the geologic processes that shaped the early Earth, and that is best preserved on the Moon".

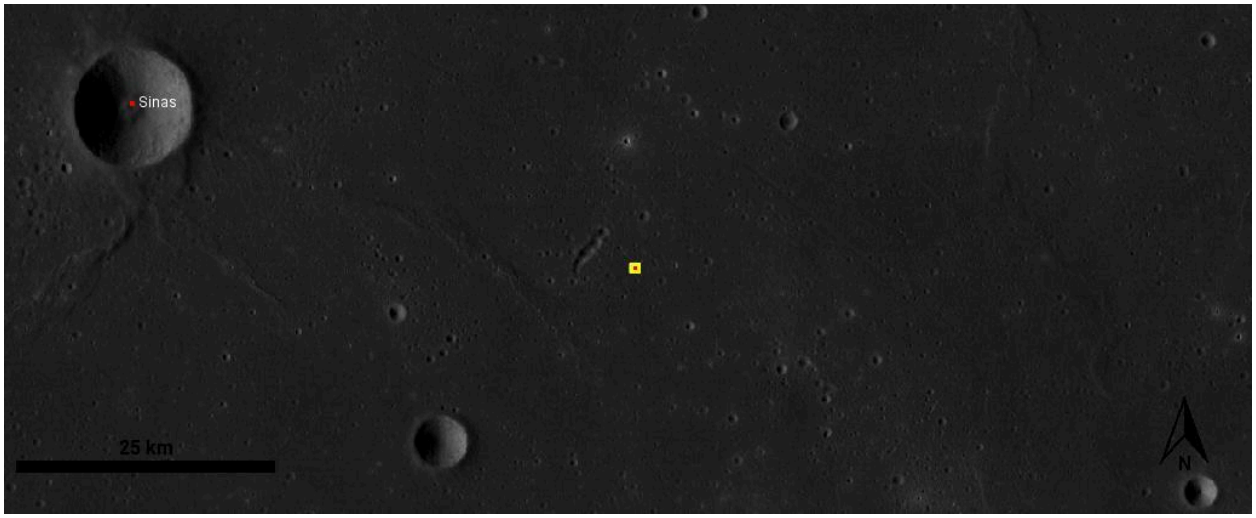


Figure 1: JMARS image showing the Mare Tranquillitatis pit's location within the Sea of Tranquility at (8.3355 degrees N, 33.222 degrees E) close to the Sinas crater

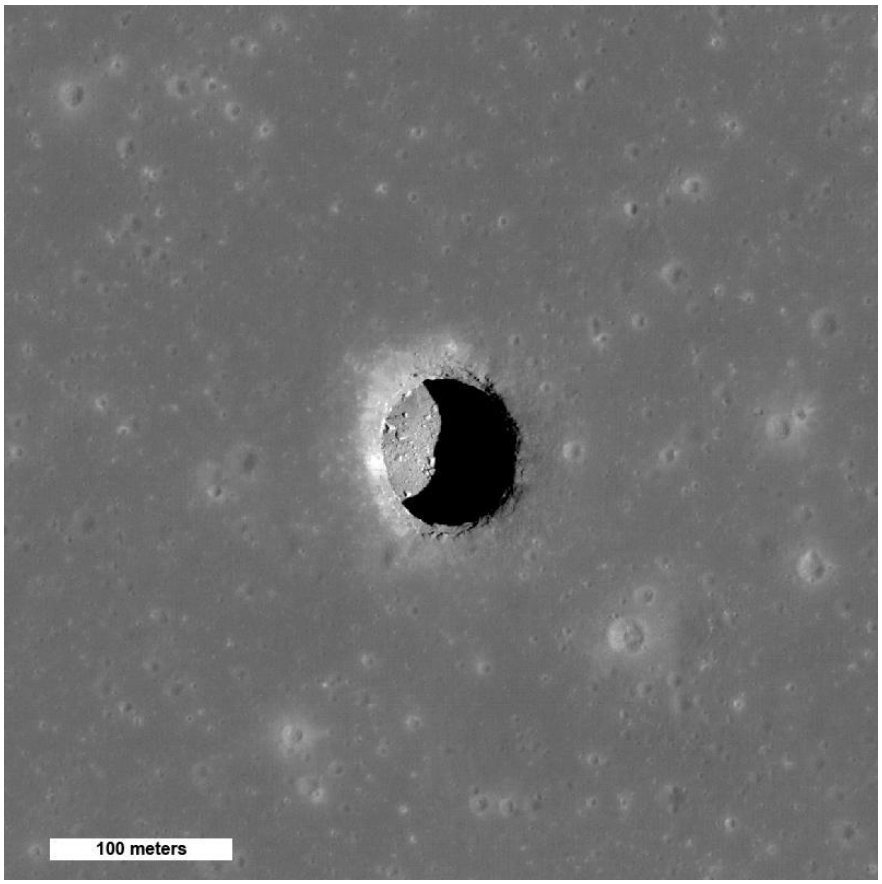


Figure 2: Lunar Reconnaissance Orbiter Camera (LROC) image of the Mare Tranquillitatis pit, NASA/GFSC/Arizona State University 2012

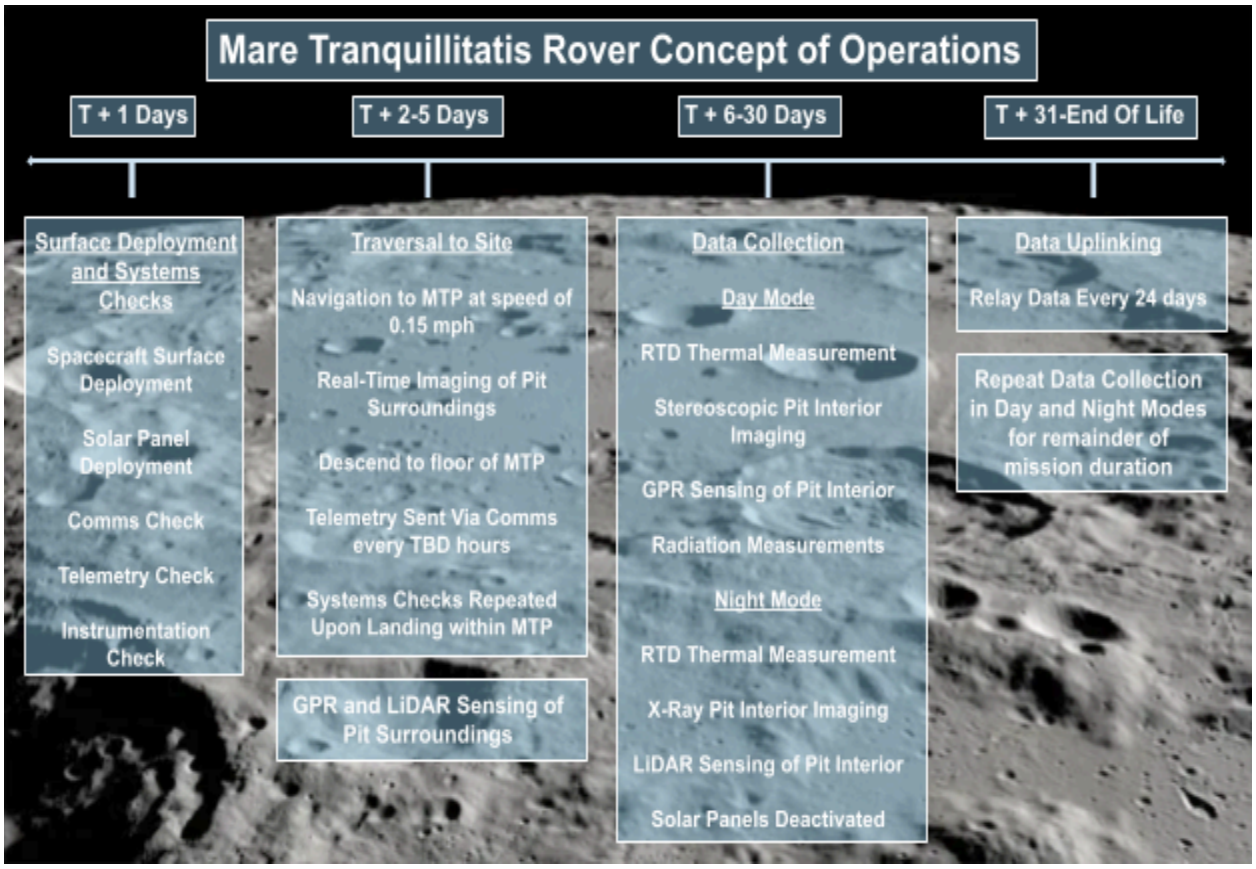
1.4. Mission Requirements

The team's top-level mission and system requirements, presented in the following table, shall be adhered to in addition to the fundamental mission constraints defined by the customer. These fundamental constraints require that the system not exceed a total mass of 350kg, a total volume of (2m x 1.5m x 1.5m), or a total project cost of $450M USD for project phases C-F. Additionally, the system shall be prepared to launch from Kennedy Space Center by March 1st, 2030. The table below outlines the parent and child requirements of the vehicle with their respective verification methods. So far, no requirements have been met; however, as the timeline progresses and testing ensues, these requirements will have to be met.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MT-5.0	The system should be able to downlink data to an orbiter in a 100km circular polar orbit.	Mission Task adherence	-	-	Analysis	Electrical, CDH	Met
NC-1.0	The system should exhibit robustness sufficient to perform mission functions defined in the ConOps.	Necessary Condition to complete the mission	-	NC-1.1, NC- 1.2, NC- 1.3	Test	Mechanical	Met
NC-2.0	The system should be able to mitigate geologic hazards presented by the lunar environment.	Necessary Condition to complete the mission	-	NC- 2.1, NC- 2.2, NC- 2.3	Inspection	Mechanical	Met
SC-1.0	The system should provide novel insights into the history and habitability of the Mare Tranquillatitis lunar pit.	Sufficient Conditions to satisfy the scientific objectives	-	SC- 1.1, SC- 1.2	Inspection	Payload	Met
NC-1.1	The system should be able to power itself for the mission's duration.	Necessary Condition to complete the mission	NC- 1.0	-	Analysis	Power	Met
NC- 1.2	The system should not sustain damage during pit entry sufficient to degrade any subsystem below operational levels.	Necessary Condition to complete the mission	NC-1.0	-	Test	Mechanical	Met
NC- 1.3	The system shall be able to withstand temperature ranges in the lunar environment.	Necessary Condition to complete the mission	NC- 1.0	-	Demonstration	Thermal	Met
NC-2.1	The system should adhere to Planetary Protection guidelines outlined by NASA-STD-8-719.27 and NPR 8715.24.	Necessary Condition to complete the mission	NC- 2.0	-	Inspection	All subsystems	Met
NC-2.2	The system should withstand lunar regolith without any subsystem degrading below operational levels.	Necessary Condition to complete the mission	NC- 2.0	-	Inspection	Mechanical	Met
NC-2.3	The system should be able to	Necessary	NC- 2.0	-	Test	Mechanical	Met

	mitigate lunar dust buildup so that all subsystems remain operational.	Condition to complete the mission					
SC-1.1	The system should be able to map the geometry of existing caves and lava tubes.	Sufficient Conditions to satisfy the scientific objectives	SC- 1.0	-	Inspection	Payload	Met
SC-1.2	The system should be able to characterize indicators of habitability as defined in the Science Traceability Matrix.	Sufficient Conditions to satisfy the scientific objectives	SC- 1.0	-	Inspection	Payload	Met

1.5. Concept of Operations (ConOps)



This section provides an overview of the concept of the mission and the definitions of operations that will deem the mission successful.

To effectively satisfy all objectives and requirements of this mission [See Science Traceability Matrix], the system architecture will take the form of a Robotic, All-Terrain

Rover. The rover will be encapsulated in a thermally shielded compartment of the entry vehicle and will be released upon successful surface touchdown.

During the launch, travel, and descent stages before the start of the mission, the system will receive auxiliary power from the primary launch vehicle to keep essential systems active. Upon separating from the primary vehicle at the landing site during the surface deployment stage, the system will be designed to operate on individual power sources: The system will utilize solar panels as a primary source of power. The “Surface Deployment and Systems Checks” phase begins upon the spacecraft’s separation from the primary vehicle at the lunar surface. The spacecraft will then perform systems checks of communication and telemetry software as well as various onboard science instruments. Software updates will be relayed from the ground station. Before the traversal stage, the rover will drive forward and backwards 5 meters to perform a mobility test. Instrumentation such as SHERLOC will be tested using test targets onboard the rover.

In the next two to five days, the rover progresses through the “Traversal to Site” phase. During traversal, the rover will not exceed speeds of 0.15 mph or 0.24 km/h as per requirement MEC.06. During traversal, the rover will begin real-time imaging of the surface surrounding MTP in order to discern major geological and topographic features of the surrounding region. The rover will also use onboard Ground Penetrating Radar (GPR) and Light Detection and Ranging (LiDAR) technology to construct models of the surrounding region on the lunar surface and to determine if there are any other lunar lava pits or lava tubes underneath the lunar surface within close proximity to MTP. During the “Traversal to Site” phase, telemetry data will be relayed back to ground operations with a frequency that is to be determined. Upon reaching MTP, the rover will descend into the lunar lava pit and land on the floor of the pit. In order to ensure that the vehicle did not sustain any damages during the traversal and descension stages, the rover will repeat systems checks of communication and telemetry software as well as payload instrumentation.

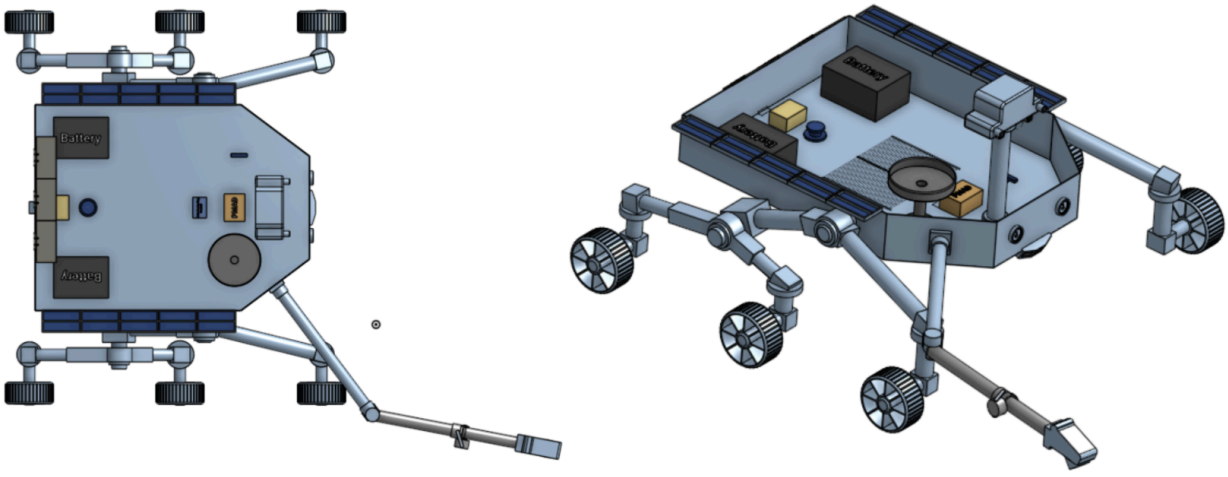
In the next 24 days, the rover will enter the “Data Collection” phase. This phase is divided into operations to be conducted during the lunar day as opposed to night. During the day, the rover will utilize its Resistance Temperature Detector (RTD) to measure thermal variation within the pit to begin constructing a thermal mapping of the interior of the pit. Secondly, the rover will utilize its Stereoscopic Camera to capture images to begin assessing the structural composition and layout of the interior of the pit. Thirdly, Ground Penetrating Radar will be utilized to determine structure of the interior of the pit as well as structure of other lava pits beyond the walls of the pit. The rover will also use a spectrometer to measure environmental characteristics of the atmosphere of

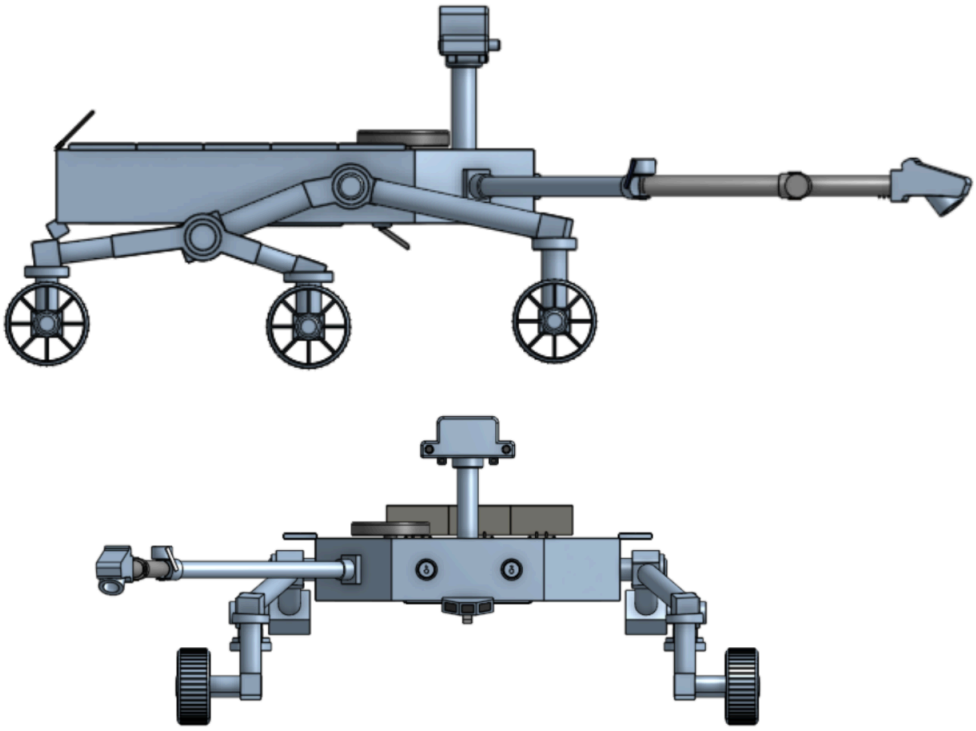
the interior of the pit. Finally, the rover will utilize a UV Radiometer to begin measuring radiation levels within the pit. During the night, the rover will cease power supply to the latter three of the four previously mentioned instruments, but continue to perform thermal measurements of the interior of the pit to determine the varying surface temperatures and sunlight levels affect temperatures within the pit. During night mode, the rover will utilize an X-Ray Camera to perform analyses of cracks within the walls of MTP. Secondly, LiDAR will be used to continue analyzing the structure of the interior of the pit. In order to conserve power usage, solar panels will be deactivated during night mode.

Upon completion of this 24 day “Data Collection” phase, data will be uplinked to be relayed to the ground station in the “Data Uplinking” phase. Upon successful transfer of data, the rover will return to the “Data Collection” phase. This cycle will continue to repeat until the rover’s end of life. After descending into MTP in the “Traversal to Site” phase, the rover will not exit the pit for the remainder of the mission timeline. Any further traversal required will only be within the volume of the pit itself.

1.6. Vehicle Design Summary

The MTP Rover consists of the mechanical, thermal, CDH, power and payload subsystems. The total mass of the spacecraft is 274.82 kg and has a maximum power draw of 110 watts. The dimensions of the rover when in the stowed configuration are 2m by 1.5m by 1.5m.





1.7. Science Instrumentation Summary

The Mare Tranquillitatis robotic exploration mission hosts a suite of five instruments supporting the science objectives detailed in section 3.1. The first of these instruments is a thermal infrared sensor (TIRS) that measures surface temperature using Quantum Well Infrared Photodetectors (QWIPs) that detect wavelengths of light in the infrared range (Landsat Science 2021). These photodetectors contain gallium arsenide semiconductors that will trap electrons in a quantum “well” unless they are excited by incident infrared radiation (Landsat Science 2021). If excitation occurs, an electric signal is read out, creating an image portraying temperature gradients. This sensor is equipped with multiple channels. Each channel will measure the solar radiation reflected from the surface, the atmospheric temperature inside the pit, and the thermal infrared radiation at the surface (Martinez 2017). Such measurements will allow the team to acquire accurate albedo measurements to identify surface temperature fluctuations and measure the pit's neutral temperature.

The Close-UP Imager (CLUPI) was flown on previous missions, such as the ExoMars Rover. It aims to acquire high-resolution images of soils and rocks to help determine the geological environment (Josset 2017). In the same context, CLUPI will help assess the structure of the basalt and regolith inside MTP. CLUPI will take multiple images of a single target at different distances and combine them using its Z-stacking function to reveal a high-resolution image with a depth of field that will be able to reveal the fine structure of the rock location on the pit’s overhangs and walls (Josset 2017).

Ground-penetrating radar (GPR) is a technique used to generate 2-dimensional images of a sub-surface without drilling, digging, or altering any geophysical features of the observed area (Rowell 2010). To investigate potential tunnels, lava tubes, or similar structures, the team plans to employ this technique to build a more extensive profile of MTP. GPR transmits radio waves to the surface via an antenna; any cavities or tubes present will reflect the radio waves to the surface (Rowell 2010). As the wavelength of the emitted pulse increases, so does the penetration depth, so higher wavelengths will allow the rover to identify deeper networks of lava flows (Grant 2021). After standard processing of these images, the locations of lava tubes that extend beyond the current radio mapping capabilities will be identified.

One of the primary goals of this mission is to assess the habitability of lunar pits for astronauts. A significant reason for this objective is the lack of atmosphere on the Moon, rendering the surface vulnerable to solar radiation and cosmic radiation from extragalactic sources. A radiation assessment detector (RAD) is required to fulfill this objective. A RAD contains a solid-state detector stack and scintillators made with various substrates like plastic. This instrument detects high-energy events from coronal mass ejections (CMEs) from the Sun and other high-energy particles from natural sources (NASA/JPL-Caltech/SwRI 2024).

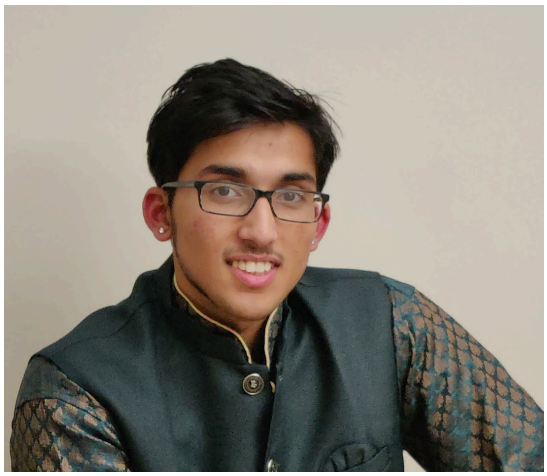
The final instrument onboard the MTP rover's science suite is an alpha-particle X-ray spectrometer (APXS). APXS has flown on multiple rovers to Mars and the Moon and is responsible for determining the chemical abundances on soil, regolith, and other materials. The sensor contains multiple parts, such as a telescope to detect alpha particles, an X-ray detector, and a pre-amplifier (NASA/APXS). In essence, APXS uses the interactions from Rutherford backscattering by bombarding a sample with alpha particles to determine chemical composition (NASA/APXS). APXS will be used to identify a host of chemicals, some vital to sustained human presence on the moon and essential for refueling boosters and replenishing oxygen supply. In contrast, others have implications for solar system formation theories.

1.8. Programmatic Summary

1.8.1. Team Introduction

Name: Krish Mehta	**Photo**

University: The Ohio State University, Columbus, Ohio	
Bio: Experienced in CAD modeling and design (particularly SolidWorks and Onshape, but learning Siemens NX currently). Worked on several end-to-end cycle engineering projects, particularly product and app development ones, followed up all with technical documentation. Passionate about defense and space, and working in a team to complete tasks and present the final deliverable to get feedback.	

Name: Vedarsh Mishra	**Photo**
University: Boston College, Chestnut Hill, Massachusetts	
Bio:Experienced in robotics and architectural design. Passionate about space and engineering, bringing skills in CAD, mission planning, and problem-solving to the team.	

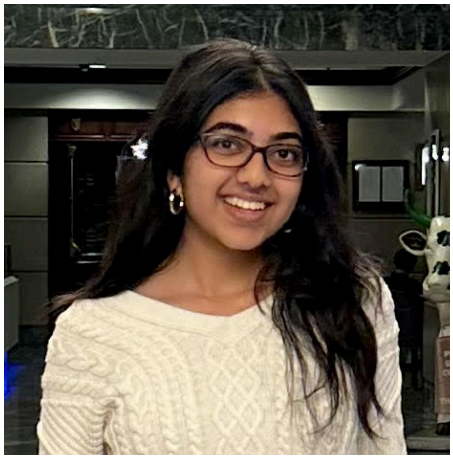
Name: Elizabeth Howard	**Photo**

University: Purdue University West Lafayette, IN	
Bio: Elizabeth has a background in biosystems engineering and experience interning in geological/civil consulting. She is a current astrodynamics student with prior student projects in solar car mechanical design, manufacturing, and racing, as well as flight testing and technical writing through NASA Langley Aeronautics Academy.	

Name: Anirudh Ramanathan	**Photo**
University: Worcester Polytechnic Institute Worcester, MA	
Bio: A skilled engineer with a background in Computer Engineering, and a specialization in Mechatronics and Computer Science, is currently working on a graduate degree in Robotics Engineering. Knowledge/Expertise in Computer-Aided Design, Electrical Equipment, and multiple software languages define a well-rounded engineer. Contributions to the Penn State Nationwide Eclipse Ballooning Project (NEBP), a NASA-funded initiative, highlight experience in collaborative and innovative engineering projects. Two years of	

work as an Electronics Engineer Intern at Northrop Grumman's Mission Systems sector further demonstrate a commitment to technical excellence and multidisciplinary problem-solving.	

Name: Liliana Zamora	**Photo**
University: The University of Michigan Ann-Arbor, Michigan	
Bio: Liliana brings expertise in robotics and space exploration, with hands-on experience in design, prototyping, and mission development. Active in SHPE, WAA, and WISE. Liliana contributes technical knowledge, leadership, and a passion for advancing space science to the NASA L'SPACE program.	

Name: Tanya Vijay	**Photo**
University: Purdue University, West Lafayette, Indiana	
Bio: Tanya is currently pursuing a major in Aeronautical and Astronautical Engineering, and brings expertise in CAD, programming, robotics and project engineering. Tanya is an active member of WiA and SWE, and is/has worked on projects to develop a payload-carrying two-stage rocket,	

autonomous microfluidic chip-controlled soft robots, and sub-scale aircraft rotor.	

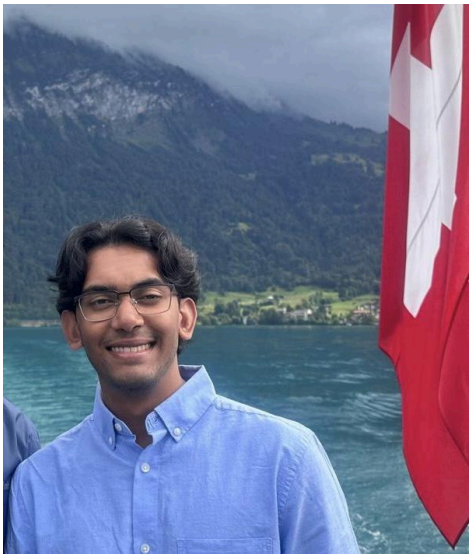
Name: Gwendolyn Seto	**Photo**
University: Columbia University, New York, NY	
Bio: Currently pursuing a degree in Industrial Engineering and Operations Research. Involved in Engineers Without Borders at university as the former Co-President. Interested in data science, astronomy, and problem-solving.	

Name: Kevin Subin	**Photo**
University: The Ohio State University, Columbus, Ohio	
Bio: Currently pursuing a Bachelor's degree in Aerospace Engineering with experience in CAD modeling and coding. Kevin is involved with the Buckeye Space Launch Initiative and the AIAA. Very passionate about the space industry and working with a team to get the project done with engineering and problem solving skills.	

Name: Abhijith Ajit	**Photo**
University: Rutgers University, New Brunswick, New Jersey	
Bio: Abhijith is currently pursuing a Bachelor of Science in Aerospace Engineering and a minor in Mathematics. He is involved with RRPL, the Rutgers rocketry team, and conducting research on the topic of Lunar Habitats. He will be interning at Blue Origin as a Test Engineering Intern next summer.	

Name: Josh Sar-Shalom	**Photo**
University: University of Central Florida, Florida	
Bio: Undergraduate Sophomore that was pursuing bachelors in Mechanical Engineering, but switched their most recent semester to Computer Engineering. They’re passionate about electronics and computer software.	

Name: Mihir Bhagat	**Photo**

University: Florida Institute of Technology, Melbourne, Florida	
Bio: Undergraduate senior pursuing a Bachelor of Science in Astronomy and Astrophysics. Currently researching the asymmetrical nature of supernova SN 1572 for the Northrop Grumman Engineering & Science Student Design Showcase. Interested in starting a career in industry.	

Name: Mason Thaochuetoua
University: Rutgers University, New Brunswick, New Jersey
Bio: Undergraduate junior currently pursuing a Bachelor of Science in Mechanical Engineering. Currently interning at McWilliams Forge and is involved in RFR, the Rutgers SAE racing team.

Name: Adriana Gaitan
University: Princeton University, Princeton, New Jersey
Bio: Experienced in environmental science, engineering, and programming. Passionate about science and astronomy, and working with the science team to bring ideas together.

1.8.2. Team Management Overview

The successful planning and execution of any mission depends entirely on the collective knowledge/skills of each team member and the team's overall coordination and cooperation.

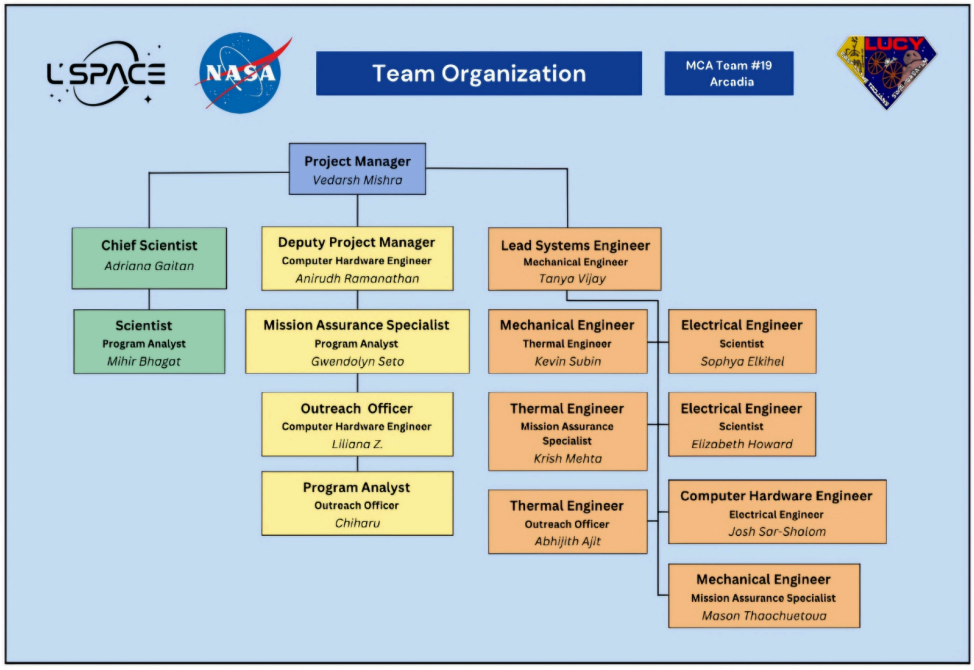
A mission of such specification requires a multidisciplinary team with specialized skills. Mechanical Engineers with expertise in CAD are essential for designing the chassis and structural components to house the mission's elements. Electrical Engineers must develop reliable power systems to ensure a consistent energy supply is delivered to all critical components. Computer Engineers play a key role in selecting devices for data collection and storage, as well as configuring communication systems to relay data back to Earth. Thermal Engineers are responsible for designing protective measures to shield the system from the harsh conditions of space. Scientists are needed to define the mission's objectives and select appropriate instrumentation to achieve them effectively. Program Analysts and Mission Assurance Specialists are crucial for managing the project’s budget and timeline, ensuring everything stays within the enforced constraints. Outreach Officers are required to publicize the mission’s purpose and provide updates throughout its lifecycle.

Effective planning for this mission requires clear leadership and collaboration across the specified divisions. To ensure this, leaders must oversee specific areas of responsibility. A Chief Scientist should lead the scientists, ensuring that mission objectives and instrumentation are properly defined. A Deputy Project Manager should oversee the Program Analyst, Outreach, and Mission Assurance teams, tracking and maintaining budget, timeline, and public engagement. A Lead Systems Engineer is needed to coordinate all engineering operations, ensuring seamless integration and collaboration between mechanical, electrical, computer, and thermal engineering efforts. To maintain alignment across all sectors, a Project Manager should oversee these subdivisions to maintain consistent progress toward mission goals.

Team Arcadia is well-equipped to meet the requirements and overcome the constraints of the mission, *Operation Lunar Descent*. Team roles were carefully assigned, accounting for key factors such as skills, time commitments, leadership abilities, and communication strengths. While leadership roles were established to guide subteams and ensure overall progress, the team adopted a collaborative approach where every member shared equal responsibility/freedom in steering the deployment of the mission. When issues arose (selecting among competing ideas or strategizing the resolution of

complex issues), they were addressed through team-wide sessions, fostering inclusive problem-solving and collective ownership of the mission's success. The team will continue to utilize such strategies for problem resolution if/when similar situations arise in the future.

The success of the mission relies on the team dynamics/operation in delegating tasks and completing deliverables as per the requirements. The team conducts regular meetings to distribute the work among the team members. Team members are assigned to parts of the deliverables based on their strengths and team roles. Members working on the same deliverables collaborate closely to complete their respective sections effectively. At the end of each week, the entire team convenes to share progress updates, address any challenges, and consolidate individual contributions into a comprehensive document, maintaining progress and continuity in the development of the project.



1.8.3. Major Milestones Schedule

The following are the main turning points in the mission's lifecycle:

It is anticipated that the Mission Concept Review (MCR) will be finished by October 7, 2024. This milestone will signal the end of the concept development phase, where the team will have determined the high-level objectives, customer needs, and the mission's scope.

By October 28, 2024, the Systems Requirements Review (SRR) will take place. Following the preliminary design stage, this review will evaluate the system requirements and designs to make sure that all specifications support the mission's objectives.

On December 9, 2024, the Preliminary Design Review (PDR) is planned. To guarantee that every component is prepared for additional development and integration, this milestone will entail the completion of the design and a thorough examination of the related documentation.

On October 5, 2024, the Test Readiness Review (TRR) is scheduled. The purpose of this assessment is to ensure that the design is ready for integration and testing by confirming that all subsystems and components are ready for the testing phase.

By April 16, 2024, the System Integration and Verification (V&V) phase will be finished. During this time, the integrated systems will undergo validation and verification to ensure that each subsystem functions as intended in the larger system.

December 19, 2024 is the date of the Integration Test Readiness Review. Before moving on with flight readiness, this milestone will assess the integrated systems' preparedness and ensure that all required tests are completed.

By March 12, 2025, launch and in-orbit validation (V&V) will occur. Verifying the launch vehicle's performance and conducting in-orbit checks to make sure the systems are functioning as intended in the space environment are part of this crucial milestone.

On December 19, 2024, the Mission Operations Start will take place, signaling the changeover from system integration to real mission operations. The system's performance in space will be tracked during this phase by continuous flight operations and in-orbit validation.

Lastly, on September 18, 2025, Mission Sustainment Initiation will get underway. Assuring that systems are maintained and functional for the duration of the mission, this phase focuses on the mission's long-term sustainability and support.

On May 19, 2027, the mission will achieve its Final Mission Milestone, which will signify the end of the sustainment phase and the accomplishment of all mission goals.

1.8.4. Budget Overview

The following section outlines the budget plans in a table format for Operation Lunar Descent through project phases C through F. All values are rounded to the nearest thousand, and only significant totals are included in the following table. A larger, more detailed budget template can be found.

Old version:

Item	Cost
Personnel	$43,205,000.00
Travel	$4,232,000.00
Outreach	$4,210,000.00
Direct Costs	$338,140,000.00
F&A	$25,386,000.00
Total Project Cost	$415,173,000.00

The NASA Cost Estimation handbook and the L'SPACE Project Management Skill Module outline the cost structure for a general Discovery Class Mission and were used as guidelines for the budgeting for this section. Each category was developed considering past small strategic missions, such as LADEE (Lunar Atmosphere and Dust Environment Explorer), Lunar Reconnaissance Orbiter (LRO), and analogous NASA rover missions like Spirit and Opportunity. The table above outlines the total costs derived from a budget template, which the following sections discuss further. Margin and Modified Total Direct Costs are not included in this table. [Details regarding the rationale behind the current budget are provided in the Appendix]

2. Overall Vehicle and System Design

2.1. Spacecraft Overview

Req #	Requirement	Rationale	Parent Req	Child Req	Relevant Subsystem	Verification method	Req met?
0.1	Spacecraft shall survive lunar pit environment for 12 month mission lifetime	Spacecraft must be able to achieve mission goals throughout duration of lifetime as defined by the client	NC-1.0	SYS.01, SYS.03, SYS.04	All	Demonstration	Met
SYS.01	Spacecraft shall generate power for itself for the duration of the mission lifetime	All subsystems and instrumention on spacecraft require power for operation	NC-1.1	PS.1.0	Power	Demonstration	Met
SYS.02	Spacecraft shall not exceed total mass of 350 kg	Spacecraft must meet launch provider constraints	-	MEC.09, MEC.09.1, MEC.09.2	All	Inspection	Met
SYS.03	Spacecraft shall be capable of operation within temperatures of 103 K to 395 K	Spacecraft must be able to operate within variable lunar temperatures	NC-1.3	MEC.02, TH.1	Thermal Management	Demonstration	Met
SYS.04	Spacecraft shall be able to withstand accumulation of lunar dust	Lunar dust is common in lunar atmosphere and may pose challenges to instrument operability	NC-2.3	MEC.04.3	All	Test	Met
SYS.05	Spacecraft shall be capable of descending into MTP	Necessary for exploration of target location	NC-1.2	MEC.04.1	Mechanical	Demonstration	Met
SYS.06	Spacecraft shall be capable of mobility within MTP	Necessary for exploration of target location	NC-1.0	MEC.04.2, MEC.06	Mechanical	Demonstration	Met
SYS.07	Spacecraft should map the geometry of interior of MTP	Relating to goals as defined in STM	SC-1.1	Struc-6, Struc-9	Payload	Demonstration	Met
SYS.08	Spacecraft should map the geometry of the surface within 8 meter radius of MTP entrance	Relating to goals as defined in STM	MT-5.0	Struc-1, Struc-4, Struc-6, Struc-9	Payload	Demonstration	Met
SYS.09	Spacecraft should measure indicators of habitability as defined in STM	Relating to goals as defined in STM	SC-1.2	Env-1, Env-2, Env-3, Env-4	Payload	Demonstration	Met

Spacecraft Overview:

Mechanical Subsystem: Composed of a durable chassis and a 6-wheel rocker-bogie suspension system for stability and terrain navigation. The chassis provides mounting points for other subsystems and instruments, while the suspension system mitigates impact forces during movement. The robotic arm with 5 DoF assists with sample collection and instrument handling.

Power Subsystem: Solar panels mounted on the chassis harness solar energy during the lunar day, while lithium-ion batteries store energy to power the rover during the night. The PMAD system ensures reliable power distribution.

Command and Data Handling (CDH) Subsystem: Centralized control hub for the spacecraft, managing data acquisition, processing, and communication. The CDH unit features a radiation-hardened CPU, memory modules, and interfaces with the communication system to send data back to Earth.

Thermal Management Subsystem: Combines multilayer insulation (MLI), heat pipes, and radiators to regulate temperature. Small electrical heaters are used to maintain the temperature during lunar night conditions.

Payload Subsystem: Houses the primary payload, including spectrometers for surface composition analysis, LiDAR for mapping the pit's topography, and sensors for temperature and radiation monitoring.

Mass, Dimensions, and Power Draw Table:

Subsystem	Mass (kg)	Dimensions (m)	Max Power Draw (W)
Mechanical	178	2m x 1.5m x 1.5m	110 W
Thermal	30.8	Radiator: 0.2 x 0.15 x 0.1; Heat Pipes: 1-2 m (length); Electric Heater: 0.5 x 0.275 x 0.11	16.2 W
CDH	34	Data Computing Module: 15 x 10 x 3 cm; Antenna: 185 mm diameter, 69 mm height	86 W
Power	17.5	Solar Panels: 1.1 x 0.6 (when deployed); PMAD: 0.2 x 0.15 x 0.1	310 W
Payload	14.52	Resistance Temperature Detector - 2 x 2 x 0.8 mm, Stereoscopic Camera - 164 x 32 x 37 mm, Ground Penetrating Radar - 203.1 × 96.5 × 30.5 cm, Radiation Dosimeter - 200 x 70 x 45 mm, Spectrometers - 29.8 x 21.6 x 12.2 cm	70 W
Total	274.82	N/A	110 W

Chassis:

- **Material Selection**: The rover will mainly be made of aluminum-based chassis. Aluminum alloy, more specifically 2000 series Aluminum has been used before in previous missions to explore the surface of Mars. Furthermore, it is extensively used in the aerospace industry. Aluminum was chosen over carbon fiber due to its cost and performance under harsh UV conditions. Carbon fiber requires an exotic manufacturing process to prevent it from deteriorating in extreme UV environments, a deficiency aluminum does not have. However, carbon fiber can be used on interior sections as it will be protected from the elements by aluminum panels facing the exterior.

- **Structural Design**: The rover will utilize a standard ladder frame chassis. This type of chassis offers good rough terrain performance and a simpler manufacturing process. The frame will be combined with aluminum panels to shield interior parts from heat and UV radiation. The majority of the interior of the

rover will consist of computers and storage devices. These are extremely vital to the mission as these components control the rover itself and store the data collected during the mission.

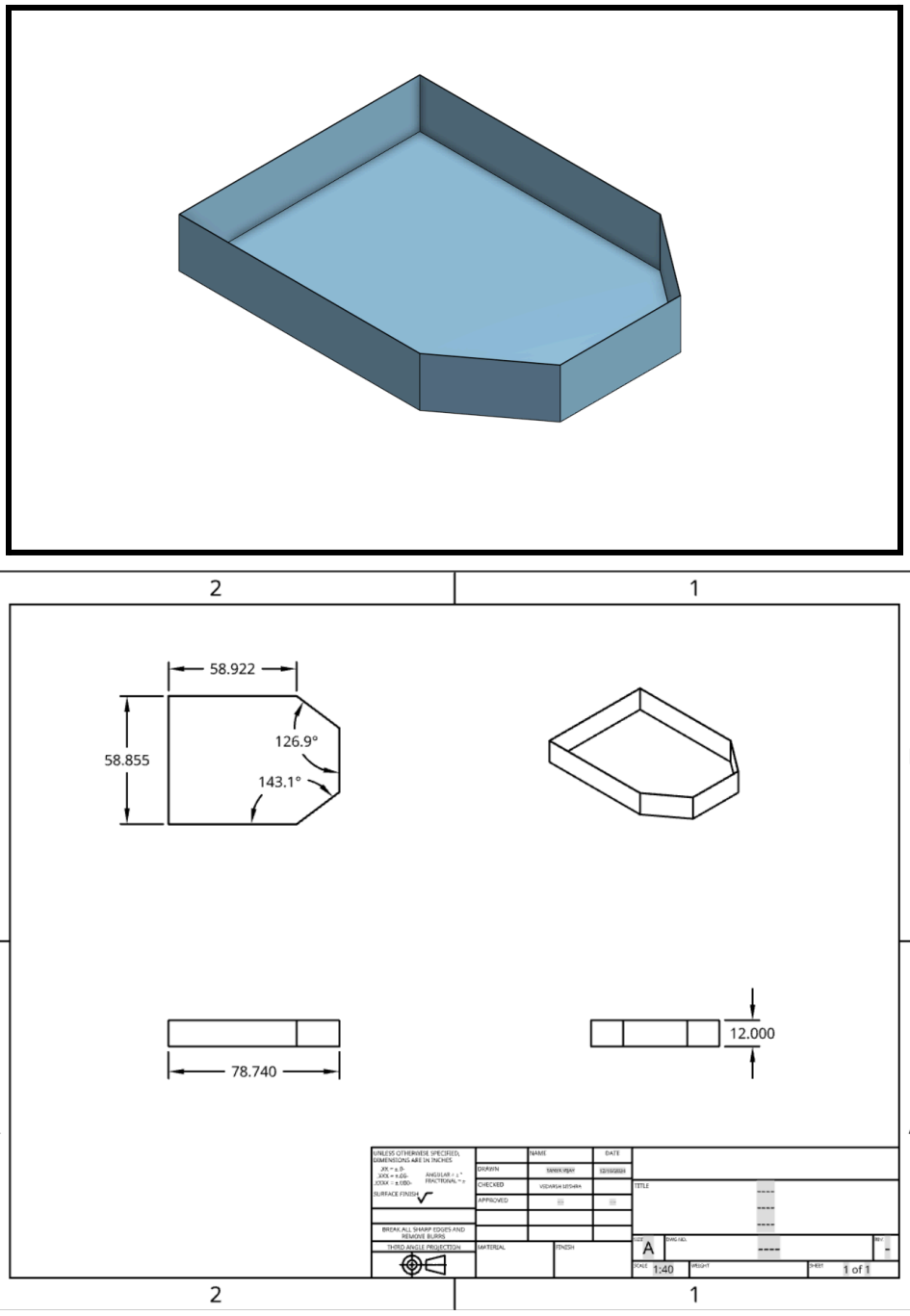
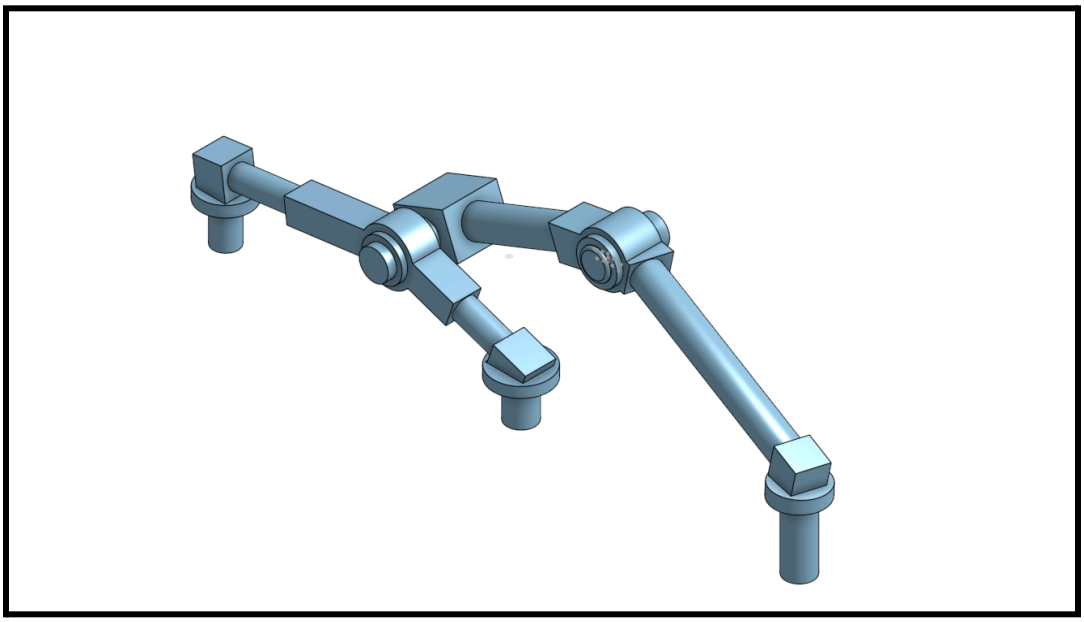


Figure 2.1.1: Chassis Design of Rover

Suspension:

- **Structural Design:** The rover will utilize a 6-wheel suspension configuration incorporated into a 4-wheel drive with rocker-bogie suspension. A 6-wheel suspension configuration allows for an even distribution of weight even on uneven terrain. The two bogie wheels are attached to the chassis by means of a passive rotating joint. A differential mechanism controls the rotation of the rocker, allowing the chassis to reorient the axes of each pair of wheels while traversing uneven surfaces. This also ensures that all wheels bear the load of the system regardless of the drive base's angle with the horizontal lunar surface. This functionality also reduces the risk of tipping. To augment uneven terrain navigability, an autonomously adaptive liquid spring/damper system will be mounted between the rocker and bogie linkages to increase the load on the center bogie wheels. This will allow the front and back wheels to more easily climb or dismount uneven surfaces. The use of rocker-bogie suspension allows the rover to navigate through obstacles with the size of at least one wheel diameter.



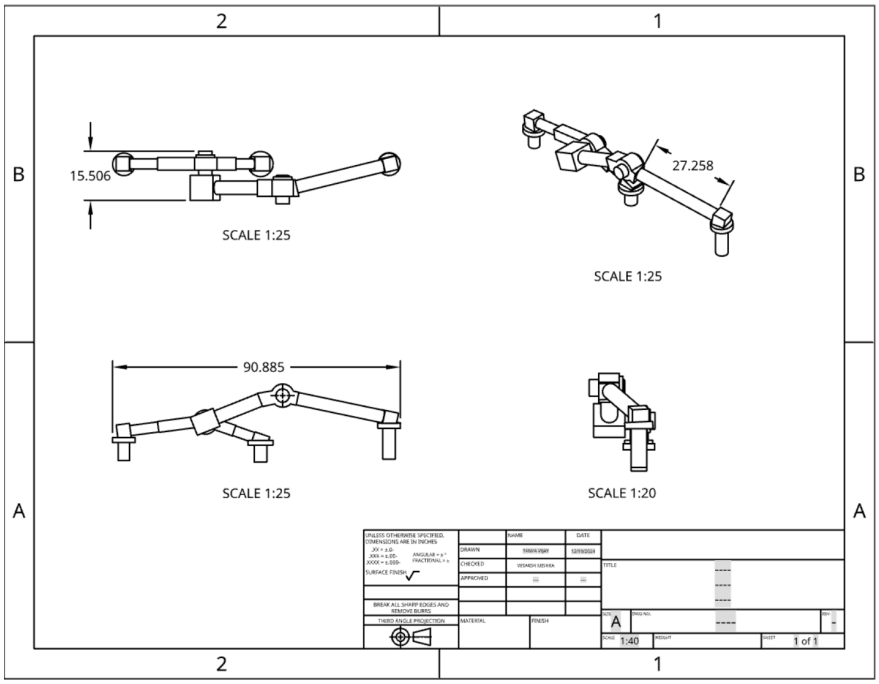


Figure 2.1.2: Rover Suspension Design Visualization

Robotic Arm:

- **Structural Design:** The robotic arm will consist of a turret and five additional axes of freedom. The arm will be capable of a maximum extension of 2 meters.

- **Material Selection:** Internal gears within the arm will be manufactured from bulk metallic glass to reduce operational wear observed on the Curiosity and Perseverance rovers' robotic arms. Bulk metallic glass also eliminates the need for heating or lubrication to operate in cold temperatures, which are often observed in areas below the lunar surface that do not receive sunlight. This allows for reduced power consumption since additional heating does not need to be provided to ensure gears do not freeze in extreme conditions. Additionally, since bulk metallic glass will not melt in high temperatures, gearboxes can be placed closer to thermal components than in prior rover designs, allowing for the optimization of space and reducing the necessity for heat shielding between mechanisms.

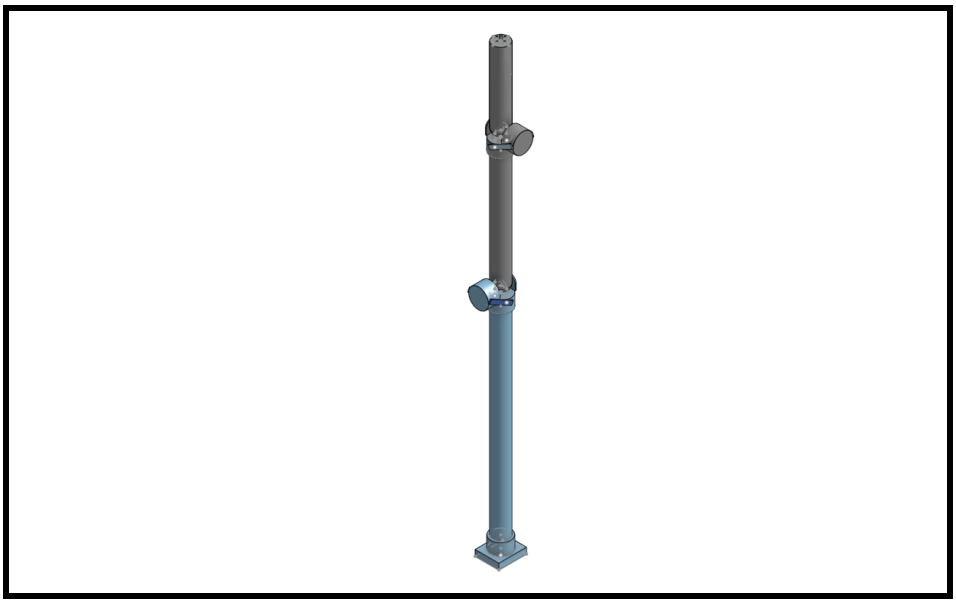
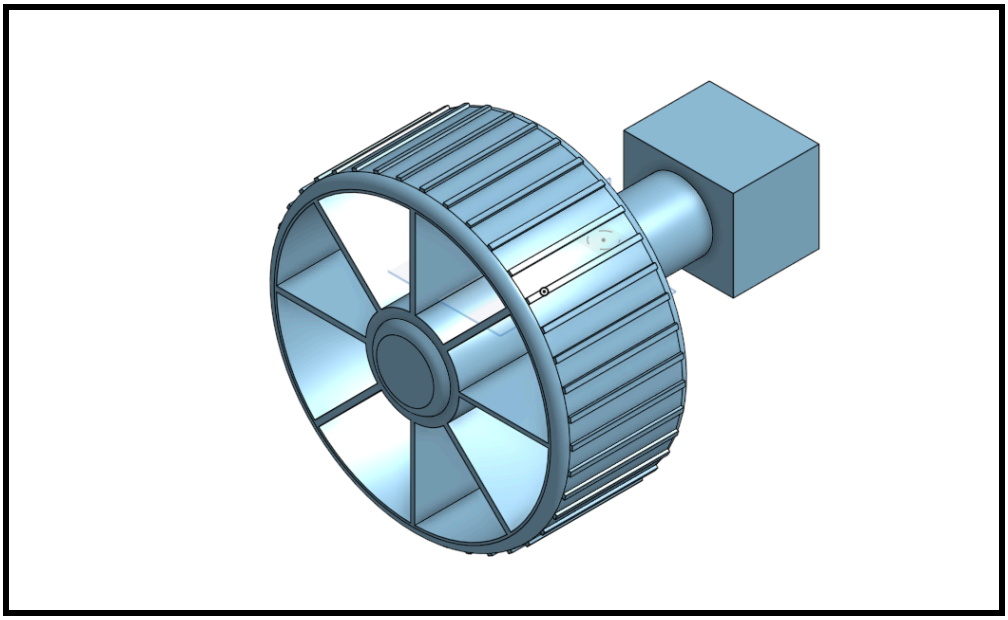


Figure 2.1.3: Robotic Arm Design Visualization

Wheels:

- **Wheel Selection:** The rover will utilize Superelastic Tires consisting of nickel-titanium shape memory alloy springs. Superelastic Tires pose several novel advantages. Firstly, they can withstand deformation with greater success than elastoplastic materials such as steel commonly used in traditional springs. Secondly, they offer strong traction. Thirdly, they do not require an inner frame, reducing the overall weight of the spacecraft and subsequently, reducing power draw.



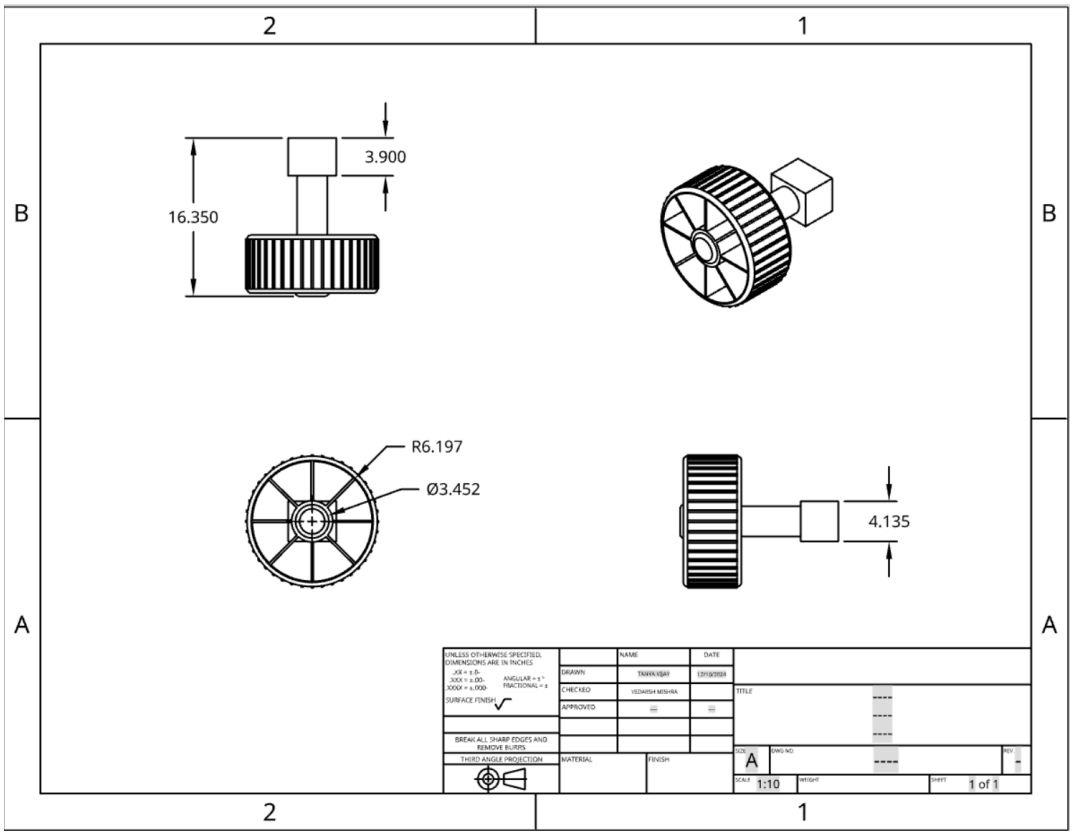
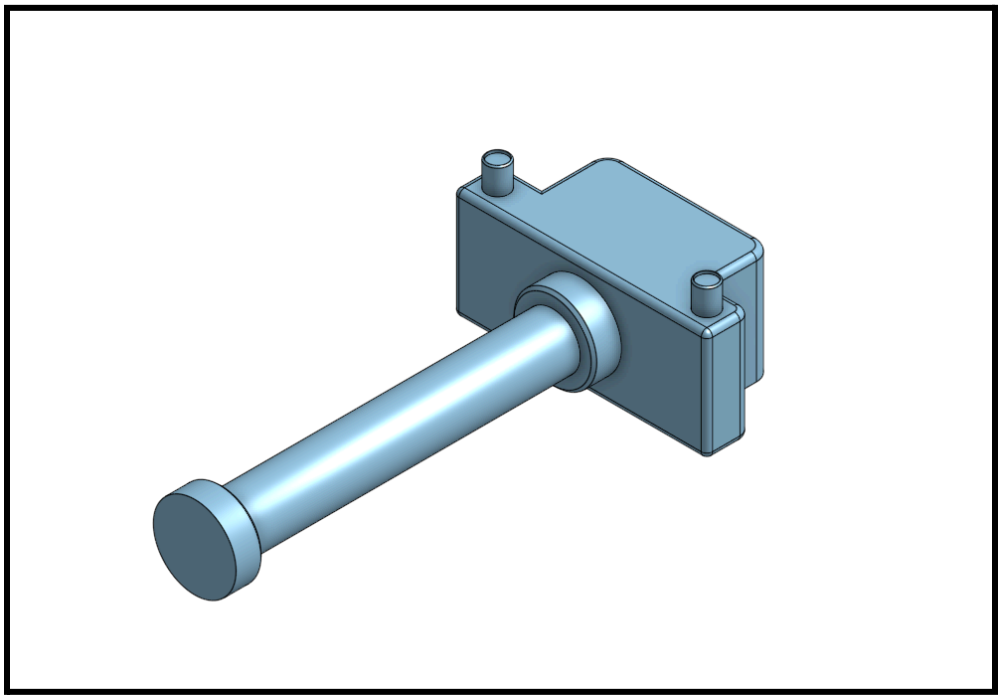


Figure 2.1.4: Wheel Model

Masthead:

- **Structural Design:** The rover will utilize a fixed masthead which will help mount the camera for imaging and headlights for vision. The method will provide plenty

of stability. A fixed masthead is also a good idea because this is a simple design and implementing a fixed masthead will be cost effective. A masthead made of aluminum material will be used due to its ability to withstand harsh environments and cost. It's also lightweight and durable making it easier to build.



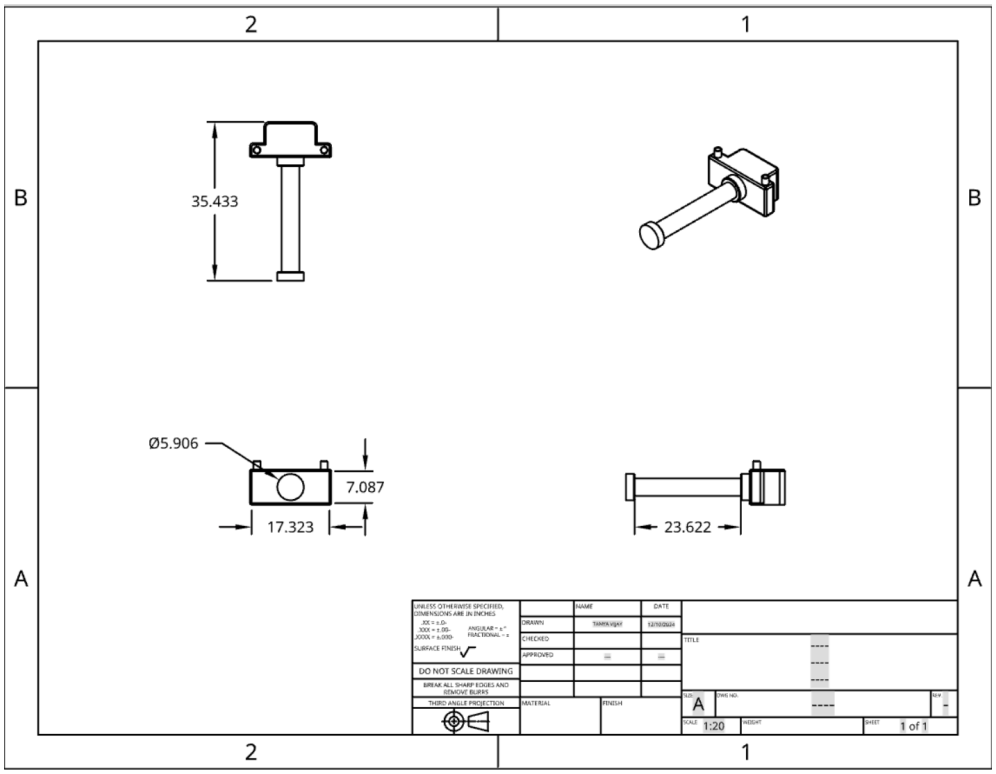


Figure 2.1.4: Masthead Model

2.1.1. Mechanical Subsystem Overview

The mechanical subsystems of the rover were designed to work as a collective unit to maximize performance and efficiency in the lunar environment. The integration of these mechanical subsystems enables the rover to traverse on the uneven lunar surface, withstand extreme temperature fluctuations ensuring thermal stability of the entire system, and maintain operation in harsh UV radiation.

The chassis serves as the structural foundation of the rover, constructed from 2000 series aluminum alloy. This material ensures durability, weight efficiency, and cost-effectiveness, making it ideal for the harsh lunar environment. The ladder frame design of the chassis provides strength and flexibility, ensuring that the rover can withstand the different forces it will experience by traversing on the lunar terrain. In order to ensure thermal stability of the computers and data storage devices inside the chassis, aluminum panels will be used to shield these devices from heat and UV radiation.

Mobility of the rover was designed with a six-wheel drive system featuring rocker-bogie suspension. This type of suspension ensures even weight distribution and high stability, enabling the rover to navigate obstacles on the lunar surface. The suspension system is

augmented by an autonomously adaptive liquid spring/damper mechanism, which enhances traction by redistributing loads across the wheels. This allows the rover to traverse steep slopes and uneven surfaces without compromising rover stability, minimizing the risk of tipping over.
The rover will utilize Superelastic Tires consisting of nickel-titanium shape memory alloy which enhance the mobility of the rover by offering good resilience. These tires can endure significant deformation, reducing the risk of damage from sharp rocks or uneven terrain, while their lightweight design lowers the overall power consumption of the rover.

The GNC (Guidance, Navigation, and Control) subsystem ensures precise maneuverability and autonomous operation of the rover to avoid hazardous situations. The GNC subsystem includes a LIDAR, stereo cameras, and an inertial measurement unit (IMU) to map the lunar environment in real time and plan efficient paths for exploration while avoiding obstacles. The control system adjusts wheel forces, speed, and direction to maintain stability throughout exploration. As a result, these rocker-bogie suspension and the wheel material ultimately plays a role in an efficient GNC system of the rover.

The fixed masthead supports imaging and illumination systems for maximum vision, utilizing aluminum for durability and minimal weight. LED headlights mounted on the mast and base provide adaptable lighting for the rover applying the high beam/low beam concept and will provide more long distance and broader vision, enhancing navigability for the rover.
Lastly, the robotic arm extends the rover’s operational capabilities. Its turret, additional 5 degrees of freedom, and 2-meter extension allow it to interact with the environment for sample collection or instrumentation placement. Bulk metallic glass gears reduce wear and eliminate the need for additional heating, ensuring reliable operation in extreme cold and hot temperatures.

Together, these mechanical subsystems enable the rover to perform a wide range of mission tasks, including traversing rocky and uneven terrain, exploring lunar pit caves, surviving temperature fluctuations, and enduring intense UV radiation. This integrated approach of the mechanical subsystems ensures the rover's capabilities for sustained exploration of lunar caves and lunar environment.

2.1.1.1. Mechanical Subsystem Requirements

Mechanical requirements outline the performance characteristics that the system must meet. These requirements are derived from customer constraints that drive what the

vehicle needs to do and what needs to be accomplished. For this section, it covers mainly structural, suspension, mobility, and GNC (Guidance and Navigation Control).

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
MEC.01	The system shall have a stowed configuration of 2m x 1.25m x 1.25m	Mission Document	Customer	N/A	Inspection	Met
MEC.02	The system shall maintain structural integrity within the temperature range of 121ºC to -133ºC	Structure expands and contracts due to temperature changes	SYS.03	N/A	Analysis	Met
MEC.03	The system shall be able to recover from a position in which at least 2 wheels lose traction	Uneven terrain will be encountered in MTP	SYS.07	N/A	Demonstration	Met
MEC.04	The system shall be able to support all instruments required.	Needs to transport all instruments to target area	0.2	MEC.04.1, MEC.04.2, MEC.04.3	Analysis	Met
MEC.04.1	The suspension of the system shall provide adequate shock absorption to protect sensitive instruments	Instruments are possibly sensitive to vibrations	MEC.04	N/A	Test	Met
MEC.04.2	The structure shall support the weight of all required science instruments, which amount to no less than 25kg	Needs to transport all instruments to target area	MEC.04	N/A	Analysis	Met
MEC.04.3	The system shall protect instruments from debris and dust.	Instruments are vital to the mission and need to be protected from damage	MEC.04	N/A	Test	Met
MEC.05	The system shall be able to withstand a collision at speeds up to 0.5 mph	Needs to operate and be able to recover on its own	SYS.07	N/A	Analysis	Met
MEC.06	The system should travel at speeds not exceeding 0.15 mph	Ensures safe operation and limits power usage	SYS.07	N/A	Demonstration	Met
MEC.07	The system shall be able to be located regardless of position.	Needed to control the vehicle	SYS.09	MEC.07.1 MEC.07.2	Demonstration	Met
MEC.07.1	Gyroscope shall have a sensing resolution of 0.01 dps/hz^1/2	Needs precise measurement for navigation, especially since GPS is not available.	MEC.07	N/A	Inspection	Met

MEC.07.2	Gyroscope shall operate at 24,000 rpm during launch, and be reduced to 15,000 rpm during surface operations.	Needs to withstand forces of launch via angular momentum.	MEC.07	N/A	Analysis	Met
MEC.08	The tether system shall be able to support the full/more weight of the entire vehicle and its instruments	Needs to support the weight of the vehicle to prevent free fall into MTP	SYS.06	MEC.08.1	Analysis	Met
MEC.08.1	The tether should be at least 400ft in length and at least 3/8 in diameter	Ensures structural the integrity of the cable as well as giving enough length to not hinder movement of vehicle	MEC.08	N/A	Analysis	Met
MEC.09	The mechanical subsystem shall be no more than 180 kgs in weight	Need to allocate a set amount of weight for the weight "budget"	SYS.02	MEC.09.1, MEC.09.2	Inspection	Met
MEC.09.1	The suspension of the system shall be no more than 30 kgs in weight	Need to allocate a set amount of weight for the weight "budget"	MEC.09	N/A	Inspection	Met
MEC.09.2	The chassis of the system shall be no more than 70 kgs	Need to allocate a set amount of weight for the weight "budget"	MEC.09	N/A	Inspection	Met
MEC.10	The system shall cost no more than $60,000,000	Cannot exceed given budget	Customer	N/A	Blank	Not Met
MEC.11	The system shall support the weight of the power subsystem, amounting to no less than 20 kg.	Needs to transport vital power systems for the survival of the vehicle.	0.1	N/A	Analysis	Met
MEC.12	The system shall support the weight of the CDH subsystem, amounting to no less than 20 kg.	Needs to transport the computer of the vehicle.	0.1	N/A	Analysis	Met
MEC.13	The system shall support the weight of the Thermal subsystem, amounting to no less than 20 kg.	Needs to withstand the weight of the thermal protection equipment.	0.1	N/A	Analysis	Met

2.1.1.2. Mechanical Sub-Assembly Overview

The mechanical subsystem is designed to allow for continuous wheeled mobility when entering MTP and for navigating within the pit itself. The mechanical subsystem consists of the chassis, wheels, suspension, GNC, deployment systems, masthead, robotic arm, and headlights.

Chassis

- **Material Selection**: The rover will mainly be made of aluminum-based chassis. Aluminum alloy, more specifically 2000 series Aluminum has been used before in previous missions to explore the surface of Mars. Furthermore, it is extensively used in the aerospace industry. Aluminum was chosen over carbon fiber due to its cost and performance under harsh UV conditions. Carbon fiber requires an exotic manufacturing process to prevent it from deteriorating in extreme UV environments, a deficiency aluminum does not have. However, carbon fiber can be used on interior sections as it will be protected from the elements by aluminum panels facing the exterior.

- **Structural Design**: The rover will utilize a standard ladder frame chassis. This type of chassis offers good rough terrain performance and a simpler manufacturing process. The frame will be combined with aluminum panels to shield interior parts from heat and UV radiation. The majority of the interior of the rover will consist of computers and storage devices. These are extremely vital to the mission as these components control the rover itself and store the data collected during the mission. Six motors will be used to power each of the wheels of the drivetrain.

- **Technology Readiness Level:** 5; An aluminum chassis/body has already been used multiple times on Martian rovers. The system has been proven on the Martian surface, however, it is unknown how it will perform in a lunar cavern, granting the system a lower TRL of 5.

Suspension

- **Structural Design:** The rover will utilize a 6-wheel suspension configuration incorporated into a 4-wheel drive with rocker-bogie suspension. A 6-wheel suspension configuration allows for an even distribution of weight even on uneven terrain. The two bogie wheels are attached to the chassis by means of a passive rotating joint. A differential mechanism controls the rotation of the rocker, allowing the chassis to reorient the axes of each pair of wheels while traversing

uneven surfaces. This also ensures that all wheels bear the load of the system regardless of the drive base's angle with the horizontal lunar surface. This functionality also reduces the risk of tipping. To augment uneven terrain navigability, an autonomously adaptive liquid spring/damper system will be mounted between the rocker and bogie linkages to increase the load on the center bogie wheels. This will allow the front and back wheels to more easily climb or dismount uneven surfaces. The use of rocker-bogie suspension allows the rover to navigate through obstacles with the size of at least one wheel diameter.

- **Technology Readiness Level:** 7; A rocker-bogie suspension configuration has been used and proven successful operation on various Martian rovers, the most recent application being on the Perseverance rover. Since the system has been tested and proven successful in an operational environment (the Martian surface), it has a high TRL. However, since the system's performance has only been verified on the Martian surface as opposed to the lunar surface, it must be assigned a TRL of 7.

Wheels

- **Wheel Selection:** The rover will utilize Superelastic Tires consisting of nickel-titanium shape memory alloy springs. Superelastic Tires pose several novel advantages. Firstly, they can withstand deformation with greater success than elastoplastic materials such as steel commonly used in traditional springs. Secondly, they offer strong traction. Thirdly, they do not require an inner frame, reducing the overall weight of the spacecraft and subsequently, reducing power draw.

- **Technology Readiness Level:** 6; The Superelastic Tire has been testing in relevant environments on Earth with conditions simulating an operational environment and has proven successful performance. However, since it has not been tested in an operational environment (a planetary surface), the Superelastic Tire must be assigned a TRL of 6.

GNC

- **Guidance:** Once the rover has been activated, it will start moving towards the direction of the cave with an algorithm that the rover will follow, However, using the scanners and sensors from the navigation system, it will develop a route. This can be changed given what feedback the control system receives from the sensors. For the rover, the guidance system will use a combination of 3D maps

and real-time data from cameras and LIDAR to plan a path that avoids large rocks, steep slopes, or regions that could cause the rover to be less efficient.

- **Navigation:** The navigation system will feature multiple components to assist in successful navigation. First, it will include a three-axis gyroscope which will help in determining the movement and orientation of the rover. This will provide continuous data of the pitch, roll, and yaw of the rover. There will also be an accelerometer designed to track speed changes. These components will be classified as the inertial measurement unit (IMU). Furthermore, wheel encoders will be added to the wheels to measure the rotational movement of the wheel which will show how far the rover has traveled from the starting point and how fast the rover is moving. A stereo camera will be added to the rover to capture 3D images of the lunar surface to create a 3D map of the surroundings which will help the rover detect obstacles such as big rocks, and steep slopes. The rover will also include a LIDAR system which will scan the environment to map the terrain. This will help the rover in moving around the obstacles mentioned above.

- **Control:** The control system will include 3 key components: Drive control, hazard detection, and stability control. These components will be mainly based on algorithms and code implemented in the rover. Given the orientation data from the IMU, the system will adjust accordingly to ensure stability. This means the control system will adjust the speed in different terrain areas to ensure efficient maneuverability. Secondly, the hazard system is important and should autonomously identify hazards, such as steep drop-offs or large rocks, and adjust the path to avoid them. In these situations, the control system will receive data from the guidance and navigation system to compute the best path to get around the obstacle. Given the data from the LIDAR system and stereo camera, the control system will identify these hazards and adjust the rover's driving behavior to maintain a safe path. The rover will have a rocker-bogie suspension, thus the stability control will be implemented due to the suspension chosen. On rough terrain, the wheels will remain on the ground. If there are uneven forces on each wheel, the control system will adjust and ensure that the force is distributed evenly to maximize stability and traction. These control systems will take the data from the navigation system which will help the rover in guidance.

- **Technology Readiness Level:** 6; The GNC system of the rover mentioned above has been used in multiple missions on the moon. Additionally, it's this same technology and processes that engineers implement to ensure the guidance, navigation, and control of the rover is successful. However, given that

this GNC configuration has not been used in previous missions, it has been assigned a lower TRL of 6.

Masthead

- **Structural Design:** The rover will utilize a fixed masthead which will help mount the camera for imaging and headlights for vision. The method will provide plenty of stability. A fixed masthead is also a good idea because this is a simple design and implementing a fixed masthead will be cost effective. A masthead made of aluminum material will be used due to its ability to withstand harsh environments and cost. It's also lightweight and durable making it easier to build.

- **Technology Readiness Level:** 8; Fixed mastheads have been used in the past before for lunar rover missions to provide live imaging and headlights for better vision. Thus, a TRL level of 8 was assigned.

Robotic Arm

- **Structural Design:** The robotic arm will consist of a turret and five additional axes of freedom. The arm will be capable of a maximum extension of 2 meters. The turret and each of the five joints will be powered by rotary actuator motors, requiring six additional motors.

- **Material Selection:** Internal gears within the arm will be manufactured from bulk metallic glass to reduce operational wear observed on the Curiosity and Perseverance rovers' robotic arms. Bulk metallic glass also eliminates the need for heating or lubrication to operate in cold temperatures, which are often observed in areas below the lunar surface that do not receive sunlight. This allows for reduced power consumption since additional heating does not need to be provided to ensure gears do not freeze in extreme conditions. Additionally, since bulk metallic glass will not melt in high temperatures, gearboxes can be placed closer to thermal components than in prior rover designs, allowing for the optimization of space and reducing the necessity for heat shielding between mechanisms. Previous NASA missions did not utilize bulk metallic glass gears due to concerns about brittleness of material when faced with extreme and frequently fluctuating temperatures. However, since the temperature within MTP is relatively stable, the concern of potential brittleness is no longer as relevant.

- **Technology Readiness Level:** 5; While bulk metallic glass has been tested in operational environments, it has not yet been tested in gearboxes outside of a laboratory environment. The structural design of the robotic arm carries a higher

TRL since it has been used on the Perseverance rover, however, the lower TRL of the bulk metallic glass supersedes the higher TRL of the robotic arm.

Headlights

- **Technology Selection:** The headlights will employ LED technology due to their efficiency. Headlights with higher intensity will be mounted on the mast to provide narrow long distance vision. Additional LEDs will be mounted at the base of the rover to illuminate a broader area, however this will be at a less intensity than the two mounted above. This applies the high beam/low beam concept and will provide more long distance and broader vision.

- **Technology Readiness Level:** 8; These LED lights have been used in space missions in the past and have been proved to be efficient and effective. In the past, these LED lights have been tested in similar environments to the moon to ensure functionality in such dark environments. These exact lights will be used for a NASA rover which will be exploring the moon. Thus, a TRL level of 8 was assigned.

Cumulative Subsystem TRL: 5; This TRL was determined by considering the lowest TRL of all of the subassemblies within the mechanical subsystem, which was the use of bulk metallic glass for the manufacturing of components of the robotic arm.

2.1.1.3. Mechanical Subsystem Recovery and Redundancy Plans

The mechanical subsystem ensures mobility, proper navigation, and setting up the subassemblies (chassis, suspension, wheels, GNC, masthead, robotic arm, and headlights). The chassis and suspension provide structural support for the mechanical framework. As a result, it is imperative to be structurally sound to support the rest of the assembly. Recovery options within this field could include redundant structural elements. This would allow for support within the structure if a part of the chassis breaks. Though this may not be a permanent solution, having this as a part of the design process would be a safeguard for an emergency. Other preventative measures can also be considered, such as emergency brakes that would help if there are failures in the system. For GNC, navigation is based on algorithms, sensors, and cameras. It could be useful to have backup sensors (for example, infrared) of the model. This would provide an alternative for using LIDAR and cameras if they malfunctioned. For the masthead, having a backup camera or a secondary masthead light can be helpful to ensure continued operation even if the primary components malfunction in the redundancy aspect. In case of failure, the system should rewire itself to rely more

heavily on LIDAR for navigation. Additional headlights can be packed in case one breaks.

Redundancy primarily focuses on the incorporation of multiple instances of critical components to prevent downtime. This includes redundant structural elements within the chassis and suspension to maintain support if a part breaks. For instance, an important topic is how to deal with potential motor failure. The motors that power the wheels of the vehicle need to be protected from dust and other risks that can damage them. Redundancy is not a reliable method to rely on when it comes to the mobility of the vehicle. Having multiple motors for each wheel would make the power system too complex as well as adding extra weight to the vehicle for what is essentially dead weight under ideal conditions is not optimal.

Furthermore, motors, when powering the same device can conflict with each other, reducing efficiency. So, for the mobility of the vehicle protection/hardening would be more valuable than redundancy. However, a solution can be proposed by using hydraulic motors as a backup in case one of the DC motors fails. The same concept applies to the wheels of the vehicle. There is no feasible way to include a redundant system for the wheels in case of damage to the device. This is not the biggest of issues when it comes to the wheels, as in a previous mission, Curiosity sustained damage to its wheels due to rugged terrain, yet its mission was still able to continue. Suspension offers the same problems as the mobility systems of the vehicle as it is difficult to offer multiple failsafe parts to rely upon in case of failure. The legs in the rocker-bogie system will need to be made out of titanium to give them the utmost strength to withstand the given conditions in the lunar cavern. In the chassis of the vehicle, there will be multiple components that will act as a redundant measure in case of failure in one element of the frame. The chassis will be rated for a certain weight class higher than is needed to ensure the whole system does not incur catastrophic failure, similar to a bridge. For the GNC systems, having alternate navigation methods and backup sensors ensures continuous operation, besides a copy of the original device, a different device can be used that measures the same/similar quantity to keep track of the position of the vehicle. Further, redundant light sources for the masthead and additional headlights can also improve reliability. By integrating these redundant elements, the mechanical subsystem can maintain functionality and operate even in the face of unexpected failures.

2.1.1.4. Mechanical Subsystem Manufacturing and Procurement Plans

Part/Assembly	Supplier	Estimated	Justification

	(Contractor/COTS/In-House)	Lead Time	
Chassis, Masthead, Robotic Arm: 2000 series Aluminum	In-House @ Jet Propulsion Laboratory Backup: Astrobotic	3 years	JPL manufactured the chassis for the Mars Perseverance rover. Astrobotic has developed several lunar landers and rovers. Lead time would increase if Astrobotic supplies the chassis, since the rovers previously developed by Astrobotic have been smaller than previous NASA rovers.
Superelastic Tires (nickel-titanium shape memory alloy springs)	In-House @ Glenn Research center Backup: The SMART Tire Company	2 years	Superelastic Tires are still being researched by NASA and currently have a TRL of 4. It is likely that more time will be required before manufacturing. The SMART Tire Company was created by NASA and now develops superelastic tires for terrestrial applications. Lead time would increase if The SMART Tire Company is contracted because the company's focus is on terrestrial applications as opposed to extraterrestrial applications.
LR-450 Inertial Measurement Unit (IMU)	Contractor: Northrop Grumman Backup: Collins Aerospace	3 months	Supplied by a trusted provider for planetary and deep space missions. LR-450 IMU is resistant to variable radiation levels to be expected within the lunar pit, and has a low weight and power draw. A short lead time can be expected since production began in 2023. Collins Aerospace has several IMU's from which a suitable configuration can be chosen. Lead time will remain the same using the backup contractor.
Robotic Arm Internal Gears: bulk metallic glass	In-House @ Jet Propulsion Laboratory (JPL)	TBD	Bulk Metallic Glass gears are already being developed through the BMGG Project.
LED Headlights	Contractor: Sierra Space Backup: Leidos	2 months	TRL 9. Low mass and power draw. A short lead time can be expected since Sierra Space has demonstrated short lead time in previous solar array

			solutions for a 2016 project with the Air Force Research Laboratory. Leidos is also developing external spacecraft lighting, but may have longer lead times since the project is still in the R&D stages.

2.1.1.5. Mechanical Subsystem Verification Plans

Req #	Requirement	Verification method	Rationale for Method	Preliminary Verification Plan
MEC.01	The system shall have a stowed configuration of 2m x 1.25m x 1.25m	Inspection	Simple measurement equipment can be utilized to measure the dimensions of the system when in a stowed configuration.	Portable Coordinate Measuring Machines (CMMs) will be used to precisely measure system dimensions. The system will have met this requirement if the dimensions are the same as defined (the nature of the launch vehicle does not permit a margin of error). Dimensions will be measured every month of development to ensure the rover remains within the maximum size limit through all stages of development.
MEC.02	The system shall maintain structural integrity within the temperature range of 121ºC to -133ºC	Analysis	It would be exceedingly expensive to physically test the stress exerted by temperature.	Thermal stress analysis can be performed on components and systems via computer software such as NASTRAN. The system will have met this requirement if the temperature thresholds are reached/exceeded without failure of the structure. Each component will be tested before testing the entire system.
MEC.03	The system shall be able to recover from a position in which at least 2 wheels lose traction	Demonstration	Need to use software to simulate a model of the vehicle and the conditions on the moon.	A model of the vehicle will be used to demonstrate the recovery system will be effective enough to prevent the vehicle from completely rolling over when traction is lost.
MEC.04	The system shall be able to support all instruments required.	Analysis	Modal analysis can be conducted to determine the modified mode shape due to weights and forces exerted by various components on the overall mechanical structure.	NASTRAN will be used to perform modal analysis focused on analyzing structural integrity under the weight of various subsystem components. The analysis will be conducted on a smaller scale between interfacing components before being conducted on a subsystem level.

MEC.04.1	The suspension of the system shall provide adequate shock absorption to protect sensitive instruments	Test	Ensure the product will survive the launch	Vibration shock testing will be used with a vibration table to identify weaknesses in the structure and to see if internal components could be damaged.
MEC.04.2	The structure shall support the weight of all required science instruments, which amount to no less than 25kg.	Analysis	Modal analysis can be conducted to determine the modified mode shape due to weights and forces exerted by various components on the overall mechanical structure.	NASTRAN will be used to perform modal analysis focused on analyzing structural integrity under the weight of various subsystem components. The analysis will be conducted on a smaller scale between interfacing components before being conducted on a subsystem level.
MEC.04.3	The system shall protect instruments from debris and dust.	Test	Evaluating how the system performs under exposure to similar lunar dust conditions as well as the possible impact from small space debris.	Two tests shall be used to test for protection against debris and dust. For possible debris such as micro meteors impact testing shall be performed against the panels protecting the internal components of the vehicle. For exposure to dust, a thermal vacuum chamber will be used to simulate lunar dust conditions to evaluate the performance of the vehicle and to monitor how dust can affect the system.
MEC.05	The system shall be able to withstand a collision at speeds up to 0.5 mph	Analysis	Modal analysis can be conducted to determine if the system can withstand the forces exerted upon it during a collision.	NASTRAN dynamic analysis will be used to perform modal analysis focused on analyzing structural integrity under the force of a collision at higher speeds than the mission requires.
MEC.06	The system should travel at speeds not exceeding 0.15 mph	Demonstration	Onboard instrumentation can measure the real-time speed of the rover while traversing on the lunar surface.	Onboard IMU can measure the real-time speed of the rover during the "Traversal to Site" phase and any traversal in the "Data Collection" phase.
MEC.07	The system shall be able to be located regardless of position.	Demonstration	Instrumentation can measure the speed and location of the rover during maneuvers.	A HIL test will be performed to simulate the vehicle traversing terrain via simulated data. Furthermore, sensors such as the IMU will be validated and calibrated based on reference values in a controlled environment.
MEC.07.1	The gyroscope shall have a sensing resolution of 0.01 DPS/hz^1/2	Inspection	Need to verify that the sensing resolution on the gyroscope is correct and if any issues that need calibration.	A HIL test will be performed to simulate the vehicle traversing terrain via simulated data. The data given to the gyroscope, to test sensing resolution would be minute angular velocity changes to verify its resolution.
MEC.07.2	Gyroscope shall operate at 24,000 rpm during launch, and be reduced to 15,000 rpm during surface operations.	Analysis	Need to verify if the gyroscope can withstand forces during launch.	Will be included with the HIL test to simulate the vehicle traversing terrain via simulated data. Furthermore, the gyroscope will be validated and calibrated which includes error propagation based on reference values in a controlled

				environment.
MEC.08	The tether system shall be able to support the full/more weight of the entire vehicle and its instruments	Analysis	Modal analysis can be conducted to determine the modified mode shape due to weights and forces exerted by various components on the overall mechanical structure.	NASTRAN will be used to perform modal analysis focused on analyzing the structural integrity of the tether under the weight of the mechanical subsystem. Analysis will be conducted as components are added to the subsystem before conducting analysis using the entire subsystem.
MEC.08.1	The tether should be at least 400ft in length and at least 3/8 in diameter	Inspection	Simple measurement equipment can be utilized to measure the dimensions of the tether.	Coordinate Measuring Machines (CMMs) will be used to precisely measure system dimensions. The system will have met this requirement if the dimensions are the same as defined (the nature of the launch vehicle does not permit a margin of error). Dimensions will be measured once the tether is acquired and once the tether is attached to the launch vehicle and spacecraft, to ensure that dimensions remain unchanged during the assembly process.
MEC.09	The mechanical subsystem shall be no more than 180 kg in weight	Inspection	Simple measurement equipment can be utilized to measure the eight of the system with all components.	Multi-point precision load cells will be used to precisely measure system weight. The system will have met this requirement if the weight is the same as defined (the nature of the launch vehicle does not permit a margin of error).
MEC.09.1	The suspension of the system shall be no more than 30 kg in weight	Inspection	Simple measurement equipment can be utilized to measure the weight of the suspension system.	Multi-point precision load cells will be used to precisely measure suspension system weight. The system will have met this requirement if the weight is the same as defined (the nature of the launch vehicle does not permit a margin of error).
MEC.09.2	The chassis of the system shall be no more than 70kgs	Inspection	Simple measurement equipment can be utilized to measure the weight of the chassis.	Multi-point precision load cells will be used to precisely measure chassis weight. The system will have met this requirement if the weight is the same as defined (the nature of the launch vehicle does not permit a margin of error).
MEC.10	The system shall cost no more than $60,000,000			
MEC.11	The system shall support the weight of the power subsystem, amounting to no less than 20 kg.	Analysis	Modal analysis can be conducted to determine the modified mode shape due to weights and forces exerted by various components on the overall mechanical structure.	NASTRAN will be used to perform modal analysis focused on analyzing the structural integrity of the chassis under the weight of the power subsystem. Analysis will be conducted as components are added to the subsystem before conducting analysis using the entire subsystem. Further analysis will be conducted with all systems together.

MEC.12	The system shall support the weight of the CDH subsystem, amounting to no less than 20 kg.	Analysis	Modal analysis can be conducted to determine the modified mode shape due to weights and forces exerted by various components on the overall mechanical structure.	NASTRAN will be used to perform modal analysis focused on analyzing the structural integrity of the chassis under the weight of the CDH subsystem. Analysis will be conducted as components are added to the subsystem before conducting analysis using the entire subsystem. Further analysis will be conducted with all systems together.
MEC.13	The system shall support the weight of the Thermal subsystem, amounting to no less than 20 kg.	Analysis	Modal analysis can be conducted to determine the modified mode shape due to weights and forces exerted by various components on the overall mechanical structure.	NASTRAN will be used to perform modal analysis focused on analyzing the structural integrity of the chassis under the weight of the thermal subsystem. Analysis will be conducted as components are added to the subsystem before conducting analysis using the entire subsystem. Further analysis will be conducted with all systems together.

2.1.2. Power Subsystem Overview

The power subsystem of the Mare Tranquillitatis Rover is designed to operate efficiently under the harsh lunar environment. The primary components include Power Generation (Solar Panels), Power Storage (Lithium-Ion Batteries), and Power Management and Distribution (PMAD). These components ensure continuous operation through critical mission phases such as Traverse, Data Collection, Data Analysis, Data Relay, Recharge, and Low-Power Survival.

Power Management and Operational Phases

1. Traverse Phase:
    - Duration: Active during lunar daytime for rover mobility.
    - Power Demand: Highest due to motor operations.
    - Power Source: Solar panels generate energy while batteries supplement during peak load.
    - Energy Strategy: Solar-generated power prioritizes propulsion; excess energy is stored.
2. Data Collection Phase:
    - Duration: Scheduled during maximum daylight hours for optimal instrument performance.
    - Power Demand: Moderate to high, based on the number of instruments active.

    - Power Source: Solar energy powers active instruments while batteries supplement if necessary.
3. Data Analysis Phase:
    - Duration: Occurs after data collection when the rover is immobile.
    - Power Demand: Moderate due to onboard data processing.
    - Power Source: Batteries provide steady energy since solar panels may not be fully oriented toward the Sun.
4. Data Relay Phase:
    - Duration: Timed with the orbital pass of the communication satellite.
    - Power Demand: High due to data transmission requirements.
    - Power Source: Solar energy during the day; battery reserves at night.
5. Recharge Phase:
    - Duration: Continuous during lunar daytime.
    - Power Demand: Low when idle.
    - Power Source: Solar-generated power fully charges the batteries.
6. Low-Power Survival Phase:
    - Duration: During the 14-day lunar night.
    - Power Demand: Minimal, limited to thermal regulation and vital communication.
    - Power Source: Batteries operate under low-drain configurations, with essential systems on a survival loop.

Power Management Plan and Decision-Making

- System Prioritization: Power allocation follows a strict operational schedule. Life-supporting and critical scientific operations take precedence over secondary tasks.
- Redundancy Plans: A modular PMAD system, lithium-ion batteries connected in parallel, and dual solar panel arrays ensure reliable operation even if faults occur.
- Energy Optimization: The system dynamically reallocates energy through real-time power management, shutting down non-essential instruments when power conservation is needed.

Power Schedule Visualization

A Power vs. Time Plot should illustrate these operational phases:

- X-axis: Time (Mission Days or Lunar Cycles)
- Y-axis: Power Consumption (Watts)

Plot Key Features:

- High Demand Spikes: Traverse, Data Relay.
- Moderate Demand: Data Collection and Analysis.
- Low Demand: Low-Power Survival and Recharge phases.

This approach to power management ensures that all mission-critical activities are completed within the rover's operational constraints.

2.1.2.1. Power Subsystem Requirements

Requirement ID	Requirement Description	Rationale	Parent Requirement	Child Requirement	Verification Method	Relevant Subsystem
PS-1.0	The power subsystem will generate a minimum of 300 W under nominal conditions	Required to sustain all mission-critical operations during the lunar day.	SYS.01	PS-1.1	Simulation, Analysis	Power Generation
PS-1.1	Solar panels will achieve at least 25% efficiency under lunar illumination conditions.	Ensures adequate energy generation with constrained lunar light levels.	PS-1.0	-	Testing, Analysis	Power Generation
PS-1.2	The power subsystem will function within an operating temperature range of -170°C to 120°C	Allows functionality during extreme lunar day-night cycles	SYS-1.0	-	Thermal Testing	Power Generation

PS-2.0	The power subsystem will store a minimum of 1500 Wh for lunar night operations.	.Sustains rover activities during the 14-day lunar night.	SYS-1.0	PS-2.1	Testing, Analysis	Power Storage
PS-2.1	Batteries will retain 80% capacity after 500 charge-discharge cycles.	Ensures long-term viability across mission duration.	PS-2.0	-	Testing	Power Storage
PS-3.0	PMAD will regulate voltage within ±5% of a 28 V nominal output.	Prevents damage and ensures stable power supply to critical systems.	SYS-1.0	PS-3.1	Simulation, Testing	PMAD
PS-3.1	PMAD will detect and isolate faults within 10 ms to avoid downstream impacts.	Rapid fault isolation is crucial for subsystem safety and operational integrity.	PS-3.0	-	Simulation, Testing	PMAD
PS-4.0	Solar panel dust mitigation will achieve 90% dust removal efficiency during lunar	Ensures sustained power output and efficiency in dusty lunar conditions	PS-1.0	-	Testing, Analysis	Power Generation

	day cycles	.				

2.1.2.2. Power Sub-Assembly Overview

Power Sub-Assembly Overview

The Power Subsystem of the Mare Tranquillitatis Rover is designed to ensure continuous energy availability during the mission's operations, regardless of the lunar day-night cycle. This subsystem is divided into three main areas: Power Generation, Power Storage, and Power Management and Distribution (PMAD). Each area is engineered to withstand the unique challenges of the lunar environment, including extreme temperature fluctuations, limited solar access, and lunar dust accumulation. The goal of the Power Subsystem is to maintain reliable operation of the rover's scientific instruments, thermal controls, communications, and mobility.

Power Generation

Technology and Material Selection:

- **Solar Cells:** Gallium Arsenide (GaAs) solar cells are selected for their high efficiency (25-30%) [National Renewable Energy Labarotory, 1998] and radiation resistance, making them optimal for lunar missions. GaAs cells offer a robust alternative to silicon-based cells, which are less efficient under the harsh lunar conditions.
- **Dust Mitigation Technology:** To counter the effects of lunar dust, which can reduce panel efficiency by up to 50%, an electrostatic dust removal system is incorporated. This non-contact method uses electric fields to repel dust particles, preventing the need for mechanical brushes that could damage the panel surface.

Array Sizing and Performance:

- **Power Requirements:** The rover requires 300 W during the lunar day to meet peak operational demands, including power-intensive activities such as communication and instrument use.
- **Array Surface Area:** Given the lunar solar constant (approximately 1361 W/m²) and a GaAs efficiency of 25%, the required solar panel surface area is calculated as:
    - A=Power per unit area, required Power=1361 W/m^2×0.25300 W≈0.88 m^2
    - To ensure consistent energy generation, this area is rounded up to 1.1 m².

Structural Design:

- **Deployment Mechanism:** Solar panels are stored compactly during transit and deploy upon landing. This deployment is automated and designed to handle the low-gravity environment, ensuring optimal orientation toward the sun.
- **Thermal Protection:** Solar panels are insulated to prevent heat damage during the lunar day and retain operational integrity during the lunar night, where temperatures can plunge to -173°C.

Technology Readiness Level (TRL): 6

GaAs solar panels have been extensively used in space missions and are space-qualified. The dust mitigation system is TRL 6, tested in relevant environments but less proven than the solar cells. Due to this, the overall TRL of the Power Generation subassembly is conservatively rated at **TRL 6**.

Power Storage

Battery Technology Selection:

- **Lithium-Ion Batteries:** Chosen for their high energy density (150-250 Wh/kg), lithium-ion batteries allow compact energy storage, essential for the rover's size constraints. [Clean Energy Institute, University of Washington, 2020] They are capable of deep discharge cycles and have a long lifespan, making them ideal for lunar missions.

Energy Capacity and Calculations:

- **Required Capacity:** To sustain operations during the 336-hour lunar night, the battery pack must store sufficient energy for low-power activities (approx. 50 W average).

Total Required Capacity=50 W×336 hours=16800 Wh

Due to volume and mass constraints, the battery capacity is capped at **1500 Wh**. The rover will enter low-power mode at night to prioritize essential systems only.

Thermal Management:

- **Temperature Control:** Lithium-ion batteries are sensitive to extreme cold, which can reduce capacity and damage internal structures. The battery pack is insulated and includes small heating elements to maintain an operational temperature range during lunar night cycles.

Technology Readiness Level (TRL): 8

- Lithium-ion technology is highly mature and widely used in space applications, making it reliable for this mission. The thermal management methods are also space-tested, securing an overall **TRL of 8** for Power Storage.

3. Power Management and Distribution (PMAD)

Voltage Regulation and Fault Protection:

- **Voltage Stability:** PMAD regulates the voltage to ±5% of 28 V, ensuring stable power supply across subsystems. This stability prevents fluctuations that could damage sensitive scientific instruments or disrupt communication links.[Metkalf, Kenneth, *Power Management and Distribution (PMAD) Model Development,* 2011]
- **Fault Isolation:** Rapid isolation of faults within 10 ms minimizes the risk of power surges and potential damage to critical components. Fault protection relays and switches enable the PMAD to identify and contain electrical anomalies, protecting the rover's electronics.
- **PMAD Model: A modular PMAD design:** A decentralized approach to managing and distributing electrical power across a spacecraft. Other than the centralized systems, where one PCDU was used to manage the power requirements of the entire spacecraft, the modular PMAD system would split the functions into several independent modules. Each module has specific tasks it performs, like regulating power to a particular subsystem, isolating faults, or managing energy flow to instruments.

System Design and Distribution:

- **Circuit Design:** PMAD employs both primary and secondary circuits, allowing it to reroute power in case of component failure. This redundancy helps ensure that critical subsystems like thermal management and communication maintain power access even if faults occur.
- **Power Routing:** Each subsystem is allocated a maximum allowable current, with distribution managed by the PMAD. This configuration prevents overloading any single circuit and enables balanced power management.

Technology Readiness Level (TRL): 7

- While PMAD components have been used in space missions, the fault isolation technology's performance in lunar conditions is rated at TRL 7, reflecting the

need for in-mission validation. This sets the Power Management and Distribution subassembly's TRL at **TRL 7**.

Subassembly	Mass (Kg)	Dimensions (m)	Max Power Draw (W)	TRL	Description
Solar Panels	5.0	1.1 x 0.6 when deployed	300	6	High-efficiency GaAs solar cells with integrated dust mitigation
Lithium-Ion Battery Pack	10.0	0.4 x 0.3 x 0.2	N/A - storage	8	Compact, high-energy density battery pack with thermal control
PMAD	2.5	0.2 x 0.15 x 0.1	10	7	Fault-tolerant power regulation and distribution system

Overall Technology Readiness Level (TRL): 7

The TRL of the Power Subsystem is driven by the lowest-rated subcomponent, which in this case is the PMAD and dust mitigation system, rated at **TRL 7**. While GaAs solar panels and lithium-ion batteries are mature technologies (TRL 8-9), the fault isolation component of PMAD and dust mitigation technology require additional testing in lunar environments, resulting in an overall TRL of **7**. This rating reflects the subsystem's readiness for deployment with minor validation efforts required to confirm functionality in mission-specific conditions.

Engineering Challenges and Mitigations

1. **Dust Accumulation**: The lunar surface is covered in fine dust, which can obstruct solar panels. The integrated electrostatic dust removal mitigates this by repelling particles, maintaining power output without mechanical wear.
2. **Thermal Extremes**: The Moon's temperature fluctuates from -173°C at night to 127°C during the day. Batteries and PMAD are insulated and heated to remain within operational ranges. Solar panels are designed to withstand high temperatures but will fold in extreme conditions to prevent heat damage.
3. **Fault Tolerance in PMAD**: To prevent power loss due to electrical faults, the PMAD includes fault protection circuits that can isolate issues within milliseconds, maintaining functionality of critical systems without mission interruption.

The Power Subsystem of the Mare Tranquillitatis Rover is meticulously designed to balance efficiency, resilience, and reliability. Each subassembly contributes to a robust energy system that ensures continuous power, supports thermal control, and maintains communication links, enabling uninterrupted mission operations. With comprehensive design choices and high TRL components, the Power Subsystem is optimized to meet the mission's demands and overcome the lunar environment's unique challenges.

Operational Phase Cycles

Due to the extreme conditions, the power sub-assembly system must work efficiently and flawlessly for a successful mission, operating at different phases to maintain high efficiency. The activities of the rover are divided into **Traverse, Data Collection, Data Analysis, Data Relay, Recharge, and Low-Power Survival phases**, each tailored to balance energy consumption with mission objectives.

Traverse is a high-power phase that involves moving between target sites and is scheduled during peak daylight hours when solar energy is plentiful. The GaAs solar cells will generate and store power within the lithium-ion batteries while power is consumed by the motors of the rover. Similarly, Data Collection, which powers scientific instruments to gather surface and environmental data, is conducted during the lunar day to leverage direct solar input. These two power-intensive functions will not run simultaneously due to large power draws. Data Analysis is generally scheduled during immobile phases when power demand is lower and includes processing the information collected. Data Relay, communication with Earth, is scheduled in a way that is combined with optimal communication windows depending on satellite trajectory and available solar power. Recharge phases will happen whenever excess solar energy is available to ensure the batteries are charged enough to sustain the rover through the lunar night. During this period of 14 days, the rover operates in Low-Power Survival mode, keeping only basic functions running, like thermal regulation and reduced communications, to save energy.

To optimize power consumption, instruments are used in rotation based on mission priorities. Power storage and generation will be active in days of transerve operation, meanwhile thermal management systems will draw much more power in a dormant phase during the two week lunar night. Adaptive scheduling adjusts operations in real time to account for environmental factors like prolonged dust accumulation on solar panels. By strategically coordinating these phases, the rover balances its energy needs with scientific objectives, ensuring reliable performance throughout its mission.

2.1.2.3. Power Subsystem Recovery and Redundancy Plans

Recovery and Redundancy

Recovery and redundancy are important aspects to cover within the mission, as it is important to plan for backup throughout the course of a complex mission. Recovery is related to software and is the process of fixing failing systems. Redundancy is related to hardware and is the process of having a backup system in case the primary mode of operation fails. These protocols ensure the mission's safety, providing a plan for the next steps in an emergency.The power sub-assembly consists of three components: GaAs solar cell, power storage via lithium-ion battery, and a modular PMAD system. These components have been chosen with redundancy as a high priority.

Solar Panel Redundancy Plan

Redundancy would be provided in the form of having several solar panels arranged together in an array configuration. There should be a minimum of two arrays; each should be connected into separate power channels to ensure that the failure of one would not cut all power to the critical communication and science instrumentation. The lightweight nature of GaAs panels allow for such freedom. Also, an electrostatic dust mitigation system would negate the buildup of lunar dust on solar panels that can reduce the efficiency. This system uses electric fields to repel dust, minimizing buildup without mechanical wear and ensuring consistent energy generation.Other challenges include extreme temperatures of the lunar surface: from -173°C during the night to 127°C in the daytime. Thermal protection-including insulation and heaters-which would be activated to protect the GaAs solar cells when the temperature would threaten panel integrity, would be equipped on every panel. The deployment mechanism could also ensure the optimal alignment of the panels with respect to the Sun during power absorption.In the event of degraded performance or panel damage, the system would make use of auto-diagnostics and reconfiguration to isolate faulty panels or reroute power. If one of the panels were to underperform because of dust or damage, the power distribution system would prioritize energy from the operational panel to ensure that critical functions stay powered.

Power Storage Redundancy Plan

The rover would be equipped with multiple battery packs connected in parallel or series configurations to provide redundancy. In case of the failure or underperformance of one of the batteries, the others would be able to keep the system running. In this case, the system automatically reroutes power from functional batteries to keep critical systems, such as communications, scientific instruments, and thermal management, up and running. More importantly, the battery management system would continually assess

the state of health of every pack, leading to early fault detection/capacity degradation and subsequent immediate isolation of faulty units.
The recovery protocol would also be engaged in the power management system if there were a degradation in battery performance or the failure of a certain pack. The management system would adjust power distribution to prioritize only the essential systems, reducing energy consumption and preventing further discharge. During lunar night, the rover could also go into a low-power mode where only very critical operations are run in order to make the batteries last until the next solar cycle. Additionally, periodic diagnostics would evaluate battery health, and there could be a recovery protocol for battery use optimization over time. In the event of the batteries reaching a critical low charge, the system would manage power flow to maintain only the most critical systems until recharging is possible.

PMAD Redundancy

A modular PMAD is chosen primarily on its redundancy options. Redundancy is built into its very design. It distributes power management across many modules, which minimizes the risk of a single-point failure of the entire spacecraft. Power distribution can be rerouted automatically to other operating modules when one module fails; that way, the power cannot be cut off from critical subsystems like communication, propulsion, or scientific instruments. This fault isolation capability enables the system to limit the functional impact of individual failures in order to maintain mission operations without immediate repair or manual action. Each module comprising the PMAD system is supported with automatic fault detection and isolation mechanisms. These systems also continuously monitor the health of each module to identify potential issues before they become major issues. When there is a failure, the module can separate itself from the rest of the power distribution network to eliminate cascading failures that could result in the compromise of functionality within the whole spacecraft. The system operates to also reconfigure itself in a feedback loop, letting the spacecraft carry on working with failed or under-performing modules bypassed.

2.1.2.4. Power Subsystem Manufacturing and Procurement Plans

Part/Assembly	Supplier (Contractor/COTS/ In-House)	Estimated Lead Time	Justification
Gallium Arsenide (GaAs) solar cells	Contractor: Spectrolab (Subsidiary of	2 years	Spectrolab manufactured the GaAs solar cells for the Spirit and Opportunity rovers. They

	Boeing)		are capable of withstanding variable radiation levels and thermal extremes.
Lithium Ion Batteries	Contractor: EaglePicher Technologies	3 years	Yardney Technical Products (now under EaglePicher Technologies) manufactured Lithium Ion batteries for Curiosity and Perseverance rovers. Lead time for Mars rovers was around 5 years, however, a shorter lead time can likely be expected due to a higher TRL.
PMAD	In-House: Jet Propulsion Laboratory	3 years	JPL managed integration and testing of power sources for Perseverance Rover.

2.1.2.5. Power Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PS-1.0	The power subsystem will generate a minimum of 300 W under nominal conditions	Simulation, Analysis	The power subsystem can include contingency or “overengineer” the power system’s capabilities should nominal conditions not be feasible during flight.	Nominal or user-defined conditions and expected power output to the system can be calculated and used in design planning.
PS-1.1	Solar panels will achieve at least 25% efficiency under lunar illumination conditions.	Testing, Analysis	Ensuring solar panel efficiency under expected conditions is necessary to ensure even work distribution amongst power subsystem facets.	Solar panel efficiency will be tested under simulated light conditions that mimic the anticipated mission state. Solar panels will both be normalized for maximum efficiency and tested for non-normalized panel

				efficiency.
PS-1.2	The power subsystem will function within an operating temperature range of -170°C to 120°C	Thermal Testing	It is highly important to the functionality of the payload suite that the power system functions under expected temperatures without experiencing thermal runaway.	Thermal vacuum testing will be used to ensure operational performance of the power subsystem under mission conditions and with outgassing possibilities.
PS-2.0	The power subsystem will store a minimum of 1500 Wh for lunar night operations.	Testing, Analysis	Ensuring sufficient power storage is necessary for the full completion of science objectives.	Power storage will be measured upon procurement and complete manufacturing of the system to ensure alignment with analysis-based expected values.
PS-2.1	Batteries will retain 80% capacity after 500 charge-discharge cycles.	Testing	Maintaining battery health throughout the project lifecycle will be highly important for ensuring the completion of science objectives.	500 charge-discharge cycles will be run to ensure that expected battery health is maintained throughout the project lifecycle.
PS-3.0	PMAD will regulate voltage within ±5% of a 28 V nominal output.	Simulation, Testing	Voltage regulation will be highly important for ensuring the completion of science objectives.	Voltage regulation will be performed upon subsystem completion and compared to simulated or manufacturer specification values.
PS-3.1	PMAD will detect and isolate faults within 10 ms to	Simulation, Testing	Ensuring proper fault isolation is necessary to avoid	Fault isolation time response will be measured upon

	avoid downstream impacts.		negative cascading effects on system performance.	subsystem completion and compared to simulated or manufacturer specification values.
PS-4.0	Solar panel dust mitigation will achieve 90% dust removal efficiency during lunar day cycles	Testing, Analysis	Dust removal will directly affect the system's ability to maneuver, collect, and downlink data and will be tested to ensure system functionality.	The solar panel dust mitigation system will perform with simulated mission conditions to ensure the required functionality is met.

2.1.3. CDH Subsystem Overview

The Command and Data Handling (CDH) subsystem is the rover's central processing and coordination unit, which is responsible for managing and distributing data across all mission-critical operations. The CDH is responsible for facilitating communication between onboard instruments, handles data and storage and retrieval, and transmits all vital data to the Lunar Reconnaissance Orbiter. A high-performance CPU unit, dependable memory and data storage options, and a long-lasting communications interface are just a few of the strong components that make up the CDH subsystem, which is designed to ensure mission success. Due to the harsh conditions, both software and hardware components are made to meet strict standards for thermal stability and radiation resistance. This strategy protects data integrity and system functionality, while guaranteeing that the CDH subsystem can adjust to communication failures.

2.1.3.1. CDH Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
CDH-1	The rover shall transmit information to the satellite	Information must be sent back to Earth in order to be verified and to plan future mission decisions	None	CDH-1.1, CDH-1.2	Test	Not Met

CDH-1.1	The subsystem shall communicate to the satellite within 100 km of range per rate	The rover will have to be within a set range to communicate with the satellite	CDH-1	None	Demonstration	Not Met
CDH-1.2	The system shall use an antenna to communicate output information at a frequency of 2 GHz	The satellite will only receive information of a certain frequency	CDH-1	None	Analysis	Not Met
CDH-2	The information shall be received from other subsystems on an autonomous schedule	Information of subsystems should always be sent and collected by mission control back on Earth	None	CDH-2.1, CDH-2.2	Demonstration	Not Met
CDH-2.1	The information shall have a way to process other subsystems data per bit	Data should be retrieved and stored by processor	CDH-2	CDH-2.1.1	Inspection	Not Met
CDH-2.1.1	The system shall have a storage capacity of minimum capacity of 500 MB of data that is stored before downlink between communication windows for continuous observations.	The OBC will control all components of the CDH subsystem as well as other subsystems	CDH-2.1	CDH-2.2	Inspection	Not Met
CDH-2.1.1.1	The subsystem shall delete information that is no longer needed after processing	The OBP will deleted information that is no longer needed to free up storage	CDH-2.1.1	CDH-2.1	Analysis	Not Met
CDH-2.1.1.2	The subsystem shall store any data saved if any malfunction occurs to the rover	The data shall be stored automatically and saved if rover does not have connection	CDH-2.1.1	CDH-2.2	Analysis	Not Met

Objective 1: Characterize the Rover's Communication Environment for Data Transportation

Rate of Range: The subsystem shall communicate to the satellite within 100 km rate of range.
Frequency Rate: The system shall use an antenna to communicate output information at a frequency of 2 GHz.

Objective 2: Transmission and Scheduling of Rover Data
Transmission: The rover shall transmit information to satellite
Schedule: The information shall be received from other subsystems on an autonomous schedule.

Objective 3: Data Processing of Subsystem Information
Data Processing: The information shall have a way to process other subsystems data per bit.

Objective 4: Data Storage and Retention Management
Storage Capacity: The system shall have a storage capacity of 500 MB of data that is stored before downlink between communication windows for continuous observations.
Data Deletion: The subsystem shall delete information that is no longer needed after processing.
Data Storage: The subsystem shall store any data saved if any malfunction occurs to the rover.

2.1.3.2. CDH Sub-Assembly Overview

I. **Data Computing Module**
   A. **Real Time Operating System - VxWorks (RTOS)**
      1. A mission control software is needed in order to run automated tasks on the rover. VxWorks is well trusted and used in modern deep space processing interfaces. It supports multi core processing and a multitude of programming languages.
         a) **Technology Readiness Level**: **6 ~** VxWorks has been used as the main operating system for space rovers in recent modern missions. It allows for programming in Python and other languages that will help with communication, calculations, data recovery and other computing tasks.

B. **Processor Unit**

1. **Radiation Hardened CPU (Rad-Hard)**

a) These types of CPUs allow for computation with little to no radiation interference. However this comes with a drop in performance when compared to modern day CPUs located on earth. Processing speeds can range from 100 MHz to 1GHz.

(1) Technology Readiness Level: **8** ~ Rad-Hard Cpus are used in modern day space missions for computation and processing in deep space. They are reliable even with the slow processing power, and have redundant systems such as multiple cores processing the same calculation.

C. **Memory Unit**

1. **Radiation Hardened DRAM (Rad-Hard)**

a) Same as the Rad-Hard CPU, the trade off in performance comes with reliability and longevity with its short term memory capacities. As the storage capacity of the rover is very limited due to power, weight, cost and energy restraints. The reliability of the Memory unit is worth the sacrifice in storage, as it would have around 256 megabytes of temporary storage allocation at one time.

(1) ToTechnology Readiness Level: 8 ~ Rad-Hard RAM is extremely dependable in mission and has been for previous and current ones.It's currently being used on the perseverance rover with 256 megabytes of memory.

II. Telecommunications Subassembly

A. Telecommunications Subsystem

1. In order to communicate to mission control and track the location of the rover a telecommunications subsystem is needed to handle receiving and transmitting signals to the LRO and earth through the deep space network. With the use of S-band Antennas and Transceiver the rover will be able to communicate to mission control. And GNSS (Global Navigation Satellite system) antennas to track the rovers coordinates on the moon.

a) Technology Readiness Level: 6 ~ The use of S-Band Antennas and Transceivers has been used to communicate with mission control back on earth for numerous missions. With the addition of GNSS antennas for tracking and

positional coordinates of the rover. Key aspects such as the data transfer rates, error correction mechanisms, and the configuration of the communication network remain to be finalized. Additionally, considerations for how the rover will handle data compression and transmission during periods of low visibility to Earth need to be addressed, along with the potential use of the LRO to enhance signal reliability and coverage.

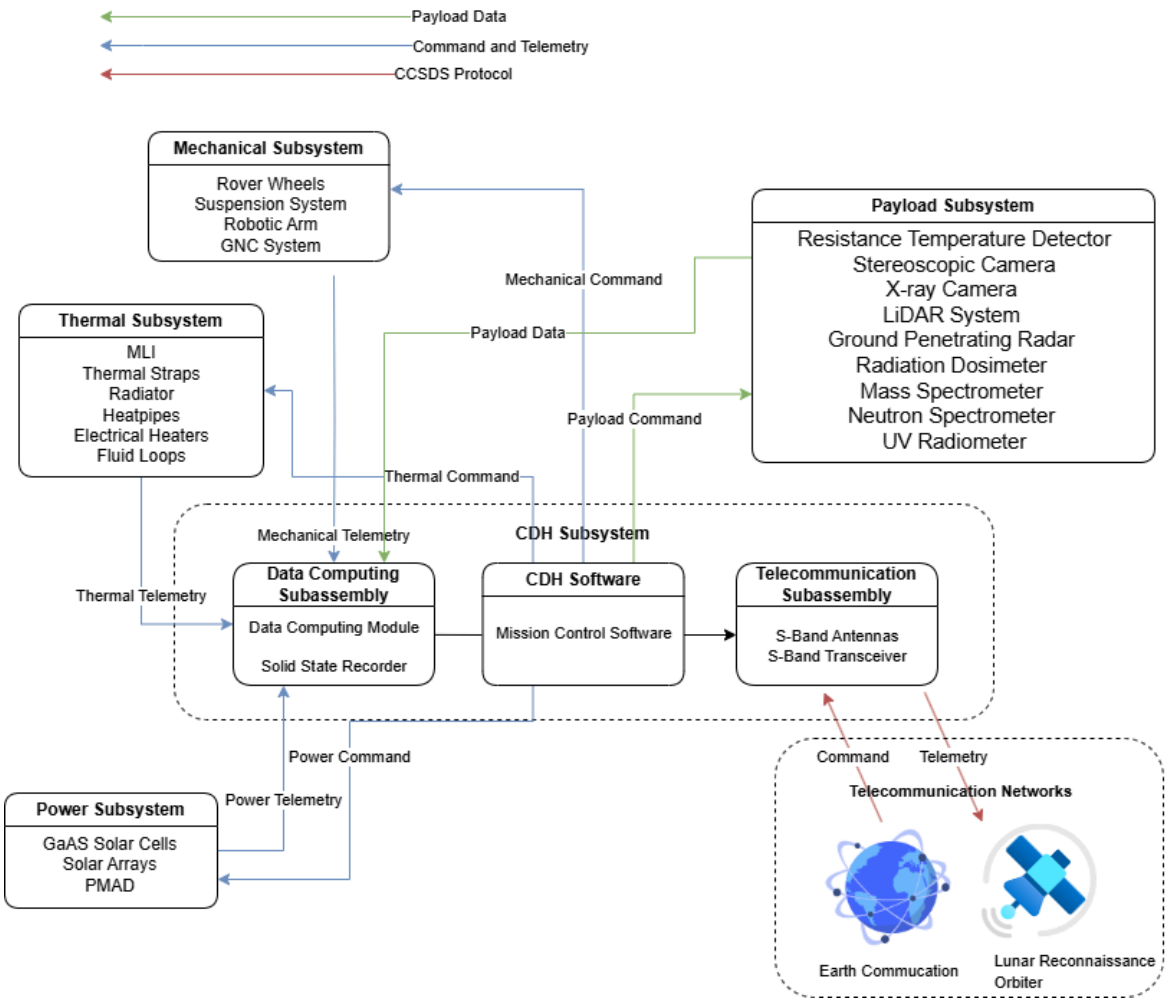
4. Technology Readiness Level (TRL) Analysis

The overall TRL of the CDH subsystem is limited by the lowest TRL score of any of the components and/or subassemblies. Given this restriction, the overall TRL score of the CDH system is a 6, as the communication interface is not as defined as the CPU and RAM data modules of the subsystem. The telecommunication subassembly is not as defined in its software aspects unlike its hardware/physical component aspects. Different strategies for communication errors and techniques have not been defined or established yet.

5. Mass, Dimensions, and Max Power Draw Summary

Subassembly	Mass (kg)	Dimensions (cm)	Max Power Draw (W)	TRL Score
Data Computing Module	~ 10 kg	~ 15 x 10 x 3	~ 15 W	6
Telecommunications	~ 7 kg	~ 60 x 60 x 30	~ 28 W	8
Total/Overall	~ 17kg	N/A	~ 43 W	6

6. Software Architecture Overview



Data Handling Workflow:

The CDH subsystem, as seen above, consists of two subassemblies that deal with data computation and telecommunication respectively. The Data Computing Module is split into two boxes to show an organized representation of inputs and outputs from the modules. The CDH software box deals with output commands to the different subsystems, while the computing module has the telemetry inputs of the different subsystems. The telecommunication subassembly strictly has connections with the Deep Space Network and the LRO and only gets inputs from the Data Computing Module.

CDH Overview Conclusion

The current state of the CDH subsystem is defined by its interconnecting hardware and software components. The communication between subsystems is crucial to the mission's success and the Data Computing Module allows for said communication and command distribution. The operating system of the Mission Control System requires

further development as well as the telecommunication sub assembly. All in all, the CDH subsystem hosts a TRL score of 6 as the lowest rating of the whole subsystem, the operating system dictates the overall score.

2.1.3.3. CDH Subsystem Recovery and Redundancy Plans

The Command and Data Handling (CDH) system is like the brain of the rover. It handles everything, from processing data to sending information back to Earth. To make sure it keeps working no matter what happens we added features for both redundancy and recovery.

The CDH system has two computers, a main computer and a backup. The main computer does all the work but if something goes wrong the backup is ready to take over right away. This setup helps the rover stay functional even if the main computer fails because of overheating, radiation, or another issue. We chose this design because it has been used in other Mars missions and works well. By having a backup computer, we make sure the rover can keep doing its job without losing any important data or communication.

If the main computer stops working, the recovery process is automatic. The CDH system is always checking itself to look for problems, like overheating or software errors. If it finds an issue, it quickly switches control to the backup computer. The switchover happens so fast that the rover doesn't miss a beat. Once the backup is in charge, the system sends a message to Earth to let the team know what happened. This recovery plan is important because it keeps the rover running smoothly, even if something unexpected happens.

2.1.3.4. CDH Subsystem Manufacturing and Procurement Plans

Part/Assembly	Supplier (Contractor/COTS/ In-House)	Estimated Lead Time	Justification
VxWorks Real Time Operating System	COTS: Wind River Systems	6 Weeks	Industry standard for operating systems it is reliable and proven efficient
Rad-Hard CPU (RAD750)	COTS: BAE Systems	1.5 Years	The RAD750 is the current processor used on perseverance, and BAE system is there manufacturer and supplier to NASA

Rad-Hard DRAM	COTS: Renesas Electronics	4 months	It has been supplied through NASA with Rad-Hard ICs along side BAE systems
S-band Antennas and Transceiver	Contractor: Lockheed Martin	5 months	Lockheed specializes in defense and communication with various systems

2.1.3.5. CDH System Verification Plans

Req #	Requirement	Verification method	Rationale for Method	Preliminary Verification Plan
CDH-1	The rover shall transmit information to satellite	Test	Functional testing confirms that the rover can send data reliably under realistic mission conditions.	Conduct a simulation that verifies data packets received without errors across multiple trials to a satellite testing receiver
CDH-1.1	The subsystem shall communicate to satellite within 100 km rate of range	Demonstration	Demonstration of communicating in this specific range is needed as the LRO won't be near the rover at all times.	Testing the rover in open-field scenarios at increasing distances up to 100 km range to confirm stable communication. And Measuring the signal strength and data integrity at each step.
CDH-1.2	The system shall use antenna to communicate output information at a frequency of 2 GHz	Test	Signal testing is needed to obtain the correct antenna communication frequency. As it's required to communicate with the LRO	The antenna will undergo performance, environmental, and range tests to confirm it meets the 2 GHz

CDH-2	The information shall be received from other subsystems on an autonomous schedule	Demonstration	Demonstrations confirm the scheduling is functioning without manual intervention.	Simulate normal operations where the CDH subsystem schedules data collection and transmission autonomously. Take into account disconnects and start ups. With a log of when and what files were transferred.
CDH-2.1	The information shall have a way to process other subsystems data per bit	Inspection	Inspection ensures that algorithms, code and hardware can handle data being received and process it accordingly.	Review software integration for data processing, focusing on algorithm efficiency and correctness. Conduct tests by inputting temporary test data and checking the processed outputs.
CDH-2.1.1	The system shall have a storage capacity 500 MB of data that is stored before downlink between communication windows for continuous observations.	Inspection	Storage inspection verifies capacity of the storage drive	Simulate maximum data accumulation during a period of no LRO communication. Verify the storage system's capacity by checking for errors during read/write operations at maximum load.
CDH-2.1.1.1	The subsystem shall delete information that is no longer needed after processing	Analysis	Analyzing data deletion ensures the system correctly identifies and removes unnecessary data after processing	Simulate real-time processing of incoming data. Check system logs for evidence of deleted processed data. Ensure that is does not delete important information/wrong data

CDH-2.1.1.2	The subsystem shall store any data saved if any malfunction occurs to the rover	Analysis	Analysis that validates the critical data is flagged and retained during any type of fault on the mission	Induce controlled failures such as power loss or forced disconnection. Make sure the data is stored and backed up just after the failure and compare against the storage without the backup.

2.1.4. Thermal Control Subsystem Overview

The extreme temperature range of the Moon, from freezing 103 K to boiling 395 K, is quite a challenge for spacecraft. The TMS will use both passive and active technologies in an integrated approach to make the spacecraft work within these bounds effectively. This will provide an optimum cost and performance benefit and enhance system reliability to further advance the mission objective of ensuring operational consistency in various lunar environments.

Passive Heating and Cooling Systems

Passive thermal control plays an essential role in operation, allowing the temperature to stay with very little consumption of power. A vital component is MLI, which shields delicate instruments against freezing temperatures from the Moon. MLI comes in a variety of aluminized Kapton films, which have higher insulation capabilities, up 19% more than Mylar films.[Finckenor, M.M.m Dooling, D, *Multilayer Insulation Material Guidelines,* 1999] The multi-layered insulation in it reflects thermal radiation impinging internally or externally, keeping critical systems from heating up or losing heat. MLI is lightweight and provides effective protection, hence it is a very important tool in minimizing thermal risk to the spacecraft, especially during long lunar nights. With a TRL of 6, MLI is well-tested in space applications and meets the mission's needs for passive thermal control.

Thermal straps, made of flexible copper ropes, conduct heat between heat sources and heat sinks, ensuring that excess heat from instruments is efficiently dissipated. These straps distribute the rover’s internal heat across its systems without adding significant structural load, thus ensuring thermal regulation in a compact and effective manner. Their TRL of 5 indicates a reliable but developing technology, having been used successfully in other spacecraft, such as the Orion capsule.

In passive cooling, the rover makes use of an aluminum honeycomb radiator coated with Teflon to enhance heat rejection. This system employs radiative heat transfer for dissipating excess heat from instruments. While its TRL of 5 places it in the realm of proven space technologies, further testing and mission-specific adaptations will be required for optimal performance in the lunar environment. Also included in passive heat distribution are heat pipes that transfer heat using a phase-change liquid. Heat pipes are an efficient low-power method of thermal control where a length of pipe absorbs heat at one end and releases it at the other. With a TRL of 5, these devices have space-proven heritage but require care to specify to mission demands.

Active Heating and Cooling

Given the extreme conditions on the lunar surface, passive systems cannot be solely relied upon. Active thermal control is, therefore, implemented to maintain the operational temperatures of critical components such as batteries and sensors. Electrical heaters, triggered by temperature sensors, provide the necessary heating to maintain components within their operating ranges. These heaters are capable of drawing up to 6.2 W/cm². However, at TRL 4, the technology needs further testing in lunar conditions to be reliable.

Active cooling is facilitated by a fluid loop system, which pumps circulating fluid from sources of heat to sinks of heat, hence dissipating heat efficiently across multiple points. This system, which utilizes MPFL technology, an extended version of that used on the Perseverance, requires only about 10W of power but can supply a flexible and scalable thermal solution [Bhandari, Pradeep, *Mechanically Pumped Fluid Loops for Spacecraft Thermal Control,* 2004]. With a TRL of 6, this technology is also well-suited for space applications, ensuring that excess heat is efficiently managed across the rover's systems.

2.1.4.1. Thermal Control Subsystem Requirements

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

0.1	Spacecraft shall survive lunar pit environment for 12 month mission lifetime	Spacecraft must be able to achieve mission goals throughout duration of lifetime as defined by the client	-	SYS.01, SYS.03, SYS.04	All	Demonstration	Met
0.2	Spacecraft will investigate habitability and potential for future exploration of MTP	Overarching mission science goal	-	SYS.06, SYS.07, SYS.08, SYS.09, SYS.10, SYS.11	Payload	Analysis	Met
SYS.01	Spacecraft shall generate power for itself for the duration of the mission lifetime	All subsystems and instrumentation on spacecraft require power for operation	0.1	PS.1.0	Power	Demonstration	Met
SYS.02	Spacecraft shall not exceed total mass of 350 kg	Spacecraft must meet launch provider constraints	-		All	Inspection	Met
SYS.03	Spacecraft shall be capable of operation within temperatures of 103 K to 395 K	Spacecraft must be able to operate within variable lunar temperatures	0.1		Thermal Management	Demonstration	Met
SYS.04	Spacecraft shall be able to withstand accumulation of lunar dust	Lunar dust is common in lunar atmosphere and may pose challenges to instrument operability	0.1	TH.1.0	All	Test	Met
SYS.05	Spacecraft shall adhere to Planetary Protection guidelines outlined by NASA-STD-8-719.27 and NPR 8715.24	Necessary for mission completion	-		All	Inspection	Met

SYS.06	Spacecraft shall be capable of descending into MTP	Necessary for exploration of target location	0.2		Mechanical	Demonstration	Met
SYS.07	Spacecraft shall be capable of mobility within MTP	Necessary for exploration of target location	0.2		Mechanical	Demonstration	Met
SYS.08	The system should be able to downlink data to an orbiter in a 100km circular polar orbit	Necessary for mission completion	0.2		CDH	Demonstration	Met
SYS.09	Spacecraft should map the geometry of interior of MTP	Relating to goals as defined in STM	0.2		Payload	Demonstration	Met
SYS.10	Spacecraft should map the geometry of the surface within 8 meter radius of MTP entrance	Relating to goals as defined in STM	0.2		Payload	Demonstration	Met
SYS.11	Spacecraft should measure indicators of habitability as defined in STM	Relating to goals as defined in STM	0.2		Payload	Demonstration	Met

2.1.4.2. Thermal Control Sub-Assembly Overview

Thermal Management Subsystem

The extreme temperatures on the surface of the Moon makes an efficient thermal management system imperative. System requirement .03 (SYS .03) requires the spacecraft to operate in an environment between a freezing 103 K to a boiling 395 K. The thermal management system will be separated into two different types of technology: active and passive. Passive thermal control maintains component temperatures without using powered equipment. They are usually low cost and low maintenance parts. However, due to the extreme temperature cycling of the Moon, only using passive elements will not suffice. Active thermal control methods rely on power for operation, yet these methods yield much better performance at the cost of increased risk and spending. A combination of the two technologies provides the most optimal, cost effective route.

Passive Heating Systems

Multilayer insulation (MLI) is utilized on the rover to protect sensitive instruments against the freezing temperatures. The layered insulation consists of layers of low-emittance films. The design will be specifically using 10 layers of aluminized Kapton

film as studies have shown a 19% improvement in insulation performance compared to Mylar films [Burgess, W ; Lebrun, P, *Compared performance of Kapton and Mylar based superinsulation,* 1984]. This effective MLI contains 15 - 40 layers of films and fabrics. The material protects the spacecraft by reflecting thermal radiation, minimizing heat transfer in and out. Metallized polyimide film is the preferred choice for the inner cover layer of MLI blankets as it provides excellent flame resistance. The film is ultra thin, ranging from only 7.6 μm - 127 μm, preventing it from obstructing sensors and mechanical instruments.
Technology Readiness Level: 6 - The technology has been used on past and present rovers and spacecraft and the products are diversified through many manufacturers. Due to different shapes, dimensions, and specifications, the technology is tailored to the specific needs of the mission, thus driving up the price and time required to design and manufacture.

Thermal straps are flexible, thermally conductive connectors used to transfer heat conductively between a heat source and a heat sink. Copper thermal straps will be used to transfer heat from instruments to heat sinks. Using such a device ables the rover to use its own heat and distribute it to maintain a regulatory temperature throughout the rover. The straps are created of flexible, copper “ropes” that dismiss any concern of additional structural load. This keeps the payload light yet increases thermal conductivity.
Technology Readiness Level: 5 - The technology have been used on many different cubesats and larger vehicles such as the Orion capsule.

<u>Passive Cooling Systems</u>
A **radiator** is a surface designed specifically for dissipating excess heat through radiative heat transfer. The rover will employ an aluminum honeycomb panel to dissipate waste heat from instruments. Furthermore, the radiator will be given an aluminum teflon coating, enabling it to reject heat from the environment.
Technology Readiness Level: 5 - Common technology used in a space application

Heat pipes will be used to distribute heat generated from certain instruments. The pipes will be made of a metal that holds a phase change fluid. When heat is applied to one end of the tube, the liquid inside the tube near the hot end vaporizes into a gas that moves through the tube to the cooler end. This closed loop passive technology efficiently transfers heat throughout the rover without energy input.
Technology Readiness Level: 5 - Common convection methods used in space application. Can be expensive and very involved due to the specifications of mission

Thermal Louvers are heat-activated shutters that control how much heat a louvered surface can dissipate by adjusting infrared emissivity. When utilized in a CubeSat-adapted design, the louvers operate without drawing power from the spacecraft.
Technology Readiness Level: 4 - Integration on smaller spacecraft is challenging, therefore also being more cost-heavy.

Active Heating Systems
Electrical heaters will be employed as the main active heating system which uses electrically insulated foil circuits that conduct heat when a current is sent through it. A temperature sensor will send signals to activate a current, and a feedback loop will be in place to maintain an equilibrium temperature. The heater will keep sensitive equipment such as batteries and sensors within their operating temperature intervals. The estimated power draw will range from 0.8 - 6.2 W/cm^2 based on the temperature limits set by a heater manufacturer endorsed by NASA.
Technology Readiness Level: 4 - Although the technology is common in the space industry, the extreme conditions of the Moon leave little precedent.

Active Cooling Systems
Fluid Loops will pump a circulating fluid from a heat source to a heat sink, such as a radiator as stated above. The most beneficial feature of this method is that it will cool multiple locations, acting as a thermal bus that will convect and deposit heat almost simultaneously. A mechanical pump fluid loop (MPFL) will be used due to the size and requirements of the rover. This pump will draw around 10W of power, based on the loop that was used in the *Perseverance* Mars rover.
Technology Readiness Level: 6 - Widely used on both smaller satellites and larger vehicles such as the Mars rover *Curiosity*
Overall Technology Readiness Level 4

Subassembly	Mass (Kg)	Dimensions (m)	Max Power Draw (W)	TRL	Description
MLI	12 kg/m^2	~1-2 m, enough to cover sensitive equipment	N/A	6	layered insulation consists of layers of low-emittance films.
Thermal straps	1	0.5 x 0.01 x 0.01	N/A	5	Flexible, thermally conductive connectors used to transfer heat conductively between a heat sthe team'sce and a heat

					sink.
Radiator	2.5	0.2 x 0.15 x 0.1	N/A	5	Dissipating excess heat through radiative heat transfer.
Heat Pipes	2.7kg /m	Diameter: 10mm Length: 1-2m	N/A	5	Pipes with phase change liquid that uses convection to dissipate heat
Electric Heater	4.3kg	0.5 x 0.275 x 0.11	6.2W/cm^2	4	Electrically insulated foil circuits that conduct heat when a current is sent through it.
Fluid Loops	8.3kg	Diameter: 25mm Length: 1-2m	10W	6	Pump a circulating fluid from a heat source to a heat sink
Total	30.8				

Overall Thermal System Operations

Passive and active thermal management instruments are designed to work seamlessly in an effort to maintain a consistent internal environment. The combination of passive and active systems plays a major role in heat management to protect the instruments onboard the rover from the icy lunar surface. The passive heating systems consist of MLI using aluminized Kapton film to guard against freezing temperatures by reducing heat transfer while reflecting thermal radiation. Thermal straps take it one step further by transferring excess heat from sensitive instruments to the heat sinks to keep the rover at a regulated temperature. Passive cooling systems include radiators with aluminum teflon coatings and heat pipes, which are used to reject excess heat by means of radiative and phase-change processes. These systems work in tandem to prevent overheating of the spacecraft by efficiently distributing and rejecting heat. Electrical heaters, meanwhile, ensure that sensitive equipment such as batteries remain within their optimum operating temperatures, while fluid loops circulate coolants to transfer heat from high-energy instruments to radiators. All these systems work together as one well-structured thermal management system, a proper balance of passive and active technologies in place to protect the systems, conserve energy, and mitigate risk for the rover on its lunar mission.

2.1.4.3. Thermal Control Subsystem Recovery and Redundancy Plans

Thermal System Recovery and Redundancy

The instruments utilized on the rover were meticulously chosen with redundancy in mind. MLI, specifically made from 10 layers of aluminized Kapton film, is one of the primary methods for protecting the rover's instruments from freezing temperatures. While MLI's primary role is to minimize heat transfer, its insulation performance can be compromised due to damage or degradation over time. If MLI fails, redundancy can be achieved through the rover's thermal straps. These flexible, copper-based straps transfer heat from instruments to heat sinks and can help mitigate the loss of insulation by distributing any available heat across the rover. The combination of MLI and thermal straps ensures that if one system faces degradation, the other can maintain temperature regulation by redistributing heat, thereby preventing critical instrument failure.

Passive Cooling Systems: Radiators and Heat Pipes

For cooling, the rover employs radiators and heat pipes. Radiators dissipate excess heat through radiative heat transfer, while heat pipes circulate phase-change fluids to evenly distribute heat across the rover. In the case of a failure in the radiator or heat pipe system, the rover can rely on a secondary system of heat pipes or thermal louvers to aid in passive heat regulation. Heat pipes can be adapted to other components or sections of the rover if certain areas face overheating, ensuring that even if one part of the system malfunctions, the rover can continue to operate within safe temperature ranges.

Active Heating and Cooling Systems

While passive systems handle the majority of temperature control, active systems are crucial for more precise temperature regulation. Electrical heaters, which use insulated foil circuits to generate heat, help keep sensitive components like sensors and batteries within their necessary operating ranges. These heaters are controlled by feedback loops that adjust the current based on the temperature sensed by the system. In case of heater failure, other heaters on the rover, or thermal straps, may take over the regulation by distributing heat from working areas to areas in need. Similarly, the fluid loop system, which pumps circulating fluid to transfer heat away from heat sources, can act as a backup in case one of its individual loops faces a malfunction. Fluid loop redundancy can be managed by isolating sections of the rover and activating alternative cooling paths if required.

Redundant Recovery Systems

In space, where failure can result in catastrophic consequences, the redundancy of the thermal control systems ensures the rover remains functional in the face of individual component failures The loss of one radiator does not necessarily cause overheating, as other cooling methods like heat pipes and thermal louvers can compensate for the deficit. This interconnected thermal management system allows the rover to continue its mission with a high degree of resilience, recovering from thermal control failures by relying on other available components. The balance of use between active and passive heating and cooling systems creates a solid system that protects against failures in the system that could jeopardize the entire mission.

2.1.4.4. Thermal Control Subsystem Manufacturing and Procurement Plans

Part/Assembly	Supplier (Contractor/COTS/In-House)	Estimated Lead Time	Justification
Multilayer insulation (MLI): Metallized polyimide film	In-House: Goddard Space Flight Center Backup: DuPont	3 months	NASA has developed and used Multilayer Insulation (MLI) for its spacecraft, such as the James Webb Space Telescope and different Artemis missions. The metallized polyimide film used by NASA has been tested. DuPont was contracted in the Endeavor mission to Mars. Lead time will likely increase due to the numerous advancements between the Endeavor mission and current missions.
Copper thermal straps	In-House: Goddard Space Flight Center Backup: Airbus	5 months	NASA specialized in thermal designs and has been used in spacecraft such as the James Webb Space Telescope and the Mars Rovers. Their thermal management expertise ensures that copper straps meet space-grade standards, including flexibility and high reliability under vibration. Goddard also specialized in spacecraft thermal management. Airbus' HiPeR Flex Links have a TRL 9 for spaceflight. Lead time will likely

			remain the same.
Radiator	In-House @ Jet Propulsion Laboratory (JPL) Backup: Lockheed Martin	4 months	JPL designs radiators for harsh environments and have been operated in such missions. This will be needed for the moon's temperature fluctuations. Lockheed Martin has demonstrated successful performance of radiators in the Transformational Satellite Communications System constellation. Lead time will likely increase due to design differences between satellite and rover design.
Heat Pipes	In-House @ Glenn Research Center Backup: Advanced Cooling Technologies	4 months	GRC's heat pipes are designed for high-performance and efficient thermal control in space applications. These have been tested and validated. Advanced Cooling Technologies has supplied Constant Conductance Heat Pipes for previous NASA missions. Lead time will likely remain the same.
Thermal Louvers	In-House @ Glenn Research Center Backup: Sierra Space	4 months	GRC has designed and developed louvers for various space missions. These include satellites and space stations. Sierra Space's passive thermal louvers were developed based on NASA design heritage. Lead time will likely remain the same.
Electrical Heaters	In-House @ Glenn Research Center Backup: Teledyne Technologies	5 months	GRC specializes in custom electrical heaters for temperature regulation in harsh lunar environments. Teledyne Technologies has supplied thermal control technologies for previous planetary missions. Lead time will likely increase due to low TRLs.
Mechanical Pump Fluid Loop	In-House @ Glenn Research Center Backup: Lockheed Martin	5 months	GRC's mechanical pumps have been used in several NASA missions, including spacecraft and satellite applications. Lockheed Martin supplied MPFL systems for the Orion crew vehicle. Lead time will likely increase due to the different designs

			of crewed spacecraft and lunar rovers.

2.1.4.5. Thermal Control Subsystem Verification Plans

The Thermal Control Subsystem Verification Plan ensures that all thermal management components operate as intended, maintaining critical instrument temperatures within operational limits during the mission. Verification involves testing under simulated lunar conditions based on the mission's defined temperature range of 103 K to 395 K. The following strategies will be employed:

Verification Methodologies:

1. Environmental Simulation Testing
    - Test Description: A thermal vacuum chamber will simulate the lunar environment by subjecting components to extreme heat and cold cycles.
    - Verification Criteria: Ensure that the rover’s thermal performance maintains internal component temperatures within safe operational ranges during simulated lunar day and night cycles.
2. Thermal Balance Test
    - Test Description: Conduct thermal balance testing by integrating the thermal management components into a full rover mock-up and exposing it to environmental tests.
    - Verification Criteria: The rover must demonstrate uniform heat distribution and avoid hot or cold spots that could damage sensitive components.
3. Thermal Conductivity Test (Heat Transfer Test)
    - Test Description: Use calibrated heat sources to verify the efficiency of heat transfer through copper thermal straps, heat pipes, and radiators.
    - Verification Criteria: Test results should meet predetermined thermal transfer rates calculated during the design phase.

Component-Specific Verification Plans:

1. Multilayer Insulation (MLI)
    - Test Method: Evaluate insulation performance by measuring heat retention and loss during cold and hot chamber tests.
    - Success Criteria: Demonstrates at least a 19% improvement in insulation compared to industry-standard Mylar-based insulation.
2. Thermal Straps

    - Test Method: Conduct thermal conductivity tests in a controlled laboratory environment using heat sources and sensors.
    - Success Criteria: Ensure uniform heat transfer between heat sources and heat sinks.
3. Radiators
    - Test Method: Perform radiative efficiency testing by measuring infrared radiation dissipation.
    - Success Criteria: Ability to dissipate excess heat while maintaining operational temperatures.
4. Heat Pipes
    - Test Method: Test using a heated liquid source to observe vapor-to-liquid heat transfer.
    - Success Criteria: No fluid leakage and proper phase-change functionality.
5. Electrical Heaters
    - Test Method: Functional testing through thermal cycling tests in vacuum conditions.
    - Success Criteria: Consistent heat output within specified temperature ranges using feedback-based control.
6. Fluid Loops (MPFL)
    - Test Method: Flow testing under variable temperatures and fluid pressures.
    - Success Criteria: Effective coolant circulation without leaks or pressure drops.

System-Level Verification Approach:

1. Integrated System Testing
    - After verifying individual components, a fully integrated system test will be conducted.
    - Verification Criteria: The entire thermal system must demonstrate stable performance under simulated mission conditions in thermal vacuum testing.
2. Thermal Cycling Endurance Test
    - Conduct extended testing over multiple lunar day-night cycles to assess long-term durability and performance stability.

Final Evaluation and Documentation:

- Test results, including performance metrics, environmental tolerance limits, and any required design adjustments, will be documented.

- All verification activities will be tracked through a shared testing log to maintain full transparency and traceability for review.

2.1.5. Payload Subsystem Overview

The current instrumentation to be used on the spacecraft to study the lunar Mare Tranquillitatis Pit has been selected so that data obtained from all instruments can when considered together, give a holistic picture of the pit's state of habitability. Instrumentation selections were made based on each of the five identified science objectives and broadly categorized into whether they would characterize the pit's thermal, structural, or environmental state.

Firstly, Objective 1, "Characterize the thermal environment of Mare Tranquillitatis Pit (MTP)," drives the team's choice to use temperature sensors as part of the spacecraft's instrumentation. The payload subsystem requirements, which state that the temperature sensors should detect temperature fluctuations between 100-300 K and should not change by more than 1 degree per year, indicate the team's priority to have stable measurements that will fall in the pit's expected range. Initially considered instrumentation included a Resistance Temperature Detector (RTD), thermocouple, or thermistor. However, the temperature range requirement for a lower bound of 100K eliminated the use of a thermistor from consideration, as thermistors tend to perform optimally at a narrower range of temperatures than the other instruments. Currently, the team is working to come to a conclusive decision between RTDs and thermocouples. RTDs work by measuring resistance fluctuation from a known temperature-resistance starting point across a metal wire, generally platinum. The higher molecular excitation characteristic of increased temperatures correlates to an increased resistance. Using the known temperature-resistance starting point and a known resistance change associated with some temperature change, the relationship between temperature change and resistance change can be represented linearly. RTDs are capable of taking measurements in the desired temperature range and are both more accurate and more stable than thermocouples but are less robust.

On the other hand, thermocouples operate by taking a temperature change-induced voltage across two distinct metals joined together. The robust nature of thermocouples lends itself to pit entry but introduces the drawback of less accuracy and stability than RTDs. Ultimately, a thermal IR sensor with a resistance temperature detector aboard for redundancy was selected to meet the first objective due to the somewhat sensitive nature of temperature detection devices.

Additionally, Objective 2, "Assess the structural integrity of the walls and overhangs of MTP," and Objective 3, "Investigate and characterize potential cave

networks and terrain in and around MTP, respectively," are considered characterizations of the structural state of the pit. In order for the pit to be reasonably viable for further habitation considerations, it should be structurally sound and ideally will include some amount of lava tube network. The first instrument that the team considered to contribute to the structural characterizations of MTP was a stereoscopic camera. A stereoscopic camera uses two lenses to mimic how human eyes perceive the world in three dimensions using information from a pair of slightly different two-dimensional images. Stereoscopic cameras are of interest for similarly demanding scientific missions, such as underwater cave mapping, which informs the team's interest in employing this instrument. In order to reduce the number of images to be taken and digitally blended together, the stereoscopic camera should have a field of view of at least 100 degrees. The larger the field of view can be, the less the spacecraft will have to accommodate imaging through powered maneuvers or additional mechanical complexity at the camera interface (ex, for swiveling the camera in lieu of full-mechanical maneuvers). After comparing previous planetary science missions, the team eventually selected the previously-flown Close-Up Imager utilized on the European Space Agency (ESA) ExoMars mission. Because it was intended for use in remote planetary science, the Close-Up Imager includes onboard data processing capabilities, which will be useful for the MTP study. Due to the use of this specific instrument for remote geological studies, this instrument is expected to successfully contribute to characterizations of MTP relevant to the second science objective.

Furthermore, the structural characterization of the pit will include an analysis of potential lava tube networks in addition to the structural integrity investigation. This analysis will occur both before and after descending the spacecraft into MTP. Prior to descending into the pit, Ground Penetrating Radar (GPR) will be employed to develop knowledge of the terrain from outside MTP. GPR, along with other instrumentation selected for structural characterization, was considered for its adherence to the team's goal of evaluating the pit using nondestructive characterization methods. Preserving the integrity of MTP during the initial habitability assessment as much as possible was decided to be the best approach for a first assessment. GPR is another imaging method that uses electromagnetic waves that is commonly used for geological assessments, making it a well-tested instrument for this mission objective. GPR has been of interest to the science community for Martian missions for its ability to penetrate well enough below the planetary surface so as to provide useful terrain characterizations. For this mission, instrumentation requirements specify that the GPR should have an antenna center frequency of 100 MHz. This is to get as much imaging depth as possible near the pit, which some scientists estimate to have a depth of around 100 meters, a relatively high depth for a GPR application.

Lastly, Objectives 4 and 5 drive instrumentation choices for the environmental characterization of the pit. These objectives are to “Quantify the radiation environment in and around MTP to understand its effect on humans and instrumentation” and “Map the distribution of volatiles and hydrogen concentrations found in and around MTP,” respectively. Three types of instrumentation will be used for the environmental characterization: a radiation dosimeter, a spectrometer, and a UV radiometer. Radiation dosimeters measure ionization radiation dose over time and are useful for assessing accumulated radiation effects on humans and instrumentation. A dosimeter absorbs radiation and stores it as energy that can then be measured. This instrument is sometimes worn by people who experience radiation exposure at work, such as in the medical field, making it a reasonable choice for assessing lunar habitability. Another instrument the team has opted to employ, the spectrometer, will work in tandem with the dosimeter to characterize the radiation environment in MTP. Spectrometers are used to identify and quantify radiation types (protons, electrons, gamma rays, neutrons, etc.) necessary to determine exposure risk by making characterizations of light wavelengths. Having this information, along with the data from the radiation dosimeter, will allow the team to analyze MTP’s habitability and risk to human health. The team is in the process of conducting trade studies to select which spectrometer types would provide the most useful information.

Technology readiness levels (TRLs) driving the design have initially been selected based on TRL data collected from TechPort, which compiles data describing instruments developed for NASA’s missions. For the initial data specifications chart, TRL ratings have been assigned by finding the NASA instrument developed for the most similar mission use from the available data, and using the TRL the instrument was rated at the end of its mission use. Based on available data, the limiting TRL for this project is a rating of 6, indicating that selected instruments have at least undergone “demonstration in a relevant environment” by NASA standards. The general standard that systems should have a TRL rating of 6 prior to flight is a favorable indication for the current payload instrumentation suite.

Instrument	Dimensions	Mass	Power Draw	NASA TRL (End TRL, Project ID)
Resistance Temperature Detector	2 x 2 x 0.8 mm	-	Quote Needed	9, 146277
Stereoscopic Camera	164 x 32 x 37 mm	0.240 kg	380mA / 5V	6, 116401

Ground Penetrating Radar	203.1 × 96.5 × 30.5 cm	13 kg	Quote Needed	6, 154777
Radiation Dosimeter	200 x 70 x 45 mm	0.206 kg	4 x 1.5V batteries	6, 9862
Spectrometers	29.8 x 21.6 x 12.2 cm	0.454 kg	4 Lithium Ion Batteries	6, 92911

As the spacecraft system is designed to house and maintain the payload instrumentation during operation to collect and downlink data effectively, the other subsystems offer explicit or implicit support to the payload's instruments. For example, the power subsystem offers explicit support to the payload subsystem, as the power subsystem directly provides the ability for the instrumentation to collect, process, and send data. Additionally, the mechanical subsystem explicitly supports the payload by housing and physically maneuvering the instruments. During terrain traversal and pit entry, the mechanical subsystem will also be responsible for ensuring the safety of payload instruments, keeping the payload from being negatively impacted by the lunar environment. These two systems are the "lifeblood" of the payload.

On the other hand, the thermal control and CDH subsystems provide implicit support: while they are not directly powering or maneuvering the payload, they are still supporting the payload subsystem's ability to carry out the science goals. Like a homeostatic mechanism, thermal control ensures that the whole system remains in operational conditions, which is necessary for the instrumentation to function. Prior to entering the pit, the instrumentation may be subject to more extreme temperatures characteristic of the lunar environment; during this segment of the mission, the thermal subsystem will be especially important for maintaining the functionality of instruments aboard the system. Finally, CDH allows for the acquisition and usefulness of data logged by the instruments, which is necessary to actually fulfill the science objectives of learning about lunar history and habitability.

2.1.5.1. Science Instrumentation Requirements

The science instrumentation requirements for the payload subsystem are primarily based on ensuring adequate performance to meet system-level requirements and complete science mission goals. SYS.03 "Spacecraft shall be capable of operation within temperatures of 103 K to 395 K" directly determines temperature measurement standards. Additionally, SYS.07 "Spacecraft should map the geometry of interior of MTP" and SYS.08 "Spacecraft should map the geometry of the surface within an

8-meter radius of MTP entrance” drive requirements related to the stereoscopic camera, LiDAR, and GPR, whose primary functions are related to general mapping of the pit. Finally, SYS.09, “Spacecraft should measure indicators of habitability as defined in STM,” leads to requirements for spectrometers, dosimeters, and radiometers, which are included on the payload to make environmental characterizations. SYS.09 is also used to determine X-ray requirements, as the X-ray is meant to supplement the general mapping by providing high-contrast imaging of pit wall indicators of structural integrity and habitability.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
PAY-1.1	The temperature sensors should detect temperature fluctuations between 100-300 K.	Instrumentation should characterize in the range MTP is expected to fall within.	SYS.03	PAY-1.1.1	Test	Not Met
PAY-1.1.1	The temperature sensors should not change by more than 1 degree per year.	Instrumentation stability increases the quality of data downlinked.	PAY-1.1	-	Demonstration	Not Met
PAY-2.1	Close-Up Imager: The close-up imager should have a field of view of at	Including a standard for cohesiveness of imagery will increase structural characterization integrity.	SYS.07	-	Inspection	Not Met

	least 100 degrees.					
PAY-2.2	Close-Up Imager: The close-up imager should have a root-mean square correlation accuracy of no greater 0.2.	Including a standard for imaging accuracy will increase structural characterization integrity.	SYS.07	-	Inspection	Not Met
PAY-2.9	GPR: The GPR should use dual-frequency scanning.	Dual-frequency scanning will allow for a more complete geophysical profile than single-frequency scanning.	SYS.08	-	Inspection	Not Met
PAY-2.10	GPR: The GPR should have a resistivity of at least 100 Ohm-m.	Including a resistivity standard will ensure GPR data integrity for a range of geological mediums.	SYS.08	-	Inspection	Not Met
PAY-2.11	GPR: The GPR should have an antenna	MTP is expected to have an entryway approximatel	SYS.08	-	Inspection	Not Met

	center frequency of 100 MHz	y 40-50 m deep.				
PAY-3.1	Spectrometers should measure the energy range of radiation between 100 keV - 10 MeV.	Including a standard for energy range will increase environmental characterization integrity.	SYS.09	-	Test	Not Met
PAY-3.2	Spectrometers should have a sensitivity of no more than 10e4 erg/g/s.	Including a standard for instrument sensitivity will increase environmental characterization integrity.	SYS.09	-	Inspection	Not Met
PAY-3.3	The radiation dosimeter should have a sensitivity of no more than 10e4 erg/g/s.	Including a standard for instrument sensitivity will increase environmental characterization integrity.	SYS.09	-	Inspection	Not Met

2.1.5.2. Payload Subsystem Recovery and Redundancy Plans

Payload Subsystem Redundancy:

Due to the mass, power draw, and budgetary constraints on the mission, the

instruments will generally not have redundant systems. This decision has been made with the knowledge that, because there are a variety of scientific observables being included in the payload suite instrumentation, the possible failure of any one instrument will not necessarily preclude the fulfillment of the general goals of the mission. Such a decision accounts for single point failures (SPF) in the payload suite- the possibility that an instrument could fail of its own accord or due to a single-event upset affecting its electronic capabilities. One exception to this decision is the inclusion of two temperature-monitoring instruments, a thermal IR sensor with a resistance temperature detector (RTD) as a backup instrument. The use of a redundant RTD was included due to the relatively low mass and size; including an RTD would definitely not push the size or mass constraint. Should mass, power, and budget allow during the assembly period, the possibility of considering another redundant instrument may be made although this is unlikely. If this were to happen, it is most likely that a redundant radiation dosimeter may be included due to its low mass. Conversely, a second ground-penetrating radar is most unlikely to have a redundant system added due to the relatively high additional mass this would add to the system.

Payload Subsystem Recovery:

Because the payload instrumentation suite includes little redundancy, the primary objective of the Recovery and Redundancy plan is to minimize the damage to mission goals should an instrument fail. As mentioned in section 2.1.5 Payload Subsystem Overview, the Close-Up Imager includes on-board data processing capabilities. In the same vein, the software aboard the system will have data logging capabilities such that data may be stored outside of the instruments themselves, to reduce the chance of single-event upset causing total data loss for a science objective. Should an instrument fail, some basic troubleshooting capabilities or responses to stored data anomalies will also be on board the system. For example, the command to store data and then power cycle a failing or anomalous instrument should take place as quickly as possible without instruction from mission control. This would save as much existing data as possible while prioritizing the long-term functionality of the payload.

Instrument Redundancy Matrix:

Legend	
○	Does not contribute to objectives
◔	Does not meet baseline
◑	Partial contribution to objectives
●	Instrument can fully meet objectives

Science Measurement Requirements		Baseline Performance Requirements		Instrument					
Physical Parameters	Observables			Resistance Temperature Detector	Thermal IR Sensor	Close-Up Imager	Ground Penetrating Radar	Radiation Dosimeter	Spectrometer
Identify temperature fluctuations throughout mission lifespan on the lunar surface and MTP floor	Observe stable floor and wall temperatures around 290 K (17°C)	Temperature Sensitivity:	150-300 K	●	●	◔	◔	◔	◔
		Spatial Resolution:	< 10 sq. m						
		Measurement stability:	± 1 K						
Conduct nondestructive testing to identify signs of structural instability through imaging	Image cracks, fractures, deformations, and debris piles near MTP entryway, walls, floor, and overhang	Spectral Range:	Visible	◔	◔	●	◑	◔	◔
		Resolution	< 2.5 mm/pixel						
		Field of View:	< 100°						
Identify hidden cave network(s) and other features using ground penetrating radar and map their terrain	Collect strong reflective radar signatures of MTP subsurface cavities	Spatial Resolution:	< 1 sq. m	◔	◔	◑	●	◔	◔
		Depth:	≤ 50 m						
		Central Frequency:	~ 100 MHz						
		Frequency Range:	> 100 Mhz						
Identify radiation dose rate and total ionizing dose in areas surrounding MTP and within MTP	Collect telemetry on total ionizing dose (TID) rate, displacement damage dose (DDD) rate, and cosmic ray flux	Energy Coverage:	100 keV - 10 MeV	◔	◔	◔	◔	●	◑
		Exposure Time:	< 1 hr						
		Sensitivity:	< 10^4 erg/s						
Identify abundances of H, CH4, SiO2, N2, NH3	Collect relative abundance of H, CH4, SiO2, N2, NH3 in MTP regolith	Infrared Wavelength Range:	780 nm - 4 µm	◔	◔	◔	◔	◑	●
		Optical/UV Range:	100 - 700 nm						
		Resolution:	~1-2 nm						

2.1.5.3. Payload Subsystem Manufacturing and Procurement Plans

Planned Payload Instrumentation Suite:

Part/Assembly	Supplier (Contractor/COTS/	Estimated Lead Time	Justification

	In-House)		
Resistance Temperature Detector	In-House: Glenn Research center	5 months	GRC has experience in designing these detectors for spacecraft thermal management systems.
Thermal IR Sensor	In-House: Goddard Space Flight Center [4]	6 months	GSFC developed their Thermal Infrared Sensor (TIRS) for their more recent iterations of the Landsat spacecraft starting with Landsat 8.
Ground Penetrating Radar	In-House: Jet Propulsion Laboratory	6 months	JPL offers specialized systems made for planetary exploration, and are used on rovers or landers. GPR systems used aboard planetary science missions to Mars from JPL have been successful.
Radiation Dosimeter	In-House: Goddard Space Flight Center [5]	5 months	GSFC develops and deploys radiation dosimeters for deep-space missions and are capable of monitoring high radiation.
Spectrometers (SHERLOC)	In-House: Jet Propulsion Laboratory [3]	1 year	JPL design and manufacturing SHERLOC to operate onboard Perseverance.
Close-Up Imager	In-House: Jet Propulsion Laboratory	1 year	Close-Up Imager was originally developed by the European Space Agency (ESA) [6] and is not commercially available. JPL has experience designing planetary science suites for Mars exploration missions. Should the design be proprietary, JPL is best positioned to develop an instrument with similar capabilities.

Backup Suppliers and Alternative Instrumentation Options:

Part/Assembly	Supplier (Contractor/COTS/ In-House)	Estimated Lead Time	Justification
Stereoscopic Camera (Alternative Instrument)	In-House: Jet Propulsion Laboratory	5 months	JPL developed the stereoscopic cameras used in Mars rovers and has high resolution.
X-ray Camera (Alternative Instrument)	In-House: Goddard Space Flight Center	6 months	GSFC has developed several advanced X-ray cameras for missions
Space Qualified Rover Lidar	In-House: Goddard	2.5 years	Project is in progress right now and is

(SQRLi) (Alternative Instrument)	Space Flight Center		projected to end in 2026 with a TRL of 8. Manufacturing for space applications will only begin after this point.
UV Radiometer (Alternative Instrument)	In-House: Goddard Space Flight Center	5 months	GSFC has developed UV radiometers for Earth observation and planetary exploration missions. They have high reliability and accuracy.
Resistance Temperature Detector (Backup Supplier)	In-House: Omega [8]	5 weeks	Omega's short lead time would make up for any lack of interfacing with the system that would need to be adapted and integrated by the team.
Ground Penetrating Radar (Backup Supplier)	In-House: Allied Associates [1]	Quote Needed	Allied Associates has over 30 years legacy of producing geophysical testing instruments such as GPR. Possible shorter lead time to balance out any additional adaptation and integration that may be necessary.
Radiation Dosimeter (Backup Supplier)	In-House: Calright Instruments [7]	3 weeks	Calright's short lead time would make up for any lack of interfacing with the system that would need to be adapted and integrated by the team.
Spectrometers (Backup Supplier)	In-House: Fisher Scientific [2]	Quote Needed	Possible shorter lead time to balance out any additional adaptation and integration that may be necessary.

2.1.5.4. Payload Subsystem Verification Plans

In addition to the verification methods described below, all of the instruments on the payload suite will undergo thermal vacuum testing to measure outgassing. Performing this test will allow the team to ensure that the mission's instrumentation will perform as expected in a space environment, and to avoid negative outcomes of outgassing such as single-event upsets during flight.

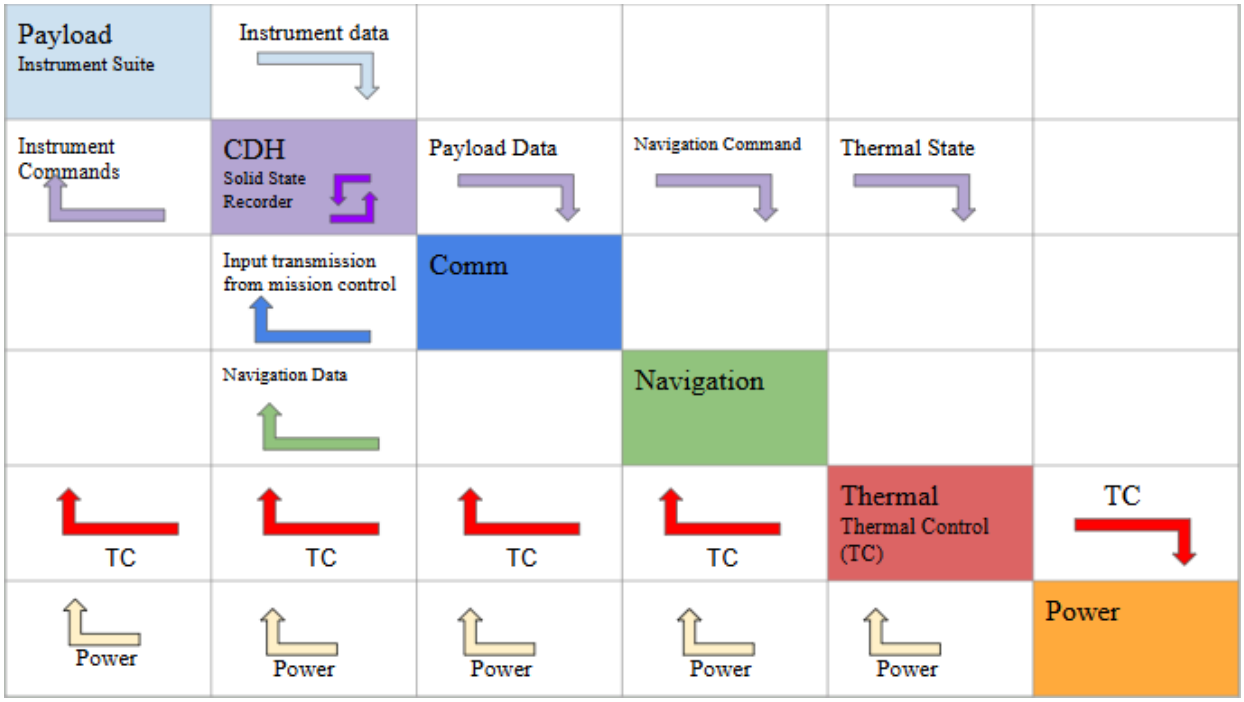
Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PAY-1.1	The temperature sensors should detect	Test	As this is a relatively easy test to perform, it will be worth ensuring	Temperature readings across the expected range will be checked against calibrated

	temperature fluctuations between 100-300 K.		the sensors' functionality.	measurements.
PAY-1.1.1	The temperature sensors should not change by more than 1 degree per year.	Demonstration	Manufacturing standards may provide an expected value, but actual use will provide more accurate information.	Use post-processing and data analysis monitoring to ensure that temperature readings are accurate over time and that sensor change is accounted for in data.
PAY-2.1	Close-Up Imager: The close-up imager should have a field of view of at least 100 degrees.	Inspection	Manufacturing standards will ensure that the product has an acceptable field of view.	In-house manufacturing of the payload suite allows for close quality assurance monitoring during instrument design and assembly.
PAY-2.2	Close-Up Imager: The close-up imager should have a root-mean square correlation accuracy of no greater 0.2.	Inspection	Manufacturing standards will ensure that the product has an acceptable accuracy.	In-house manufacturing of the payload suite allows for close quality assurance monitoring during instrument design and assembly.
PAY-2.9	GPR: The GPR should use dual-frequency scanning.	Inspection	Manufacturing standards will ensure that the product has dual-frequency scanning capabilities.	In-house manufacturing of the payload suite allows for close quality assurance monitoring during instrument design and assembly.
PAY-2.10	GPR: The GPR should	Inspection	Manufacturing standards will	In-house manufacturing of the payload suite

	have a resistivity of at least 100 Ohm-m.		ensure that the product has an acceptable resistivity.	allows for close quality assurance monitoring during instrument design and assembly.
PAY-2.11	GPR: The GPR should have an antenna center frequency of 100 MHz	Inspection	Manufacturing standards will ensure that the product has an acceptable center frequency.	In-house manufacturing of the payload suite allows for close quality assurance monitoring during instrument design and assembly.
PAY-3.1	Spectrometers should measure the energy range of radiation between 100 keV - 10 MeV.	Test	As the spectrometer is the most costly instrument to source from a backup supplier, it will be worth ensuring the instrument's functionality.	Spectrometer readings across the expected range will be checked against calibrated measurements.
PAY-3.2	Spectrometers should have a sensitivity of no more than 10e4 erg/g/s.	Inspection	Manufacturing standards will ensure that the product has an acceptable sensitivity.	In-house manufacturing of the payload suite allows for close quality assurance monitoring during instrument design and assembly.
PAY-3.3	The radiation dosimeter should have a sensitivity of no more than 10e4 erg/g/s.	Inspection	Manufacturing standards will ensure that the product has an acceptable sensitivity.	In-house manufacturing of the payload suite allows for close quality assurance monitoring during instrument design and assembly.

2.2. Interface Control

N^2 Chart

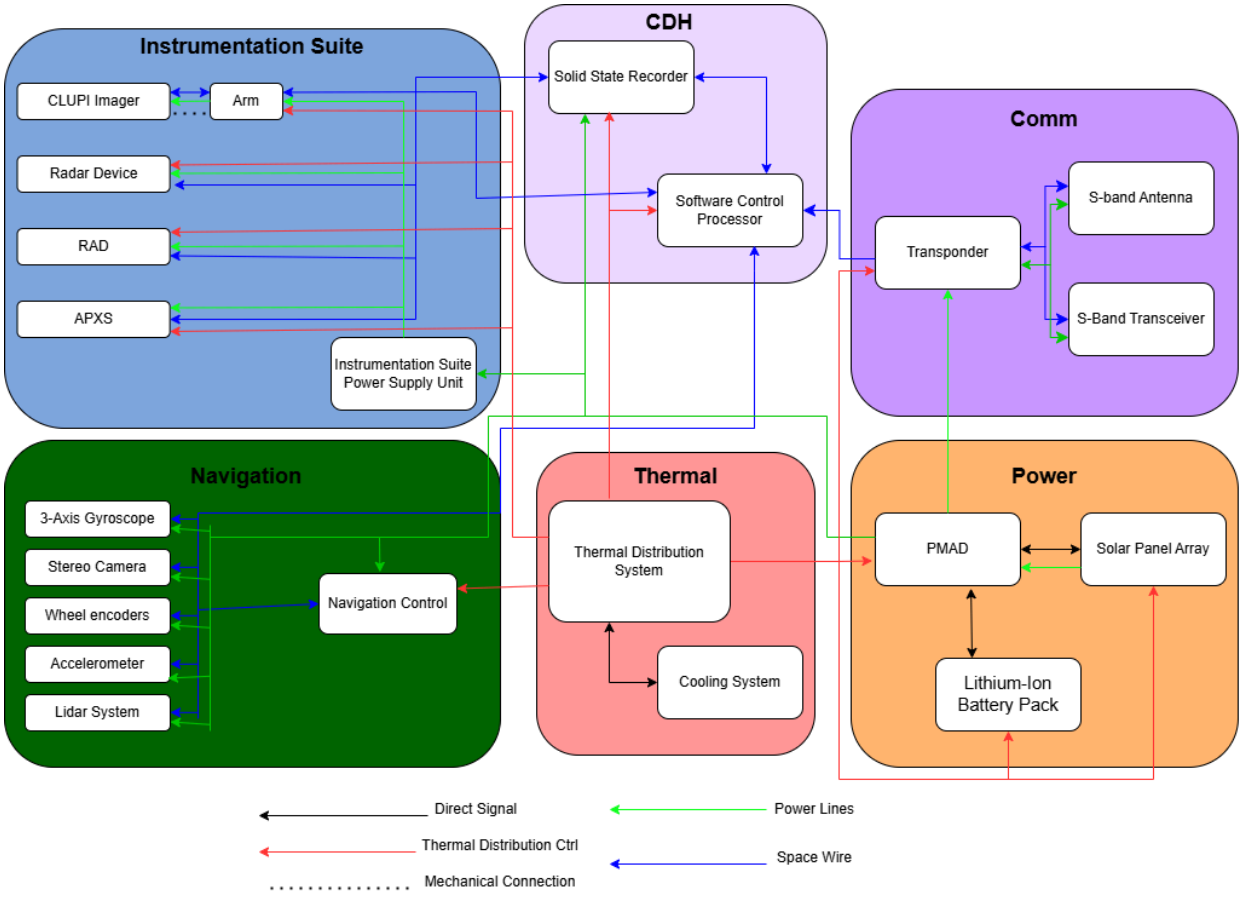


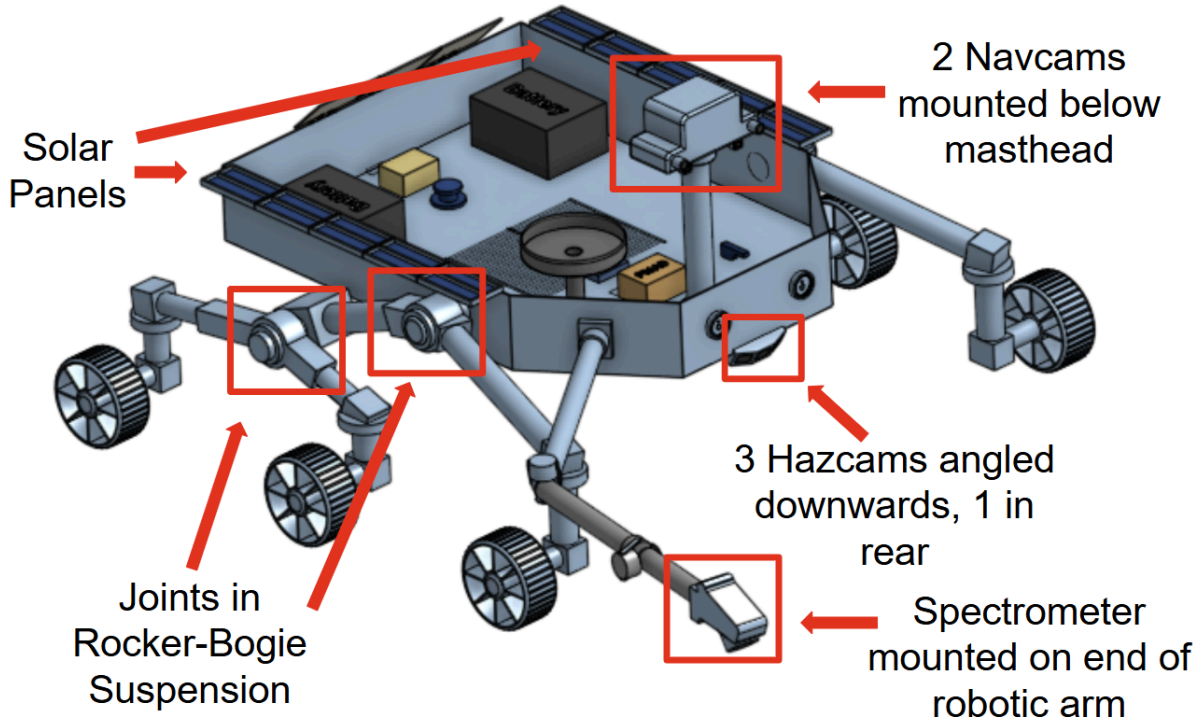
The MTP rover comprises 6 subsystems: Payload, Command & Data Handling (CDH), Communications, Navigation, Thermal Control, and Power. The N^2 diagram outlines high-level relationships between various subsystems. The power subsystem enables the operation of all other subsystems, as indicated by the yellow arrow. The thermal control system provides heat regulation to the navigational, communication, CDH, and payload subsystems necessary for operation in the extremely cold temperatures found within the pits, which will likely be made further colder by the shade in the overhang within the pit. The instrumentation in the payload subsystem provides data to fit into the data-handling hardware. This data is then used to direct the operation of the communications, navigation, and thermal control subsystems. The command system directs the operation of instrument data collection. Navigation and data from mission control center direct command hardware.

Functional Block Diagram:

The functional block diagram below shows a more in-depth relationship between the different subsystems in the rover. The instrumentation suite replaces the payload heading from the n^2 chart and displays the specific instruments that are used for data collecting. Power wires, Space wires, Mechanical connections, Thermal Distribution Connections, and Point-to-point connections are displayed in the legend and show the different kinds of relationships each component has. The power and thermal lines run throughout the whole diagram as thermal control, and power is needed for most if not all, components. Space wires all connect to the CDH subsystem and allow for the SSR and Processor to gather and send data to different subsystems when needed. The only

expectation of the trend of space wires leading to the SSR is the robotic arm that mechanically connects the CLUPI imager to the Processor directly instead of the SSR. The robotic arm needs special commands to move and work with the CLUPI imager.





3. Science Mission Plan

3.1. Science Objectives

Objective 1:

The first objective of this lunar robotic mission is to characterize the thermal environment of MTP. Lunar pits/caves such as MTP can provide shelter for future explorers. A “good” cave suitable for long-term habitation must provide a constant temperature near 15°C or approximately 290 K (Wagner 2022). Regarding the lunar surface, there are temperature fluctuations from 121°C to -133°C. Keeping these extreme conditions in mind, it would be efficient to find a temperature-neutral cave rather than construct a suitable living environment on the lunar surface (Tymchuk 2024). A thermal sensor able to measure the temperature of the pit’s floor and environment as well as the surface temperature surrounding MTP would satisfy this objective.

Objective 2:

Another characteristic of the habitation regime is longevity. A cave or tunnel must be able to preserve its structure for decades without showing signs of structural damage. Any sign of structural damage poses a significant threat to an astronaut’s life and

potentially ends a robotic mission in the event of a sudden collapse. Lunar caves are capable of preserving delicate structures for long periods of time (Wagner 2022). Science objective 2: “Assess the structural integrity of the walls and overhangs of MTP” strives to verify this characteristic for MTP since previous attempts to use ground-penetrating radar and radiometers have found inconclusive results (Carrer 2024). A camera/imager, either in the X-ray or optical spectrum, could provide evidence of the geological stability of these lunar pits.

Objective 3:

Previous objectives explore the implications of habitability of lunar pit MTP; however, a robotic mission has to overcome the challenges of terrain variation without previous knowledge or prediction of the kinds of terrain encountered (Carrer 2024). In addition, data gathered about the terrain characteristics would serve as a baseline for future mission planning. Therefore, this mission must gather valuable information on the accessibility of lunar pits and extended cave conduits (Carrer 2024). Objective 3: “Investigate and characterize potential cave networks and terrain in and around MTP” serves to work around this challenge. A ground-penetrating radar in situ would provide conclusive evidence of potential lava tubes and an extended cave network.

Objective 4:

High energy radiation harms humans and robotics alike; therefore, it is essential to quantify the amount of exposure received in space. Solar radiation is more harmful on the surface of the Moon than on Earth (Tymchuk 2024) due to a lack of atmospheric shielding and magnetic fields. In addition, cosmic rays from extragalactic sources may threaten life and any onboard instruments (Wagner 2022). In a hostile environment like the Moon, with little to no atmosphere, Science Objective 4 aims to fill this knowledge gap and fulfill the stakeholder objective to develop precursor robotic experiments for astronauts. Experiments measuring the amount and strength of radiation exposure will help the science and engineering teams develop better instrumentation that will survive on the surface. Moreover, it will provide key insight into how long astronauts will be able to survive inside MTP without being exposed to fatal doses of radiation. The team has decided to employ a radiation detector aboard the rover to assess the radiation exposure.

Objective 5:

The final objective of this mission is to study the volatile content and hydrogen abundance in the lunar regolith. A significant aspect of the team’s objective is identifying resources for in-situ use on the surface and within MTP. Exploration of lunar caves may have essential molecules such as hydrogen, methane, nitrogen, and ammonia that can

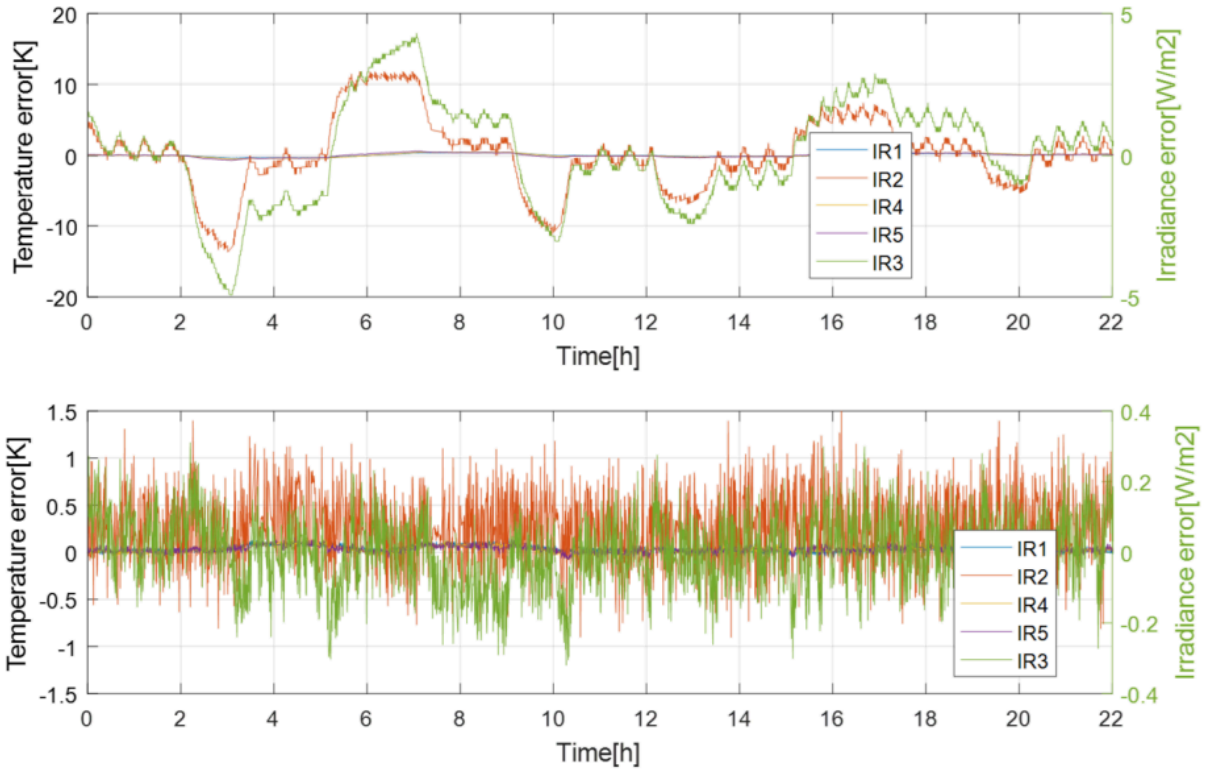
be harvested to create resources that would otherwise need to be flown in on another mission. In addition, these caves have the potential to have ice or water in them; however, ice is more abundant on the poles than near the equator (Tymchuk 2024). A mass spectrometer or alpha-particle spectrometer is a necessary addition to the rover's instrument suite to answer questions about the presence of such chemicals.

3.2. Experimental Logic, Approach, and Method of Investigation

Instrument-by-Instrument Logic, Approach, and Method

TIRS: Thermal Infrared Sensor

According to the mission's parent mission requirements from the STM, the rover shall collect temperature data daily so that the science team can analyze the day-to-day variations on the Lunar surface. These values are well known, and multiple measurements of the albedo of the surface have been taken; however, more precise measurements can be taken in situ by TIRS. The thermal infrared sensor aboard the MTP rover is characterized by its ability to measure the thermal temperature of the surface environment in the pit and the surface. Referring to the mission Concept of Operations, the rover will touchdown near MTP at T+1 days and begin initial checks. After this initial check is completed and the rover's systems operate at their desired levels, experimentation, and scientific data collection can begin. Before this data collection phase, TIRS must undergo several calibration tests that test the sensor's responsivity compared to standards like Earth's atmosphere, vacuum, etc. These tests should reveal the errors in the temperature measurements due to thermal gradients (Rodriguez-Manfredi 2021). These errors should look similar to this figure:



This figure from Rodriguez-Manfredi et al. 2021 shows the errors in the different thermal irradiance over time. An error profile can be created from these results to mitigate this error during data collection.

Once the TIRS has been properly calibrated, surface temperature measurements can be made daily during the rover's journey to MTP. Ideally, the rover will stop every few meters for thermal measurements. This is repeated over a day/night cycle as often as possible to generate a conclusive day/night surface temperature variation throughout the day. At the end of a 24-day cycle, telemetry and measurements will be sent back to Earth for analysis. This ensures that a day-to-night variation and a monthly variation are examined. Once the rover descends into MTP, thermal measurements of the pit's floor will be made similarly; however, the rover will sweep the floor in a grid-like manner. This data will create a thermal gradient of the pit's interior over a day/night cycle.

CLUPI: Close-UP Imager

CLUPI is a powerful camera that can take images of rock features in multiple FOVs and consists of a unique feature to create almost 3-dimensional images using its Z-stacking feature (Josset et al. 2017). After telemetry checks and standard calibration of the imager, CLUPI will start to take pictures of the surrounding environment using its first FOV mode to analyze the textures of the regolith. In this configuration, CLUPI will take images of the regolith and interesting rock formations near MTP as the rover traverses

to the point of interest. Once the rover has descended into the PIT, CLUPI will begin to observe the overhangs. Ideally, observations should begin where the rover has landed, and then, as the rover traverses through the pit by hugging the walls, CLUPI can take close-up images of the walls. After further analysis of these images post T+24 days, targets of interest will be chosen. These targets of interest will have features that feature signs of structural instability within the pit, and further observations will help the science team understand the geographical structure of MTP.

GPR: Ground Penetrating Radar

As the rover nears MTP, the ground-penetrating radar under the rover will begin to take stratigraphic observations to locate and identify previously unknown features based on satellite images. Multiple recordings of the subsurface from the surface are unnecessary. They may waste energy and time in conducting other experiments, so only a few pulses from the GPRs antenna will be used to map the subsurface from the surface. After descending into the pit, however, the GPR will be used to identify additional lava tubes and subsurface features. On the surface, the GPR will send a series of signals down towards MTP. After sending one signal down, GPR will collect reflectance data of any radio waves that may have reflected toward the rover. Considering the possibility that the pit floor may reflect most, if not all, of the radio waves, calibration and testing to mitigate the reflectance from the floor must be conducted before taking real measurements on the surface. Once the rover has touched down on the pit floor, GPR will be used in multiple directions to identify any lower levels that can't be identified from satellite imagery.

RAD: Radiation Assessment Detector

The Radiation Assessment Detector (RAD) is critical for evaluating the safety of the Mare Tranquillitatis Pit as a potential habitat for astronauts. Due to their subsurface environments, lunar pits may provide natural shielding from harmful cosmic and solar radiation. The RAD will begin by taking baseline measurements at the landing site to establish a radiation profile of the surface environment. These measurements will be taken periodically as the rover traverses toward the pit to capture variations in solar radiation flux and cosmic radiation levels. During the rover's descent, the RAD will record radiation levels at different depths, providing a gradient of exposure within the pit. Inside the pit, the RAD will monitor radiation levels over a complete lunar day and night cycle, offering a temporal profile of radiation shielding; data from RAD will complement thermal data from TIRS, identifying areas with thermal stability with radiation protection, critical for defining safe zones for human exploration. This

experimental approach was developed using JMARS imagery, identifying potential overhangs and shadowed regions that may offer shielding.

APXS: Alpha-particle X-ray Spectrometer

APXS will help identify crucial elements on the surface and inside MTP's interior that astronauts will harvest for in situ resource utilization. Chemicals such as silicon dioxide, hydrogen, methane, and oxygen are critical for refueling landers and replenishing the oxygen supply. After postlaunch calibration and calibration were conducted on the lunar surface, measurements taken with APXS utilized a simple command interface. Once a target has been chosen for APXS, a commence and end command will be used to start/stop measurements of the target (Rieder et al. 2003). The chosen targets will be candidates that are prime regolith samples or lunar rocks that may contain the chemicals mentioned earlier. Temperature calibrations will be taken around every 30 seconds the instrument is powered on. These calibrations ensure that the results are accurate to a particular energy resolution. To search for trace elements in the lunar regolith and rock samples, an exposure time of 2-4 hours is required to generate a sufficient amount of counts/s to determine the presence of the substance (Rieder et al. 2003). Longer periods of exposure can also be taken after a particularly interesting sample has been identified using short exposure data.

3.3. Payload Success Criteria

Temperature measurement, which has a redundant instrument aboard, should optimally record accurate measurements for the majority of the system's lifecycle. Measurements from either instrument (primary or redundant) are considered acceptable so long as readings are consistent between instruments so as to corroborate one another. In this case, failure mode would constitute total reliance on the redundant instrument since there is no twice redundant instrument aboard the payload suite. The readings from this part of the mission are expected primarily to act as indicators of habitability. While scientists have theorized the temperatures within lunar pits, having an empirically-affirmed range of temperatures will give a more complete picture as to whether Mare Tranquillitatis could be a viable location for a habitat.

The Close-Up Imager was designed with planetary science studies in mind. Because of this, a similar instrument would be expected to at least produce high-resolution imagery of enough of the MTP interior to allow for geological and habitability studies. The team believes it is reasonable that imaging and studying the interior environment of at least half of the pit's interior will reveal the general state of MTP's geology, given the minimum categorical success of the ground penetrating radar is achieved in tandem.

Studying MTP's interior using high-resolution imagery will ideally reveal any cracks, sedimentation layering, or other indicators of the pit's history and structural stability. Additionally, the Close-Up Imager's fully successful deployment would reveal the possible existence and nature of any lava tubes connected to MTP.

Similarly, the success of the GPR will be considered in tandem with the Close-Up Imager. Both instruments are intended to provide insight to the structure of the pit, and the successful downlinking of data from both instruments would allow researchers to develop a complete initial understanding of MTP. Using information from both imaging techniques, planetary information about the formation of MTP, whether it is structurally viable for habitation, and detailed pit dimensions could be concluded. Possible use cases for such information may even allow simulations of pit infrastructure to be developed. For both the Close-Up Imager and GPR, an acceptable failure mode would be for either one or the other to fail to downlink accurate imaging data. Ideally, information from both would fully complete the desired science objectives; partial completion of an objective (ie. one of the two instruments returns faulty or no data) would be considered acceptable though undesirable.

The last two instruments have no acceptable failure modes because they do not have redundant or corroborative instruments aboard the payload suite. A Radiation Assessment Detector (RAD) will be included on the suite primarily to perform habitability studies. Lunar pits are considered a possible option for establishing a lunar base because they may protect astronauts from the harsh radiative conditions which exist beyond the Van Allen belts. While it may be possible to perform a habitability condition assessment without physically testing the radiation present in MTP, the team considers empirical confirmation of lunar pit habitability with regards to this a critical component of the mission goals. Therefore, successful performance of the RAD would include accurate measurements successfully downlinked spanning the majority of the system lifecycle.

Finally, the spectrometer aboard the payload suite also does not have an acceptable failure mode, as it is costly to procure and has no adjunct instrument it works with. Successful downlinking from the spectrometer will provide insight to the chemical composition of the MTP interior, information which would be useful for studying planetary history and geological formation, human habitability, and in-situ resource potential. While it is desirable to have data on as much of the pit's interior composition as possible, the baseline for success will be considered met if 50% of the pit's composition can be reasonably modeled using spectrometer data. This number would allow for a general scientific understanding of Mare Tranquillitatis' condition and decrease the chance of studying MTP using outlier data.

Category	Minimum Success	Optimum Success	Stretch Goal
Thermal IR Sensor	Thermal IR Sensor or redundant instrument accurately takes temperature measurements at desired intervals throughout 60% of the mission lifecycle.	Thermal IR Sensor or redundant instrument accurately takes temperature measurements at desired intervals throughout 80% of the mission lifecycle.	Thermal IR Sensor accurately takes temperature measurements at desired intervals throughout 90% of the mission lifecycle. No redundant system is used.
Close-Up Imager	Close-Up Imager accurately images a full 180° of the MTP interior.	Close-Up Imager accurately images 270° of the MTP interior.	Close-Up Imager accurately images a full 360° of the MTP interior.
Ground Penetrating Radar	Close-Up Imager accurately images a full 180° of the terrain surrounding MTP.	Close-Up Imager accurately images a full 270° of the terrain surrounding MTP.	Close-Up Imager accurately images a full 360° of the terrain surrounding MTP.
Radiation Assessment Detector (RAD)	RAD accurately takes temperature measurements at desired intervals throughout 60% of the mission lifecycle.	RAD accurately takes temperature measurements at desired intervals throughout 80% of the mission lifecycle.	RAD accurately takes temperature measurements at desired intervals throughout 90% of the mission lifecycle.
Spectrometer	Spectrometer accurately identifies chemical composition of 50% MTP interior through evenly spaced physical data collection points.	Spectrometer accurately identifies chemical composition of 70% MTP interior through evenly spaced physical data collection points.	Spectrometer accurately identifies chemical composition of 90% MTP interior through evenly spaced physical data collection points.

3.4. Testing and Calibration Measurements

Upon landing, the rover will initiate a series of preliminary tests to ensure that all scientific instruments are operational, calibrated, and providing accurate data. These tests will be conducted sequentially, focusing on each instrument's unique operational environment. The tests will incorporate internal checks, control variable measurements, and environmental benchmarks. Below is the detailed testing procedure by instrument:

Thermal Infrared Sensor (TIRS):
Purpose: To measure thermal variations across the lunar surface and within the Mare Tranquillitatis Pit to create detailed thermal maps.

- Testing Procedure:
    - Conduct an initial scan of sunlit and shaded areas at the landing zone.
    - Compare surface temperatures of nearby rocks and regolith with expected thermal profiles.
- In-Situ Calibration Method: The TIRS will use an onboard blackbody radiator with a precisely known emissivity and temperature range to validate sensor accuracy.
- Control Variables: Known temperature ranges from lunar regolith during previous missions and solar exposure effects.
- How Accuracy is Ensured: Thermal readings will be cross-referenced with preloaded thermal profiles from prior lunar data.
- Expected Result: Temperature maps with a margin of error of ±1K, highlighting thermal stability in potential habitat zones.

Close-Up Imager
Purpose: To capture high-resolution images for 3D terrain mapping and navigation.

- Testing Procedure:
    - The stereoscopic camera will first image onboard calibration targets mounted on the rover. These include geometric shapes and patterns with known dimensions.
    - Next, it will capture images of the surrounding terrain to verify depth and clarity.
- In-Situ Calibration Method: The calibration targets on the rover will serve as reference points to validate image clarity and depth perception.
- Control Variables: Known distances to calibration targets (e.g., 1 m) and ambient lighting conditions.
- How Accuracy is Ensured: Comparing the captured images with the expected dimensions and distances of the calibration targets.
- Expected Result: Clear, distortion-free images with accurate depth resolution within ±79 μm/pixel.

Ground-penetrating radar (GPR)

Purpose: To map subsurface structures and detect voids or lava tubes beneath the lunar surface.

- Testing Procedure:
    - The GPR will conduct an initial scan of flat, known terrain near the landing site to establish a baseline signal profile.
    - This will be followed by scans of areas with expected subsurface variations.
- In-Situ Calibration Method: Simulated test signals stored onboard will be used for cross-comparison with real-time radar data.
- Control Variables: Lunar regolith density and expected subsurface signal reflection times.
- How Accuracy is Ensured: Signal reflections will be analyzed for consistency with geological models of the landing site.
- Expected Result: Accurate subsurface mapping up to 50m depth with signal integrity confirmed by consistent reflection patterns.

Radiation Dosimeter

Purpose: To measure radiation levels to assess environmental safety and habitability.

- Testing Procedure:
    - The dosimeter will be activated in shaded and exposed regions to measure cosmic radiation flux and ionizing doses.
- In-Situ Calibration Method: An onboard radiation shielding system will create a low-radiation reference zone to validate measurements.
- Control Variables: Expected radiation levels based on prior lunar missions (Apollo and LRO).
- How Accuracy is Ensured: Measurements will be compared against preloaded radiation benchmarks for the lunar surface.
- Expected Result: Accurate radiation level readings within a margin of ±5% from expected values.

Spectrometer

Purpose: To analyze the elemental composition of the lunar surface for resource identification.

- Testing Procedure:
    - The spectrometer will target an onboard calibration plate with a known elemental composition (e.g., basalt simulant).
    - It will then scan surrounding regolith samples for comparison.

- In-Situ Calibration Method: The known calibration plate spectra will be used to validate the spectrometer's readings.
- Control Variables: Known elemental composition and spectral signatures of the calibration plate.
- How Accuracy is Ensured: Data will be matched with preloaded reference spectra to confirm detection accuracy.
- Expected Result: Elemental detection within a ±5% error margin, confirming functionality.

Resistance Temperature Detector (RTD) (alternative)

Purpose: To measure the thermal environment within the lunar pit and its surroundings.

- Testing Procedure:
    - The RTD will initially take temperature readings in shaded and sunlit areas of the landing zone.
    - It will compare ambient readings with expected lunar surface temperatures (-170°C to 120°C).
- In-Situ Calibration Method: The RTD will use an onboard reference heat sthe team'sce with a known and stable temperature value to validate sensor accuracy.
- Control Variables: Ambient temperature variations due to solar exposure and lunar day/night cycles.
- How Accuracy is Ensured: Data will be cross-referenced with preloaded thermal profiles of the lunar surface from previous missions. Stable and consistent results will confirm functionality.
- Expected Result: Accurate temperature readings with a margin of error of ±1K.

LiDAR System (alternative)

Purpose: To create 3D topographical maps of the lunar terrain and interior of the pit.

- Testing Procedure:
    - The LiDAR will perform an initial scan of the surrounding flat terrain and onboard geometric calibration targets.
    - Following the baseline scan, it will attempt to map a small section of the lunar pit's interior.
- In-Situ Calibration Method: Calibration targets with known geometric dimensions will be used to verify alignment and accuracy.
- Control Variables: Fixed distances to targets and surface irregularities within the landing zone.
- How Accuracy is Ensured: The LiDAR-generated models will be compared against preloaded data of the calibration targets.

- Expected Result: Terrain maps with an accuracy of ±2.5 mm/pixel, correctly capturing terrain features.

UV Radiometer (alternative)

Purpose: To measure solar UV radiation intensity on the lunar surface.

- Testing Procedure:
  - The UV radiometer will perform initial measurements during lunar noon and in shaded areas.
- In-Situ Calibration Method: Calibration with expected UV intensity benchmarks based on the landing site's coordinates.
- Control Variables: Known solar radiation flux and shading.
- How Accuracy is Ensured: The data will be compared to preloaded UV profiles from previous missions.
- Expected Result: Reliable UV intensity measurements within ±5% of expected values.

3.5. Precision and Accuracy of Instrumentation

Thermal IR Sensor

The Thermal IR Sensor aboard the Mars Environmental Dynamics Analyzer will be used to identify temperature fluctuations throughout the mission lifespan on the lunar surface and the Mare Tranquillitatis lunar pit. The instrument measures surface temperature and irradiance solar flux at an accuracy of ~10% when accessing the entire atmosphere. This level of uncertainty may potentially affect the ability to categorize geological features, such as the differences between the rim of the pit or the floor.

Close-Up Imager (CLUPI):

The CLUPI has a resolution of app 15 microns, which provides extremely high detail images of geological features. This precision allows for the identification of fine structural details, such as small fractures, sedimentation layers, and textural differences in regolith. While the instrument's high resolution ensures accurate imaging, minor distortions may arise due to environmental factors such as dust or lighting conditions. These issues will be mitigated by using Z-stacking, which integrates multiple focal planes to create near-3D images, minimizing data loss due to depth variability. The precision of CLUPI ensures that structural and geological analyses of MTP are performed with a high degree of reliability.

Ground-Penetrating Radar (GPR):

The GPR provides subsurface data with a depth resolution of ±10 cm and a penetration depth of up to 50 meters in lunar regolith. This accuracy is sufficient for detecting voids, stratigraphic layers, and potential lava tubes. However, the resolution may be affected by variations in regolith density, which could result in minor signal distortion or reduced clarity at greater depths. To address these limitations, calibration scans on flat terrain near the landing site will establish baseline signal responses, and cross-referencing with CLUPI imagery will help validate subsurface anomalies. The ±10 cm depth resolution ensures that the GPR can reliably identify key subsurface features critical to assessing MTP's geological stability and resource potential.

Radiation Assessment Detector (RAD):

The RAD measures radiation levels with an accuracy of ±5%. This level of precision is sufficient for monitoring variations in radiation exposure across different environments, such as the surface and interior of MTP. However, environmental factors such as temperature fluctuations and solar activity could introduce minor variability in the readings. To ensure data reliability, the RAD will perform repeated measurements over a full lunar day/night cycle and compare them with baseline readings collected at the landing site. The ±5% accuracy margin ensures that the RAD provides a reliable assessment of MTP's shielding potential, aiding in the identification of safe zones for future human habitation.

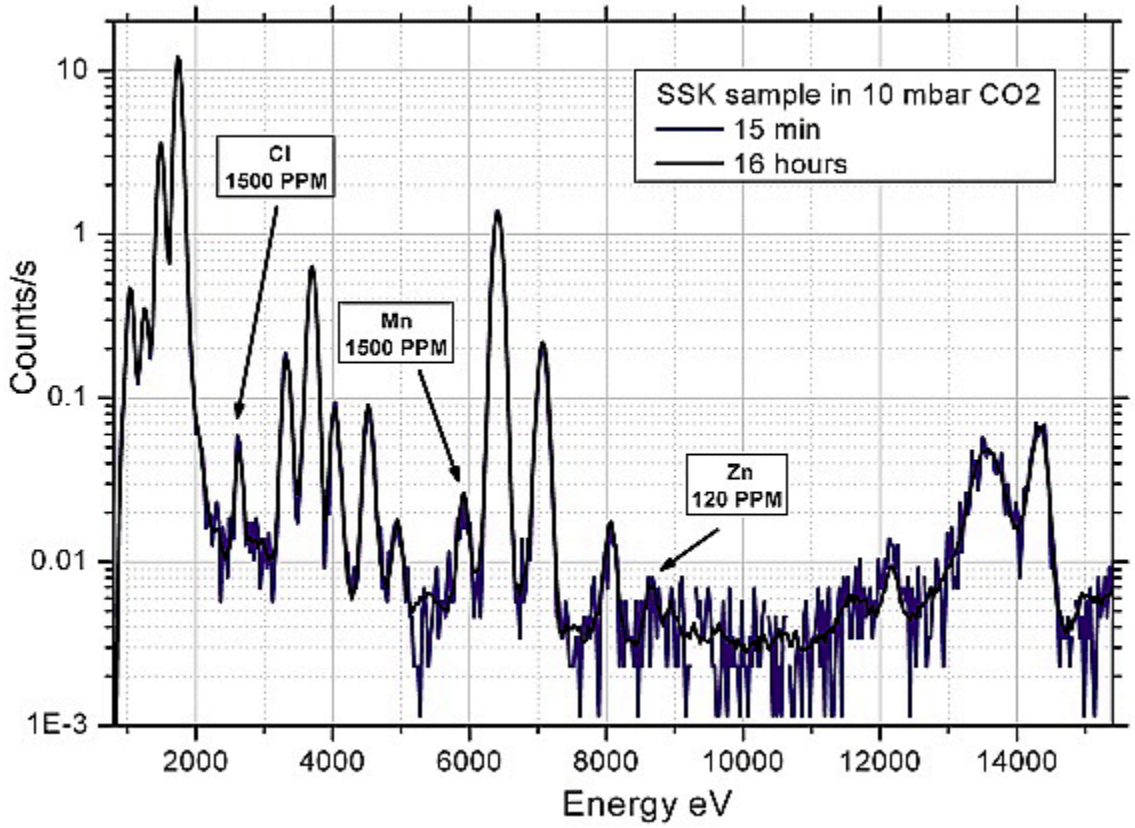
Spectrometer:

The spectrometer has an elemental detection accuracy of ±5% for most target volatiles and minerals, such as hydrogen, methane, and ammonia. This level of precision is critical for determining the distribution and concentration of resources within the regolith. Variability in the instrument's readings may arise from sampling inconsistencies or environmental interference, such as dust deposition on the spectrometer lens. To mitigate these factors, the spectrometer will analyze regolith samples in a grid pattern, ensuring even spatial coverage. Cross-referencing spectrometer data with GPR findings will help validate resource-rich zones. The ±5% accuracy margin allows the spectrometer to reliably assess ISRU potential, supporting the mission's resource utilization objectives.

3.6. Expected Data & Analysis

APXS: Alpha-particle X-ray Spectrometer

APXS bombards a sample (i.e., lunar regolith) with alpha particles and X-rays, then observes the X-ray emission from the Rutherford backscattering interactions within the sample (Rieder et al. 2003). Sample data typically received by the onboard sensor are counts that hit the detector and the measured energy value of that photon. Usually, these energy values are in the thousands of electronvolts. The following is a sample analysis of a rock matrix that simulates the performance of APXS.



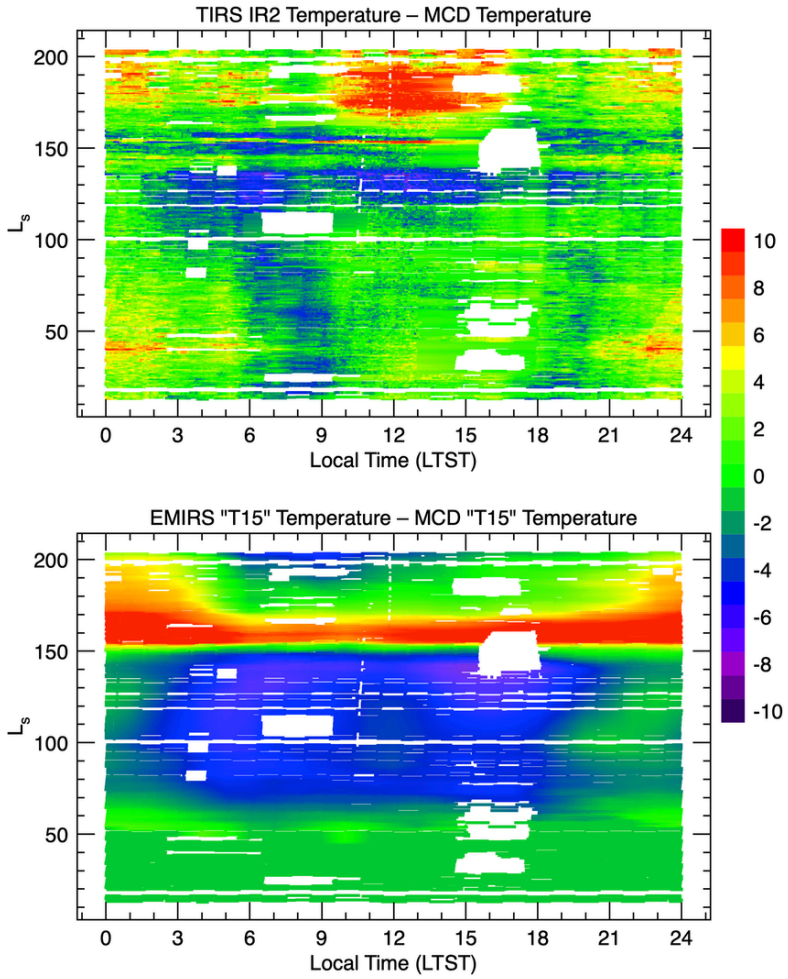
This figure from Rieder et al. shows a simulated spectra of a rock matrix. Various trace elements, such as zinc and chlorine, can be identified by plotting the data. This data was simulated at 10 millibars, and different trace elements are the targets for this mission, so data taken by the MTP rover will likely be different from the one simulated above.

To derive the peaks of these traces, a deconvolution of the raw data is taken, including any statistical errors. Using the deconvoluted data, a theoretical model spectrum is constructed using APXS's response function (Rider et al. 2003). Finally, a fitting routine is applied to the data until errors are minimized. This analysis will be conducted similarly for data collected on the lunar surface and MTP's interior. APXS has a precision of 200 eV and a spectral range of 1-25 KeV, meaning it is extremely precise at acquiring trace elements in the lunar landscape, and a broad spectral range allows for greater identification of elements. If evidence of trace abundances of hydrogen, methane,

silicon dioxide, and other essential substances is found, then MTP could become a potential habitat for refueling and replenishing oxygen.

TIRS: Thermal Infrared Sensor

TIRS is designed to measure long-wavelength infrared radiation of lunar surfaces and will allow the science team to quantify the MTP's pit floor surface energy budget (Perez-Izquierdo et al. 2017). A thorough thermal data collection on MTP's walls and floors will reveal whether the pit's temperature fluctuates wildly. If the evidence of large-scale fluctuations on the pit floor is shown, the pit cannot be deemed fit for habitation. Sample data may look like this figure from Smith et al. 2023:



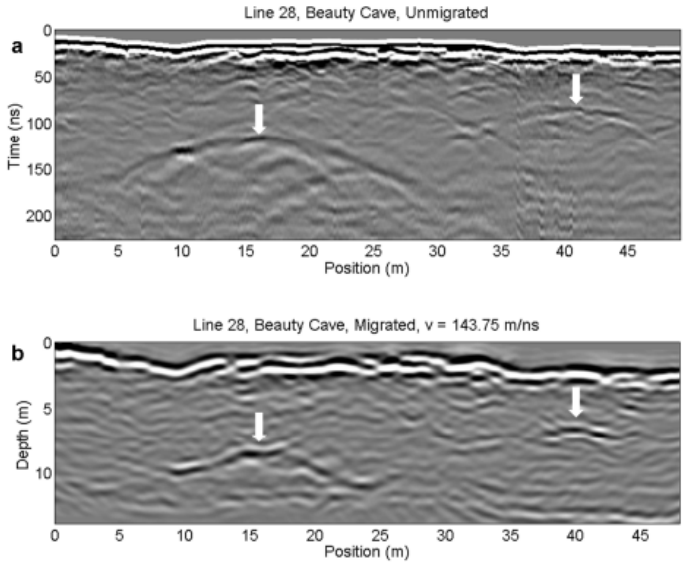
This data shows temperature differences between the IR2 channel of TIRS and the equivalent temperature from the Mars Climate Database in graphical format. More than likely, however, raw data from each channel will ideally appear in a table format like this figure from Rodriguez-Manfredi et al. 2021:

Channel	K [mK/K]	K' [mK/K/h]
IR1	13.70	-1.205
IR2	1.93	-1.602
IR3	14.91	-3.861
IR4	16.21	-1.513
IR5	9.21	-1.326

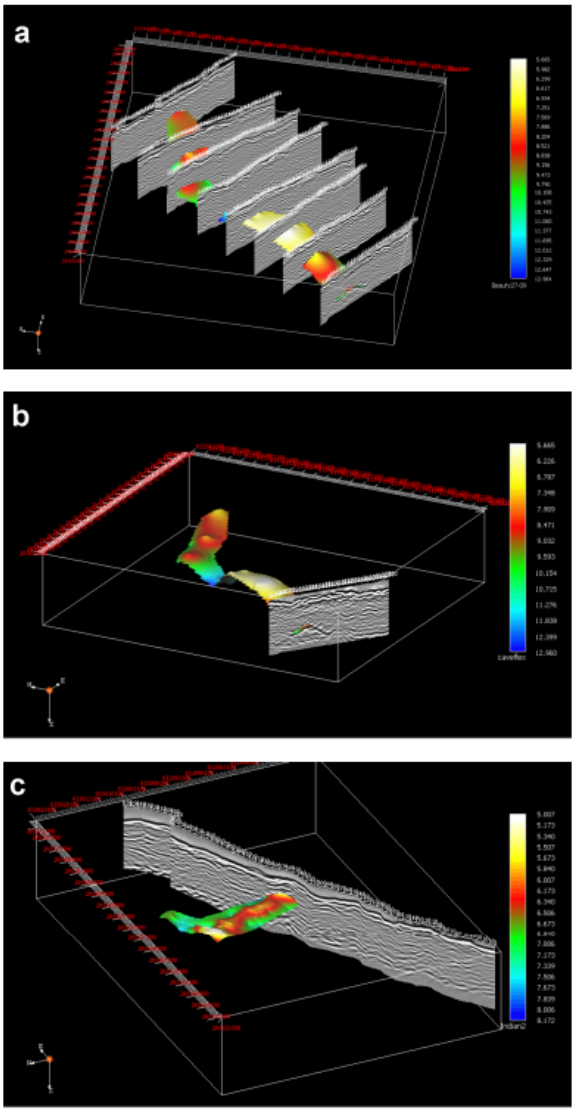
Once multiple measurements have been taken and sent back to Earth, analysis and construction of a thermal map of MTP can be created and look similar to the first figure. Like any instrument, errors associated with TIRS may be due to calibration uncertainties, the sensor's response function, or differences between the target and actual temperatures. To overcome this, multiple temperature samples of the same target and generating probability distributions for errors will be conducted (Rodriguez-Manfredi et al. 2021).

GPR: Ground Penetrating Radar

GPR is a technology used in multiple geophysical/terrestrial applications. It is widely used on Earth to uncover lava tubes and subsurface cavities threatening residential areas. A GPR can be used in the same way to map the subsurface of MTP before the rover descends. After descending, the GPR can be utilized to search for cavities or lava tubes that the rover won't be able to access. Generally, GPR sends a radio pulse towards the point of interest. If a cavity exists, the radio wave is reflected, which can be sensed by the detector. Example data that would look similar to measurements conducted on the lunar surface look like these figures from Rowell et al. 2010:



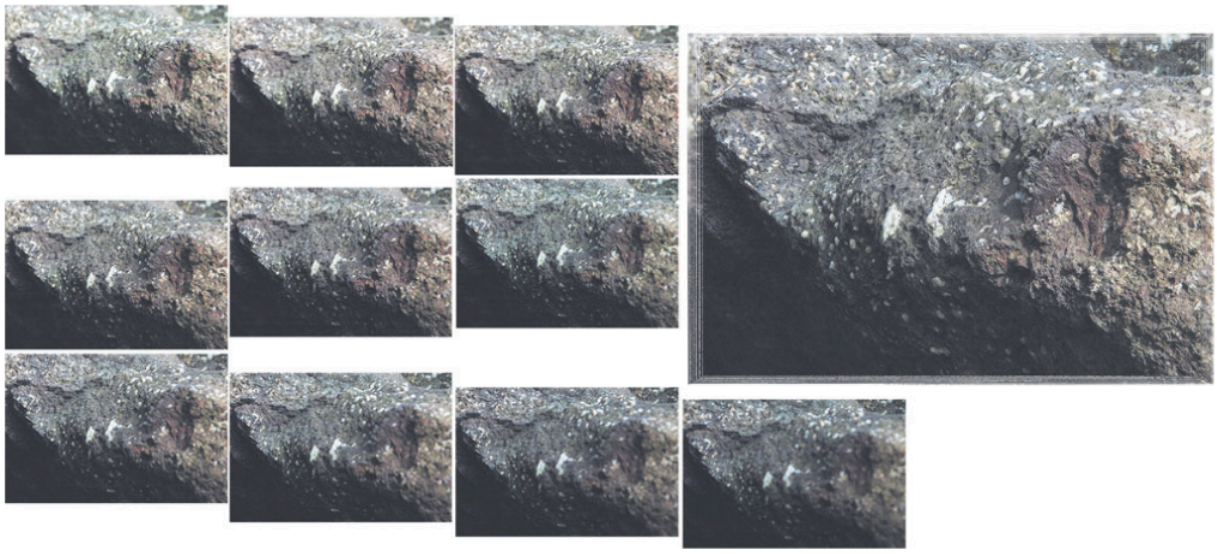
This figure shows a stationary GPR above a cave. The diffraction pattern of the cave roof is visible from these images, and the estimated depth can be found. These figures can be generated from width and depth data collected from the reflectance data. Further analysis can also be done after the data has been sent to Earth. Using multiple profiles of the GPR and steadily moving it while it is recording measurements, a 3D profile can be created:



Source: Rowell et al. 2010

CLUPI: Close-Up Imager

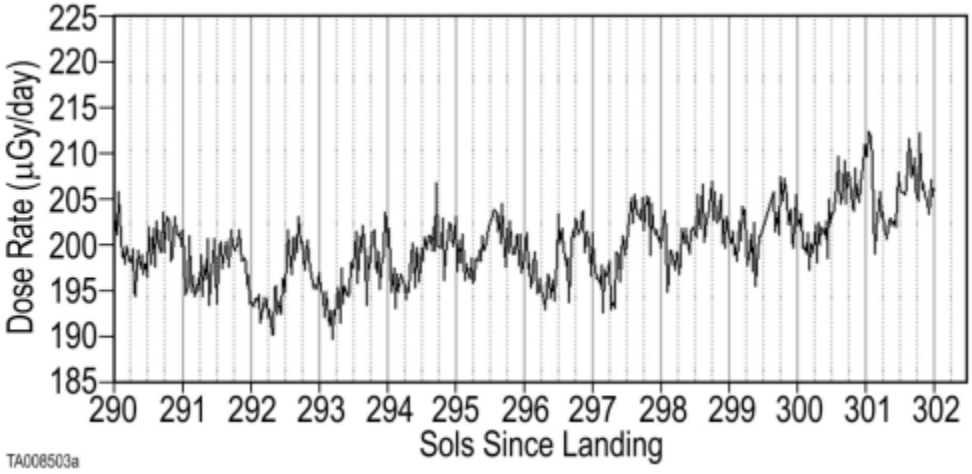
CLUPI is a high-resolution color camera specifically used for close-up observations. It will be used on the mission to conduct nondestructive testing to identify any signs of structural instability. The CLUPI aids in characterizing in terms of their texture, structure, and color - any geological identifier. Josset et al. 2017 illustrate the unique Z-stacking feature that CLUPI offers to identify small structural changes in a sample.

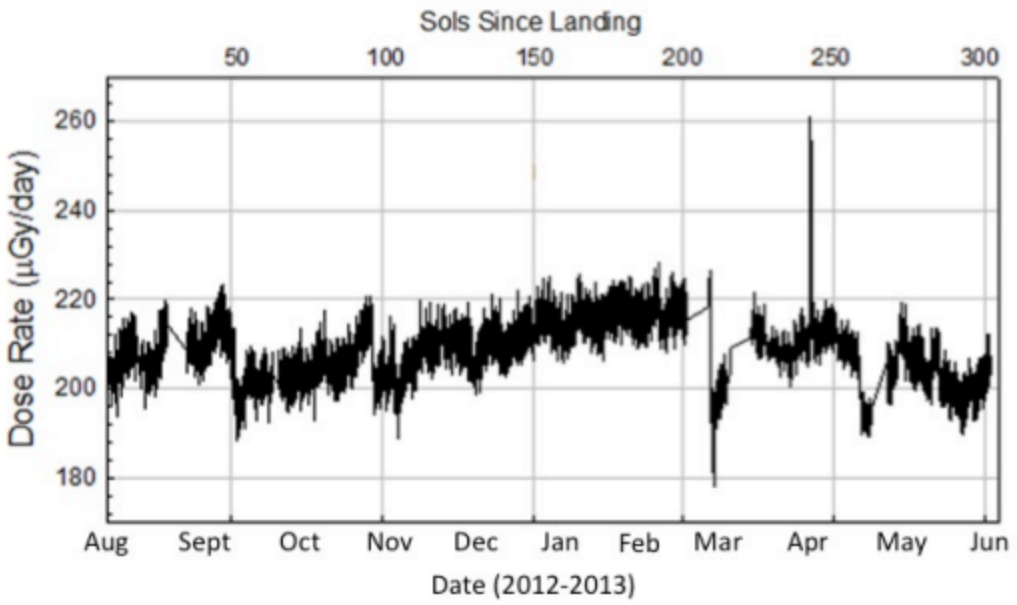


This figure depicts the same sample imaged with different foci compiled to make one “three-dimensional” image revealing a fine structure. This analog will resemble CLUPI’s capabilities on the lunar surface and in MTP’s interior. Qualitative and quantitative analysis of these observations will be crucial to determine if MTP can preserve its structure for long periods of time.

RAD: Radiation Assessment Detector

RAD will measure the radiation environment around the rover while other operations are ongoing. Due to the lack of a lunar atmosphere, RAD will collect event files over time throughout the lifespan of the mission. The collected data will be similar to those from missions flown to Mars that measured radiation dose rates. For example, these figures from Hassler et al. 2014 graphically represent the dose rate in micrograys per day on Mars.





Data plotted from measurements would be in a similar format, although the actual data would differ. Since the primary purpose of this mission is to investigate lunar pits, this mission data collection will differ in the sense that radiation dose rates from the surface and inside the pits will be shown. If there's a strong disconnect between the data gathered on the surface and in MTP, it could mean that lunar pits can potentially safeguard astronauts and equipment from solar and cosmic radiation.

4. Mission Risk Management

4.1. Safety and Hazard Overview

For the mission to be successful and safe, risks must be identified and analyzed. In order to systematically identify potential hazards throughout the mission lifespan, the team's team has developed a comprehensive risk management approach, using industry-standard techniques like Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Hazard and Operability Studies (HAZOP). By using these techniques, we can assess programmatic and technological risks and make sure that every danger is proactively addressed.

The team recognizes that lower-cost missions generally incur a higher risk because of limited resoursces and unproven technology, which is relevant to the nature of this mission, which may involve the demonstration of new technologies. However, the team make sure that risks are carefully evaluated and reduced to a manageable level for vital systems like communication, propulsion, and power generation. To make sure these vital systems can survive expected operating circumstances, they undergo extensive

testing and failure simulations. To guarantee that no serious hazard is left unchecked, any hazards that are found and judged acceptable are supported by convincing arguments.
Another important component of the team's risk management approach is planetary protection.

The team understands that avoiding biological contamination of alien habitats is crucial, especially for missions aimed at Mars or other celestial bodies. To make sure that the spaceship doesn't bring in creatures from Earth that would harm regional ecosystems or contravene international accords, planetary protection procedures must be followed. We have put in place stringent procedures for sterilizing and cleaning spacecraft parts in order to reduce this danger, and we will keep an eye on compliance during the voyage.

Throughout the operation, the data obtained from these risk analysis techniques will be essential to preserving a sound risk posture. Frequent evaluations and updates will guarantee that all risks are sufficiently reduced and that emerging concerns are quickly found and dealt with. In the end, this flexible strategy guarantees mission success and adherence to safety and planetary protection regulations by allowing the crew to pursue mission goals while upholding a strong safety culture.

4.1.1. Risk Analysis

1. Overview of the Methodology for Risk Identification and Management

An essential part of the mission planning process is identifying and managing risks. To guarantee mission success, the main goal is to methodically identify, evaluate, and reduce risks. Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and other resources like the NASA Risk-Informed Decision Making Handbook and the L'SPACE Risk Management Skill Module are among the industry-standard approaches that the team has used to identify and manage risks. These techniques assist in identifying risks related to programmatics, the mission environment, and vehicle systems. Technical vehicle risks, programming risks, and environmental hazards were the three main categories into which risks were divided.

Following risk identification, the team carried out comprehensive risk assessments to rank the risks according to their likelihood and possible outcomes. For the most important hazards, mitigation techniques were then created and put into action. For instance, programmatic risks like budget overruns were reduced by continuously monitoring project costs and timetables, while technical risks like spaceship component failures were managed through redundancy designs. Strict adherence to planetary

protection procedures was used to address environmental concerns, especially those related to planetary protection.
The team keeps an ongoing risk assessment procedure in place for identifying and monitoring hazards. Risks are updated often as the mission advances, and the efficacy of the mitigation techniques is assessed. Acceptable risks are supported by good logic, guaranteeing that important risks are suitably managed while striking a balance between the mission's goals and limitations.

By ensuring that risks are continuously assessed and revised in light of new information, this procedure keeps the risk management strategy flexible enough to respond to the changing mission environment.

2. Risks of Updated Vehicle Systems

The System Requirements Review (SRR) lessons are reflected in the updated vehicle system risks. These hazards center on the vital subsystems of the car, including the communication, power generation, and propulsion systems. Based on fresh data and analysis, we have updated and improved the team's comprehension of the risks found during the SRR.

For instance, deterioration of solar panels as a result of radiation exposure in deep space is a major vehicle danger. Solar panels are crucial for producing electricity, thus any deterioration could result in a major mission failure. The following is the risk statement:

- Condition: Considering that strong radiation settings accelerate the deterioration of solar panels,
- Departure: the spacecraft's solar panels run the risk of being harmed by radiation exposure.
- Asset: impacting the system that generates power,
- Consequence: The spacecraft's subsystems might not receive enough energy as a result of this consequence.

The spacecraft's solar panels have been developed with improved radiation shielding to reduce this risk, and backup power systems have been included to guarantee power continuity in the event of degradation.

The spacecraft's solar panels have been developed with improved radiation shielding to reduce this risk, and backup power systems have been included to guarantee power continuity in the event of degradation.

The propulsion system failing as a result of system or component failures is another danger associated with vehicles. This could put the mission at risk by causing the spacecraft to lose its capacity to move or maintain its orbit. This is the risk statement:

- Condition: Considering how important the propulsion system is for orbital corrections and trajectory control,
- Departure: there is a chance that an issue with the engine or fuel system could cause the propulsion system to fail.
- Advantage: affecting the spacecraft's capacity to alter its trajectory or arrive at its target,
- Consequence: might cause the mission to fail.

This has been lessened by including redundant propulsion components in the design and putting the propulsion system through extensive testing throughout the development stage. Furthermore, throughout the voyage, ongoing performance monitoring of the propulsion system will provide the early identification of possible problems and the immediate implementation of corrective measures.

3. Programmatic Hazards

Risks associated with the mission's budget, timeline, and resource management are known as programmatic risks. To make sure the mission continues on track and under budget, these risks have been recognized and grouped. Potential budget overruns brought on by unforeseen difficulties in system development or component procurement represent a considerable programmatic risk. The following is the risk statement:

- Condition: Because space missions are complicated and cutting-edge technology is expensive,
- Departure: unforeseen cost overruns in component development or integration could cause the budget to surpass its allotted amount.
- Asset: could have an impact on the mission's scope and financial viability,
- Consequence: this can cause delays or compromises to the goals of the mission.

Regular budget reviews and the allocation of contingency funds for unforeseen expenses are two ways to reduce this risk. Cost-cutting strategies are also taken into account, such as utilizing already-existing components or technology.

Timeline delays are another programmatic risk that could cause the launch of the mission or important milestones to be delayed. This can have an impact on the mission's overall timeline and limit adaptability to unforeseen difficulties. This is the risk statement:

- Condition: Due to the short development timelines for some mission components,

- Departure: there's a chance that important milestones could be delayed due to manufacturing or testing delays.
- Asset: impacting the mission's overall schedule,
- Consequences: Potentially leading to a missed launch window is the consequence.

The team has set up a thorough project schedule with distinct milestones and keeps a careful eye on developments to prevent delays in order to reduce this risk. Backup preparations are also in place in case of unanticipated difficulties. To guarantee that contamination hazards are continuously controlled over the course of the mission, mission staff must receive ongoing training on planetary protection procedures.

4. Hazards to the Environment and Planetary Protection

Environmental hazards are those brought on by the space environment, including solar storms, radiation, and impacts from micrometeorites. The functioning of the spacecraft and the success of the mission could be greatly impacted by these hazards. High radiation exposure in outer space is one of the main environmental hazards since it can harm delicate spacecraft parts. The following is the risk statement:

- Condition: Because deep space missions are known to be at risk from space radiation,
- Departure: the spacecraft's electronics could be harmed by radiation exposure.
- Resource: could have an impact on the communication system,
- Consequence: resulting in a loss of contact with Earth as a consequence.

Radiation shielding in key spacecraft regions and the installation of redundant communication systems to guarantee dependable communication in the event of a system breakdown help to reduce this risk.

Another significant environmental danger associated with trips to other celestial planets is planetary protection. To prevent polluting other planets and potentially breaking planetary protection procedures, the spacecraft needs to be completely cleansed. This is the risk statement:

- Condition: Considering how crucial it is to follow planetary protection guidelines,
- Departure: microbiological contamination from the spacecraft during launch or landing is a possibility.
- Asset: which might cause the target planet or moon to become contaminated,
- Consequence: breaking scientific and ethical rules and perhaps jeopardizing upcoming missions.

Strict sterilization protocols are used during the spacecraft's assembly, launch, and landing stages to reduce this risk.The crew will conduct a quick risk assessment and take the required steps to lessen the chance or impact of any new, high-impact hazards that may arise during the mission.

5. Risk Matrix and Continuous Risk Control

One technique for ranking risks according to their likelihood and possible outcomes is the Risk Matrix. The matrix assists in identifying which dangers can be tracked over time and which need to be addressed right away. For instance, there is a high chance that radiation will harm the spacecraft's electronics, yet there is a moderate chance that microbiological contamination will occur.

- Likelihood (1–5): The likelihood scale goes from 1 (very unlikely) to 5 (quite probable).
- Consequence (1–5): The scale goes from 1 (little impact) to 5 (catastrophic impact) for consequences.
- Risk Level: The sum of likelihood and consequence is used to calculate the overall risk level; higher ratings correspond to greater priority risks.

Throughout the mission lifecycle, the team will keep an eye on and record any hazards that are detected. Frequent risk assessments and mitigation updates will guarantee that any emerging hazards are identified and dealt with as well as that the efficacy of the mitigation techniques in place is assessed. Over time, risk levels will be modified in response to successful mitigation actions or a decline in the likelihood of occurrence. Continuous risk management keeps the mission on course for success while tackling the most pressing issues.

The team guarantees that risks are efficiently handled, reduced, and regularly observed to improve mission success while upholding safety and ethical standards by adhering to this thorough risk analysis.

4.1.2. Failure Mode and Effect Analysis (FMEA)

Failure mode and effect analysis (FMEA) is a vital tool for risk management. It helps the team identify, assess, and mitigate potential risks. FMEA is important because it increases the system's reliability. Many issues can be detected earlier, and processes can be formulated on how to deal with a failure in the system. This ensures that the vehicle will be able to carry out science objectives for the entire duration of the mission. Using a risk priority number, based on the severity of the failure if it occurs, the rate at which it can potentially occur, and how likely the team would be able to detect said failure, the team was able to identify high-risk areas to formulate prevention methods

and action plans. This highlights the main benefit of using an RPN as it helps quantify risk.

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Power	Solar power reduction in efficiency	It greatly reduces the power available to the spacecraft's systems.	7	Dust accumulation over the solar panels from lunar regolith.	7	Special dust repellent coating, or using electrostatic devices to prevent dust particles from building up.	2	98	Dust needs to be cleaned off using a vacuum device combined with an electrostatic device.
	Lithium Ion battery capacity reduction	There is an increased risk of current power not being sufficient when solar panels cannot be used. Due to cold temperatures, the battery's life span can also be reduced. Lithium plating can also occur, which is dangerous to the components.	7	Cold temperatures on the lunar surface.	6	Proper temperature control such as heating during cold conditions, proper insulation, and proper UV protection.	3	126	The battery needs to be warmed in case of cold temperatures. If lithium plating occurs, the only solution is to rely on a secondary battery.
	PMAD fault	Loss of power regulation causes damage to components and loss of data. Also affects efficiency.	8	Temperature changes	2	Proper temperature control such as heating during cold conditions as well as proper insulation, and proper UV protection.	5	80	Identify the cause of the issue, but need a redundant system to rely upon in case of failure.
CDH	Computer Failure	The vehicle is unable to operate.	9	Dust, radiation, temperature changes, power fluctuations, memory failure.	4	Proper temperature control such as heating during cold conditions as well as proper insulation, and proper UV protection. Dust protection is also needed.	2	72	A backup computer is needed in case the primary one fails. Once the system is stable on the secondary computer, the issue can be troubleshooted and solved.
	Data Failure	Data is potentially lost, extremely negative to the scientific	9	Radiation, temperature changes, debris, collisions, software glitches.	4	Data needs to be regularly backed up and the system must be protected from environmental conditions.	2	72	Troubleshoot the system and see what the error is and if the system can be repaired.

		objectives of the mission with the loss of collected data.							
	Telecommunications failure	Unable to transmit data back to Earth which is detrimental to the mission's science objectives. Furthermore, can leave the whereabouts of the vehicle unknown, and unable to troubleshoot other problems.	8	Radiation, interference from other celestial bodies, data failure	3	Needs protection from radiation. Frequencies must be chosen specifically to reduce the impact of other bodies in space from affecting transmissions.	4	96	The issue needs to be diagnosed and repaired.
Thermal	Loss of thermal protection	Damage to sensitive components and even destruction of spacecraft.	10	Degradation of passive insulation over time due to lunar temperature cycling.	2	Needs a protective layer to prevent damage from physical/environmental damage. Cannot be subject to excessive compression.	4	80	Needs a redundant layer of thermal insulation in case of a breach.
	Radiator fault	Increased energy consumption, loss of efficiency, and reduction in heat transfer.	10	Dust accumulation over the radiator panels. The dust acts as a layer of insulation trapping heat.	2	Needs protection from dust.	3	60	Dust needs to be cleaned from panels. Can also have a redundant system/backup if a failure occurs.
	Thermal strap fault	Can cause sensitive systems to overheat, damaging them.	7	Improper installation, excessive vibration, deformation due to loads, or extreme temperature changes.	2	Needs adequate sensors to detect the status of thermal straps.	6	84	Needs multiple thermal straps in case of a failure due to fatigue.
Mechanical	Tether fault	Possibly mission ended due to the possibility of the destruction of the vehicle from free fall.	10	Overloading/fatigue	1	Extensive testing is needed to prove that the tether can withstand the load of the vehicle and more. Otherwise, a second cable can be used.	4	40	If the tether fails, then the mission is most likely a failure, as the vehicle will be damaged into a nonperforming state.
	Gyroscope failure	This can lead to incorrect orientation data, leading to a loss of	5	Bearing failure due to fatigue/wear, dust contamination, or	5	The gyroscope must be calibrated regularly. It must be thermally regulated and needs to be	2	50	The gyroscope needs to be calibrated. Multiple gyroscopes are needed on the vehicle.

		direction and control for the vehicle.		physical damage.		protected from dust via electrostatic devices.			
	Structural failure	Compromises structural integrity of the vehicle, hindering mobility of the vehicle. Possibly mission ended due to the rough driving conditions on the lunar surface.	9	Improper manufacturing, collision/physical damage.	1	Hardening of structure is needed. Redundant systems need to be in place for vital structural components in case of failure. Careful handling is a must to prevent collisions with terrain.	4	36	No action is required as the vehicle cannot repair itself in case of structural damage.
	Rocker-bogie fault	Vehicles unable to traverse required terrain to acquire data, cannot offer stability to instruments and other systems.	8	Extremely rough terrain, debris, collision, fatigue/wear on joints. Differential failure.	1	Careful monitoring is needed to ensure no damage is sustained during travel. Cautious handling of the vehicle is needed to prevent damage to the differential.	3	24	Check to see if the differential can be adapted to via software.
	Rollover	The mission will be terminated if the vehicle cannot be recovered from a rollover. Can cause damage to solar panels, masts, and other instruments.	10	Extreme terrain.	1	Terrain needs to be deemed safe to traverse to prevent a rollover case.	1	10	The vehicle has the means to flip itself upright in case of a rollover.
	Motor failure	The effect depends on the type of motor. Mobility of the vehicle will be hampered if a motor fails, each wheel has its own motor. If motors for the robotic arm fail, the arm will lose mobility	8	Fatigue/wear, dust accumulation, temperature changes. Issues with power management can cause a motor failure.	3	Needs protection from dust, proper thermal protection, and surge protection.	3	72	Identify if the issue can be solved via software. If not power can be rerouted to different systems, and the mission can continue due to the vehicle having multiple motors.

		depending on which joints fail.							

4.1.3. Personnel Hazards and Mitigations

Safety is the utmost priority of the team's mission. Although the mission is unmanned, hundreds of man-hours will be spent on the manufacturing, integration, and testing phases of the team's project. Identifying these hazards and implementing effective mitigation strategies is essential to prevent injuries, ensure compliance with safety regulations, and maintain operational efficiency. Below is a comprehensive exploration of key hazards and their associated mitigations.

Machining Hazards: All personnel using machine shops must be certified to operate the machines. This certification includes necessary safety training. All machine shops will be up to code with relevant fume hood and ventilation technology, as inhalation of particles may be injurious and carcinogenic. Each shop must also have machine guards and emergency shut-off switches throughout the shop. PPE must be provided within the shops, such as eye protection, gloves, ear protection, etc.

Chemical Exposure: Workers may handle a variety of hazardous chemicals, such as solvents, adhesives, coatings, and cleaning agents. Prolonged exposure to these substances can result in skin irritation, respiratory issues, or more severe long-term health effects. To mitigate the risks, the team must follow strict guidelines for the safe handling and storage of chemicals, using PPE like gloves, goggles, and respirators. Adequate ventilation systems, including fume hoods and air filtration units, should be employed to prevent the accumulation of harmful fumes. Additionally, Material Safety Data Sheets (MSDS) should be available for all chemicals used, and employees must be trained on the potential hazards and the proper emergency response procedures. Those working on propellent must be under a special unit with special equipment, as such materials are extremely flammable and pose a high risk to human life.

Integration Hazards: The integration testing phase may include the use of heavy machinery such as cranes and lifts. Hazards include but are not limited to working at heights, risk of electrical shock, and misuse of machinery or tools. Integration protocols must be set before the phase starts, as clear instructions need to be communicated across all team members. Live circuits and wiring may be exposed to workers in this stage and must be addressed. To mitigate such hazards, the use of scaffolding and harnesses will decrease the risk of a fall. Furthermore, connecting all workers to a ground source may mitigate the risk of an electrical shock.

Thermal Hazards: Thermal hazards are prevalent in testing phases, especially when working with high temperatures generated by electronic systems, heating elements, or thermal testing devices. Exposure to excessive heat can lead to burns or heat-related illnesses. To reduce this risk, team members should wear heat-resistant gloves and clothing when working near hot equipment or surfaces. Additionally, temperature control systems should be used during testing to ensure that components are within safe operating ranges. High-quality ventilation systems must be in use within the facility, with constant monitoring of temperature levels and the implementation of safety barriers or enclosures around hot systems can help prevent accidents.

Laboratory Hazards: Laboratory and research facilities pose additional risks related to specialized equipment and confined spaces. Laboratory environments often involve the use of high-pressure systems, vacuum chambers, or cryogenic equipment, each of which can present unique dangers. Personnel should be trained in the specific hazards associated with these systems, and appropriate safety protocols must be in place. For example, cryogenic safety training is essential when handling extremely cold liquids, as ultra-cold substances such as liquid nitrogen are commonly used in space applications. Pressure testing systems also require monitoring to prevent over-pressurization or rupture. Regular inspections of equipment and the implementation of emergency response drills are crucial in ensuring that workers are prepared for unexpected incidents.

Heavy Machinery Hazards**:** Large-scale manufacturing equipment are used for tasks like component assembly, integration, and testing. The potential hazards associated with these machines include mechanical failures, malfunctions, and human error, which can lead to accidents, injuries, or damage to expensive components. The use of large presses, cranes, and automated systems for component handling can lead to crushing injuries if safety protocols are not followed. To mitigate these risks, it is essential to develop comprehensive risk assessments and training programs. Regular maintenance, proper supervision, and emergency response drills are vital for ensuring the machinery operates within safe parameters.

5. Activity Plan

5.1. Project Management Approach

The successful execution of the mission objectives for the exploration and evaluation of Mare Tranquillitatis Pit (MTP) requires an extended team beyond the Academy personnel. An estimated 25–30 additional personnel are necessary, covering expertise

in engineering, science, operation, and programmatic roles. Each subteam will address specific mission components with clear responsibilities, ensuring alignment with the mission's technical and scientific objectives.

Personnel and Roles

1. Engineering Division
    - Mechanical Subteam:
        - Focus: Design and testing of rover components, including the chassis, mobility systems, and robotic arm.
        - Skills: CAD modeling, materials engineering, structural design, and mobility integration.
        - Team Size: 4–5 engineers.
    - Thermal Subteam:
        - Focus: Development of systems to regulate spacecraft temperatures in extreme lunar conditions.
        - Skills: Heat transfer analysis, insulation design, and active thermal control.
        - Team Size: 3–4 engineers.
    - Electrical and Power Subteam:
        - Focus: Design of solar panels, battery systems, and power distribution systems.
        - Skills: Solar array design, energy storage optimization, and fault isolation.
        - Team Size: 3–4 engineers.
    - Command and Data Handling (CDH) Subteam:
        - Focus: Management of onboard computing, telemetry systems, and data storage.
        - Skills: Software development, telemetry protocols, and systems integration.
        - Team Size: 3–4 engineers.
2. Science Division
    - Planetary Geology Subteam:
        - Focus: Analysis of the MTP environment, including geological mapping and pit stability.
        - Skills: Remote sensing, geological analysis, and surface characterization.
        - Team Size: 4 scientists.
    - Instrumentation and Data Analysis Subteam:
        - Focus: Operation of spectrometers, radiometers, and other instruments to collect and analyze mission-critical data.

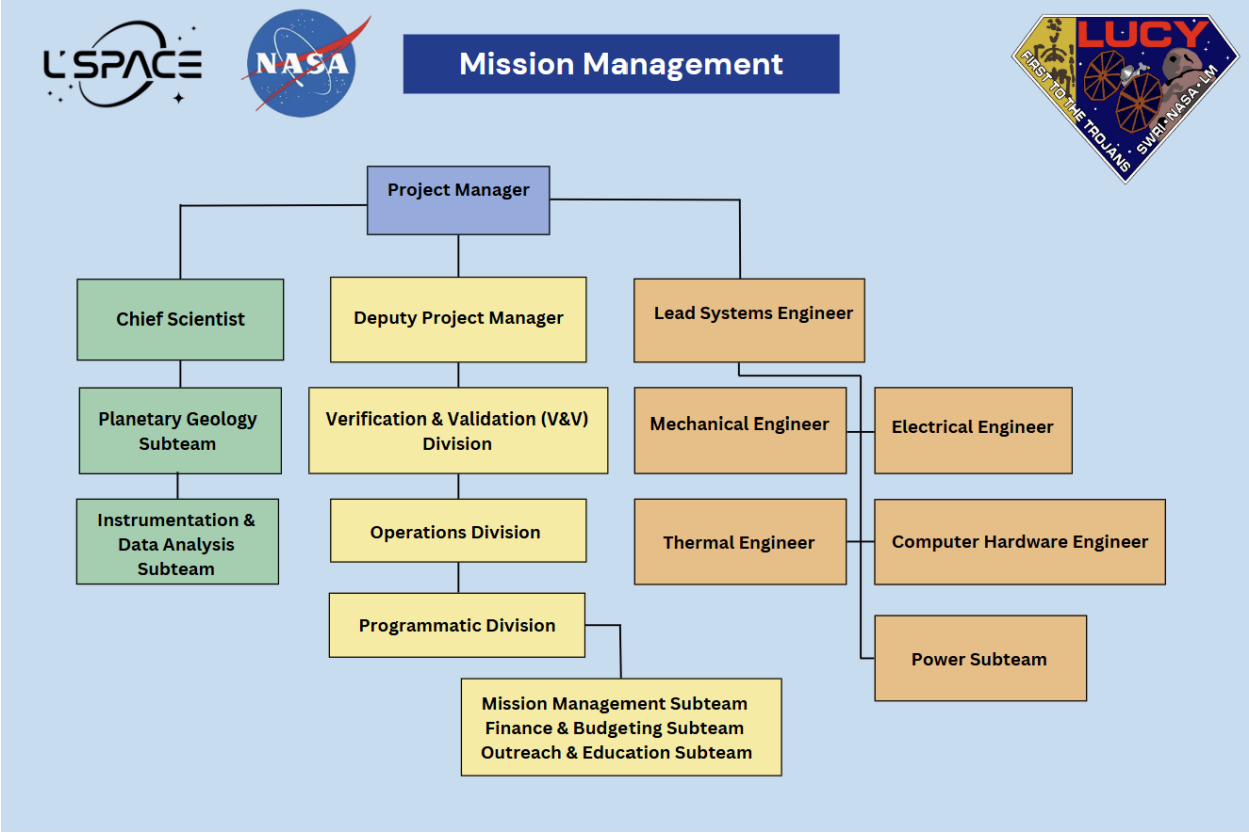
        - Skills: Instrument calibration, data modeling, and interpretation.
        - Team Size: 4–5 scientists.
3. Verification & Validation (V&V) Division
    - Focus: Ensuring all systems meet mission requirements through testing and quality assurance.
    - Skills: Failure analysis, system integration, and subsystem validation.
    - Team Size: 3 engineers.
4. Operations Division
    - Focus: Management of spacecraft activities post-launch, including telemetry monitoring and data collection scheduling.
    - Skills: Mission planning, satellite navigation, and anomaly resolution.
    - Team Size: 5 specialists.
5. Programmatic Division
    - Mission Management Subteam:
        - Focus: Oversight of mission planning, risk management, and resource allocation.
        - Skills: Leadership, decision-making, and communication.
        - Team Size: 2 program managers.
    - Finance and Budgeting Subteam:
        - Focus: Budget tracking and financial management.
        - Skills: Cost estimation, financial planning, and reporting.
        - Team Size: 2 finance specialists.
    - Outreach and Education Subteam:
        - Focus: Public engagement and educational content creation.
        - Skills: Marketing, content development, and public speaking.
        - Team Size: 3 specialists.

Team Structure and Responsibilities

Each subteam operates with defined autonomy to manage its technical or programmatic responsibilities. Subteam leads ensure progress within their domains, reporting regularly to the Project Manager (PM) and Deputy Project Manager (DPM). Decision-making is collaborative, with major milestones reviewed by the PM and the Lead Systems Engineer (LSE) to ensure alignment across all subsystems.

Subteam leads do not have direct budgeting authority but propose resource allocations to the PM and DPM for approval. A contingency reserve is maintained to address unforeseen challenges.

Organizational Chart:



5.2. Mission Schedule

5.2.1. Schedule Basis of Estimate

Drivers, Assumptions, and Ground Rules

Efficiency, dependability, and conformity to established procedures from prior space missions have all been prioritized in the development of the mission timetable. The schedule's creation and timeline estimation have been influenced by the following fundamental presumptions and guidelines:

Ground Rules:

1. Mission Phases: In accordance with the NASA Systems Engineering Handbook, the mission lifecycle begins at Phase C, presuming that preceding stages (including concept and design) have been finished before Phase C begins. This makes it possible to concentrate on system testing and integration, which are essential to achieving mission goals.

2. Resource Availability: In accordance with the project schedule, it is anticipated that critical individuals and resources (technical, programmatic, and engineering staff) would be available. This covers the accessibility of facilities for production, testing, and system integration.
3. The critical route, which is the order of tasks that directly affects the total mission completion time, is taken into consideration by the timetable. The mission timetable will be directly impacted by delays in critical route tasks.
4. Review and Decision Points: To guarantee sufficient time for review, feedback, and integration, important decision points are spaced out, including the Critical Design Review (CDR), the Preliminary Design Review (PDR), and other milestone reviews. The standard NASA procedure for mission clearance will be followed in these evaluations.
5. Risk Mitigation: The timeline provides sufficient leeway to handle unforeseen problems, such as changes to the design, delays in integration, and difficulties acquiring hardware.

Presumptions:

1. Analog Mission Timeline: To estimate the timeline, we have called comparable lunar exploration missions "analogs," paying special attention to mission durations and significant dates. Due to technological breakthroughs, improved project management techniques, and lessons learned from prior missions, we expect a 20% reduction in overall timeline duration when compared to analogs.
2. Procurement and Acquisition: Procurement will begin at the beginning of the first fiscal year after the Critical Design Review (CDR), which is anticipated to take place by the end of FY2025. When possible, off-the-shelf components will be preferred in the acquisition approach, which will adhere to industry best practices.
3. Schedule Flexibility: To ensure compliance with financing and resource allocation procedures typical of NASA missions, critical project milestones and budget cycles will be defined using the fiscal year (FY) rather than the calendar year.

Important Drivers:

1. Mission Complexity: The timetable was modified to take into consideration the difficulties of integrating a new lunar surface vehicle as well as the possible difficulties in pit exploration, which calls for the integration of complicated hardware and software.
2. Technology Readiness: The timeline has taken into account the availability and preparedness of cutting-edge technology, such as autonomous navigation

systems. Schedule modifications and backup plans will be used to handle any delays in the development of these technologies.

3. Risk management: Time buffers are incorporated into the schedule to accommodate for recognized risks, such as unanticipated testing difficulties, launch vehicle delays, and subsystem integration problems. Although these buffers are included in the schedule, they will be reviewed at every review step to make sure they are still reasonable.

In conclusion, this mission's timetable is based on NASA's conventional mission development lifecycle, with modifications made in response to mission-specific requirements and industry norms. It exhibits a well-rounded strategy for guaranteeing on-time completion while reducing any risks and difficulties.

5.2.2. Mission Schedule

Major Milestones:

The schedule can be assumed to begin January 2025, after phase B and the PDR for the project have been completed. Given that the mission must be prepared to launch from Kennedy Space Center by March 1st, 2030, phases C-D must be completed within a span of 62 months. The schedule overview is based off of the expected Robotic Mission Project Life Cycle from NASA's Systems Engineering Handbook.

Beginning at phase C, the team is anticipating using 16 months, or approximately a quarter of the time leading up to the launch, for completing phase C. This is a conservative scheduling estimate- leaving sufficient time available for phase D will help ensure that any delays in production and test success or schedule overruns in phase C will not impede the timely launch of the mission.

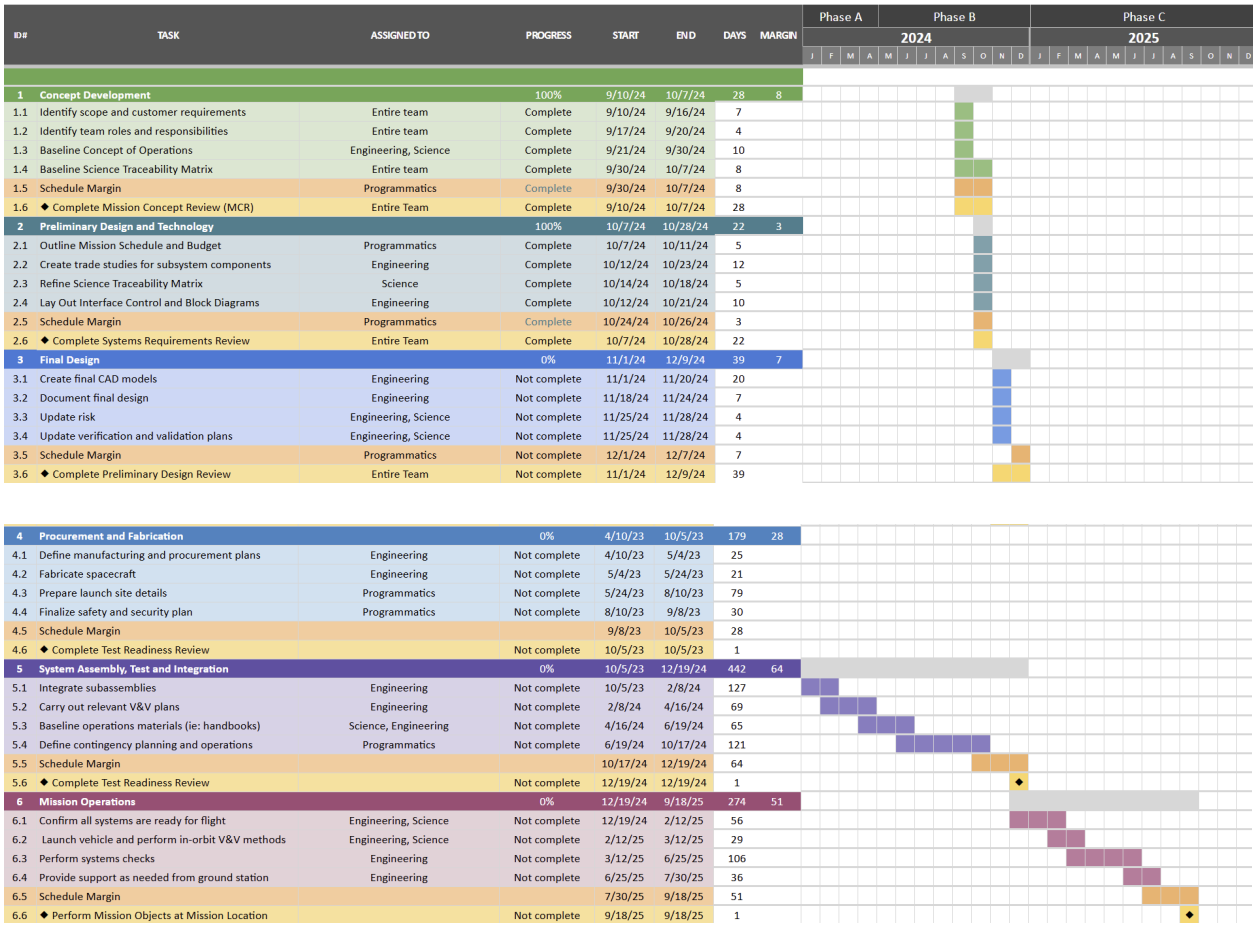
Although the team does not anticipate the spacecraft taking a full month to reach luna after launch, a month has nominally been allotted between launch and lunar landing to signify that this milestone will be reached within a month. Additionally, this allows for contingency scheduling should an initial launch be scrubbed for any reason. A three month period has been allotted between lunar landing and pit entry to allow for checking system performance and downlinking, as well as taking pit surface data.

While the team currently does not know exactly how many months the spacecraft will retain performance-level health in the Mare Tranquillitatis pit, the schedule will currently accommodate four months of testing and data downlinking. This period has been selected based on previous lunar rover operational periods: should the spacecraft remain healthy for longer than originally anticipated, the team may consider the possibility of requesting funding to operate the spacecraft within any lava tubes detected to obtain a more complete characterization of the pit's habitability.

Milestone	Phase	Maximum Time from Previous (months)	Maximum Time from Start of Phase C (months)
Begin Phase C of Mission Lifecycle with Key Decision Point (KDP) C	C	0	0
Critical Design Review (CDR)	C	6	6
Production Readiness Review (PRR)	C	2	8
System Integration Review (SIR)	C	7	15
Key Decision Point (KDP) D	C-D	1	16
System Acceptance Review (SAR)	D	3	19
Operational Readiness Review (ORR)	D	20	39
Mission Readiness Review (MRR)	D	13	52
Safety and Mission Success Review (SMSR)	D	5	57
Key Decision Point (KDP) E	D	4	61
Launch	D	1	62
Post-Launch Assessment Review (PLAR)	D-E	1	63
Lunar Landing		0	63
Critical Events Readiness Review (CERR)	E	2	65

Pit Entry	E	1	66
Decommissioning Review (DR)	E	3	69
End of Mission	E	1	70
Key Decision Point (KDP) F	E-F	1	71
Disposal Readiness Review (DRR)	F	3	74
Final Archival of Data	F	3	77

Gantt Chart



ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
1	**Concept Development**		100%	9/10/24	10/7/24	28	8
1.1	Identify scope and customer requirements	Entire team	Complete	9/10/24	9/16/24	7	
1.2	Identify team roles and responsibilities	Entire team	Complete	9/17/24	9/20/24	4	
1.3	Baseline Concept of Operations	Engineering, Science	Complete	9/21/24	9/30/24	10	
1.4	Baseline Science Traceability Matrix	Entire team	Complete	9/30/24	10/7/24	8	
1.5	Schedule Margin	Programmatics	Complete	9/30/24	10/7/24	8	
1.6	◆ Complete Mission Concept Review (MCR)	Entire Team	Complete	9/10/24	10/7/24	28	
2	**Preliminary Design and Technology**		100%	10/7/24	10/28/24	22	3
2.1	Outline Mission Schedule and Budget	Programmatics	Complete	10/7/24	10/11/24	5	
2.2	Create trade studies for subsystem components	Engineering	Complete	10/12/24	10/23/24	12	
2.3	Refine Science Traceability Matrix	Science	Complete	10/14/24	10/18/24	5	
2.4	Lay Out Interface Control and Block Diagrams	Engineering	Complete	10/12/24	10/21/24	10	
2.5	Schedule Margin	Programmatics	Complete	10/24/24	10/26/24	3	
2.6	◆ Complete Systems Requirements Review	Entire Team	Complete	10/7/24	10/28/24	22	
3	**Final Design**		0%	11/1/24	12/9/24	39	7
3.1	Create final CAD models	Engineering	Not complete	11/1/24	11/20/24	20	
3.2	Document final design	Engineering	Not complete	11/18/24	11/24/24	7	
3.3	Update risk	Engineering, Science	Not complete	11/25/24	11/28/24	4	
3.4	Update verification and validation plans	Engineering, Science	Not complete	11/25/24	11/28/24	4	
3.5	Schedule Margin	Programmatics	Not complete	12/1/24	12/7/24	7	
3.6	◆ Complete Preliminary Design Review	Entire Team	Not complete	11/1/24	12/9/24	39	
4	**Procurement and Fabrication**		0%	4/10/23	10/5/23	179	28
4.1	Define manufacturing and procurement plans	Engineering	Not complete	4/10/23	5/4/23	25	
4.2	Fabricate spacecraft	Engineering	Not complete	5/4/23	5/24/23	21	
4.3	Prepare launch site details	Programmatics	Not complete	5/24/23	8/10/23	79	
4.4	Finalize safety and security plan	Programmatics	Not complete	8/10/23	9/8/23	30	
4.5	Schedule Margin			9/8/23	10/5/23	28	
4.6	◆ Complete Test Readiness Review		Not complete	10/5/23	10/5/23	1	
5	**System Assembly, Test and Integration**		0%	10/5/23	12/19/24	442	64
5.1	Integrate subassemblies	Engineering	Not complete	10/5/23	2/8/24	127	
5.2	Carry out relevant V&V plans	Engineering	Not complete	2/8/24	4/16/24	69	
5.3	Baseline operations materials (ie: handbooks)	Science, Engineering	Not complete	4/16/24	6/19/24	65	
5.4	Define contingency planning and operations	Programmatics	Not complete	6/19/24	10/17/24	121	
5.5	Schedule Margin			10/17/24	12/19/24	64	
5.6	◆ Complete Test Readiness Review		Not complete	12/19/24	12/19/24	1	
6	**Mission Operations**		0%	12/19/24	9/18/25	274	51
6.1	Confirm all systems are ready for flight	Engineering, Science	Not complete	12/19/24	2/12/25	56	
6.2	Launch vehicle and perform in-orbit V&V methods	Engineering, Science	Not complete	2/12/25	3/12/25	29	
6.3	Perform systems checks	Engineering	Not complete	3/12/25	6/25/25	106	
6.4	Provide support as needed from ground station	Engineering	Not complete	6/25/25	7/30/25	36	
6.5	Schedule Margin			7/30/25	9/18/25	51	
6.6	◆ Perform Mission Objects at Mission Location		Not complete	9/18/25	9/18/25	1	

5.3. Budget

5.3.1. Budget Basis of Estimate

The budget for this project is constructed based on comprehensive research/analysis of previous NASA missions as well as standard assumptions based on average/expected data collected from relevant company websites and sources, all of which contributed to the development of a custom System Model CER. A structured set of ground rules, assumptions, and cost drivers have been taken for the cost estimation of the mission. These measures allow for transparency between advisory boards and the project team while also staying consistent with price quotes and estimates.

Inflation Rate: To maintain simplicity and avoid variability or incorrect numbers, it is assumed that the overall inflation rate is 2.6% per year based on the Consumer Price Index for the 2024 fiscal year, according to the U.S. Bureau of Labor Statistics. This increase in price for around 5 years is built into the budget, as the launch date will not be any later than March 2030. The main cost that will be affected the most by inflation is salary. Current salary ranges between $60,000-$120,000/year. Salary is subject to increase based on inflation for employee retention and talent acquisition. Costs associated with instruments and development will be affected minimally due to inflation as all instrumentation will be purchased sooner rather than later.

Team Size: It is assumed that the project team is not limited to the amount of MCA team members. The amount of team members may vary depending on the project phase. The budget accounts for enough salary to accommodate team sizes over the 5-year time period. The budget allocations account for the predictive demands and the number of personnel listed for each mission phase.

Instrumentation Costs Estimate: Instrumentation is the biggest cost for the mission and is allocated as so. However, estimating instrumentation is quite meticulous. For example, thermal management systems such as radiators or MLI are custom-fitted based on the mission specification, dimension of the rover, and mission objectives. A certain price cannot be found through just online research. Instrumentation costs have a certain level of uncertainty associated with it and it is accordingly built into the budget. The current instrumentation estimates are based on similar-sized technology used on previous lunar and Mars missions, adjusted for inflation.

Direct/Instrumentation costs for each rover subsystem are calculated using the NASA Cost Instrument Model (NCIM), considering factors such as payload mass, energy consumption, and design life. The resulting figures were refined using the Mission Concept Cost Estimate Tool (MCCET) to align with 2024 economic conditions. Facility

and production costs for each phase are estimated as a percentage of the total subsystem costs.

Mission Travel: Throughout the life cycle of the mission, it is necessary for team members to travel to certain sites to advance the project. Travel expenses are calculated for Project Managers, Administrative Personnel, and Scientists attending conferences and meetings to discuss and promote the mission. These costs include discounted roundtrip ticket rates for U.S. government officials traveling from the most distant airports in the Continental U.S. to Cape Canaveral, Florida. The *highest* economy ticket cost is used in the estimate as airline ticket prices are highly variable.

Hotel Costs: Hotel costs are estimated based on an approximate 1–3 day stay, using average hotel pricing data from the Orlando and Cape Canaveral areas.

Transportation Costs: Transportation expenses assume the use of public transportation, taxis, or rental cars for travel within a 30-mile radius of the venue. Stipend amounts are based on average gas prices in the Orlando/Cape Canaveral region.

Per Diem Costs: Per diem allocations cover basic necessities such as food, hygiene, and incidental expenses for employees on travel. These estimates are based on typical monthly spending data and practical considerations.

Outreach Costs: Outreach expenses are determined by factors such as event type, scale, and external support requirements. This includes costs for internships, university lectures, public talks, and launch watch events. Allocations cover food, merchandise, salaries, and materials necessary for planning and executing these events.

Cost Margins: Cost margins are strategically calculated and allocated, either evenly across phases or prioritized for phases with the highest anticipated demand.

Risk Mitigation and Compliance: A contingency of 5-10% is built to account for unforeseen risks or cost increases. This is consistent with standard risk management practices for projects of this size and scope. Furthermore, the prices of permits and environmental regulation licenses are built into the budget using standard FAA and environmental license costs in Florida.

5.3.2. Total Mission Cost

NASA L'SPACE Mission Concept Academy Budget - ARCADIA

	Mission Phase	Phase A-B	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	$ 1,200,000	$ 1,231,200	$ 589,120	$ 603,680	$ 441,600	$ 904,000	$ 4,969,600
	Engineering Personnel	$ 800,000	$ 984,960	$ 1,262,400	$ 1,293,600	$ 706,560	$ 723,200	$ 5,770,720
	Technicians	$ 180,000	$ 369,360	$ 946,800	$ 1,617,000	$ 993,600	$ 1,017,000	$ 5,123,760
	Administration Personnel	$ 240,000	$ 246,240	$ 378,720	$ 323,400	$ 198,720	$ 203,400	$ 1,590,480
	Project Management	$ 240,000	$ 492,480	$ 631,200	$ 776,160	$ 397,440	$ 406,800	$ 2,944,080
	Total Salaries	$ 2,660,000	$ 3,324,240	$ 3,808,240	$ 4,613,840	$ 2,737,920	$ 3,254,400	**$ 20,398,640**
	Total ERE	$ 742,406	$ 927,795	$ 1,062,880	$ 1,287,723	$ 764,153	$ 908,303	**$ 5,693,260**
	Personnel Margin	$ 1,000,000	$ 3,000,000	$ 4,000,000	$ 4,000,000	$ 1,500,000	$ 1,000,000	**$ 14,500,000**
	TOTAL PERSONNEL	$ 4,402,406	$ 7,440,588	$ 9,332,418	$ 10,673,885	$ 5,522,289	$ 5,833,854	$ 43,205,441
	TRAVEL							
	Total Flights Cost	$ 2,400	$ 9,600	$ 10,000	$ 14,000	$ 9,600	$ 3,000	**$ 48,600**
	Total Hotel Cost	$ 3,000	$ 12,000	$ 13,000	$ 16,000	$ 12,000	$ 4,500	**$ 60,500**
	Total Transportation Cost	$ 3,600	$ 14,400	$ 15,000	$ 16,000	$ 14,400	$ 4,500	**$ 67,900**
	Total Per Diem Cost	$ 4,800	$ 19,200	$ 20,000	$ 21,500	$ 19,200	$ 5,500	**$ 90,200**
	Travel Margin	$ 400,000	$ 700,000	$ 700,000	$ 700,000	$ 700,000	$ 500,000	**$ 3,700,000**
	Total Travel Costs	$ 413,800	$ 774,835	$ 797,416	$ 827,365	$ 833,741	$ 584,775	**$ 4,231,932**
	OUTREACH							
	Total Outreach Materials	$ 18,000	$ 20,000	$ 25,000	$ 28,000	$ 26,000	$ 18,000	**$ 135,000**
	Total Outreach Venue Costs	$ 30,000	$ 35,000	$ 40,000	$ 50,000	$ 45,000	$ 30,000	**$ 230,000**
	Total Outreach Travel Costs	$ 7,500	$ 10,000	$ 12,500	$ 15,000	$ 10,000	$ 7,500	**$ 62,500**
	Total Outreach Services Costs	$ 138,000	$ 160,000	$ 200,000	$ 240,000	$ 215,000	$ 138,000	**$ 1,091,000**
	Total Outreach Personnel Costs	$ 7,500	$ 10,000	$ 12,500	$ 15,000	$ 10,000	$ 7,500	**$ 62,500**
	Outreach Margin	$ 300,000	$ 150,000	$ 200,000	$ 800,000	$ 800,000	$ 100,000	**$ 2,350,000**
	Total Outreach Costs	$ 501,000	$ 395,010	$ 515,480	$ 1,237,544	$ 1,221,024	$ 340,130	**$ 4,210,188**
	DIRECT COSTS							
$5.00	Mechanical Subsystem	$ 2,272,000	$ 32,376,000	$ 5,452,800	$ 22,152,000	$ -	$ -	**$ 62,252,800**
$10.00	Power Subsystem	$ 1,348,000	$ 19,209,000	$ 3,235,200	$ 13,143,000	$ -	$ -	**$ 36,935,200**
$5.00	Thermal Control Subsystem	$ 572,000	$ 8,151,000	$ 1,372,800	$ 5,577,000	$ -	$ -	**$ 15,672,800**
$4.00	Comms & Data Handling Subsystem	$ 604,000	$ 8,607,000	$ 1,449,600	$ 5,889,000	$ -	$ -	**$ 16,549,600**
$4.00	Guidance, Nav, & Control Subsystem	$ 532,000	$ 7,581,000	$ 1,276,800	$ 5,187,000	$ -	$ -	**$ 14,576,800**
$30.00	Science Instrumentation	$ 3,524,000	$ 50,217,000	$ 8,457,600	$ 34,359,000	$ -	$ -	**$ 96,557,600**
	Spacecraft Cost Margin	$ 1,000,000	$ 2,000,000	$ 2,000,000	$ 500,000	$ -	$ -	**$ 5,500,000**
	Total Spacecraft Direct Costs	$ 9,852,000	$ 131,472,666	$ 24,453,530	$ 93,577,946	$ -	$ -	**$ 259,356,142**
$15.00	Manufacturing Facility Cost	$ 1,327,800	$ 18,921,150	$ 3,186,720	$ 12,946,050	$ -	$ -	**$ 36,381,720**
$15.00	Test Facility Cost	$ 1,327,800	$ 18,921,150	$ 3,186,720	$ 12,946,050	$ -	$ -	**$ 36,381,720**
	Facility Cost Margin	$ 500,000	$ 1,000,000	$ 1,000,000	$ 100,000	$ -	$ -	**$ 2,600,000**
	Total Facilities Costs	$ 3,155,600	$ 39,852,200	$ 7,756,859	$ 28,019,484	$ -	$ -	**$ 78,784,142**
	Total Direct Costs	$ 13,007,600	$ 171,324,866	$ 32,210,388	$ 121,597,430	$ -	$ -	**$ 338,140,284**
	Total MTDC	$ 9,852,000	$ 131,472,666	$ 24,453,530	$ 93,577,946	$ -	$ -	**$ 259,356,142**
	FINAL COST CALCULATIONS							
	Total F&A	$ 885,200	$ 12,947,267	$ 2,245,353	$ 9,307,795	$ -	$ -	**$ 25,385,614**
	Total Projected Cost	$ 19,210,006	$ 192,882,566	$ 45,101,055	$ 143,644,018	$ 7,577,054	$ 6,758,759	**$ 415,173,459**
	Total Cost Margin	$ 3,200,000	$ 6,850,000	$ 7,900,000	$ 6,100,000	$ 3,000,000	$ 1,600,000	**$ 28,650,000**
		16.7%	3.6%	17.5%	4.2%	39.6%	23.7%	
	Total Project Cost	$ 19,210,006	$ 192,882,566	$ 45,101,055	$ 143,644,018	$ 7,577,054	$ 6,758,759	**$ 415,173,459**
								$425,000,000
	********** Do not change the numbers in the cells below unless mission concept instructions specify otherwise.							$9,826,541
	F&A %	10%	10%	10%	10%	10%	10%	
	ERE - Staff	28%	28%	28%	28%	28%	28%	
	Inflation Rate	0.0%	2.6%	5.2%	7.8%	10.4%	13.0%	
	Science Personnel Salary	$ 80,000						
	Engineering Personnel Salary	$ 80,000						$ 38,476,541
	Technicians Salary	$ 60,000						
	Administration Personnel Salary	$ 60,000						$71,567,263.94
	Project Management Salary	$ 120,000						$ 343,606,195
								$ 303,606,195

This budget overview displays the total financial framework for the team's mission. It highlights the projected expenses across Phases A-F of the mission, including travel,

outreach efforts, personnel salaries, and direct costs associated with spacecraft research and development and facility use. The table as a whole emphasizes how resources are allocated to meet project requirements, and how the spending is adapted as the mission transitions from conceptualization to execution.

5.3.3. Personnel Budget

Personnel Budget Chart

Mission Phase	Phase A-B	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	$ 1,200,000	$ 1,231,200	$ 589,120	$ 603,680	$ 441,600	$ 904,000	$ 4,969,600
Engineering Personnel	$ 800,000	$ 984,960	$ 1,262,400	$ 1,293,600	$ 706,560	$ 723,200	$ 5,770,720
Technicians	$ 180,000	$ 369,360	$ 946,800	$ 1,617,000	$ 993,600	$ 1,017,000	$ 5,123,760
Administration Personnel	$ 240,000	$ 246,240	$ 378,720	$ 323,400	$ 198,720	$ 203,400	$ 1,590,480
Project Management	$ 240,000	$ 492,480	$ 631,200	$ 776,160	$ 397,440	$ 406,800	$ 2,944,080
Total Salaries	$ 2,660,000	$ 3,324,240	$ 3,808,240	$ 4,613,840	$ 2,737,920	$ 3,254,400	**$ 20,398,640**
Total ERE	$ 742,406	$ 927,795	$ 1,062,880	$ 1,287,723	$ 764,153	$ 908,303	**$ 5,693,260**
Personnel Margin	$ 1,000,000	$ 3,000,000	$ 4,000,000	$ 4,000,000	$ 1,500,000	$ 1,000,000	**$ 14,500,000**
TOTAL PERSONNEL	$ 4,402,406	$ 7,440,588	$ 9,332,418	$ 10,673,885	$ 5,522,289	$ 5,833,854	$ 43,205,441

Rationale

A diversified team with specialized knowledge is required to successfully carry out the Mare Tranquillitatis Pit (MTP) exploration mission. To guarantee that all mission objectives are fulfilled, 25 more employees are needed in addition to the Academy's core staff. This number is derived from an analysis of workload fluctuations and technical milestones throughout the mission lifecycle.

The personnel count is structured to align with the intensity of the workload at every mission phase (C-F). For example, Phases C-D, which highlight system design and integration, require a surge in engineering resources. On the other hand, Phases E-F, centered on data analysis and operational tasks, demand a greater allocation of science and operations specialists. This dynamic staffing approach ensures both technical and operational milestones are met without resource strain or redundancy.

Overall, personnel levels are matched to the highest-demand phases as needed to avoid resource bottlenecks. Each team’s size corresponds to the unique demands of Phases C-F, ensuring an avoidance of overlap with earlier phases (A-B) managed by the MCA.

Breakdown of Subteam Roles and Responsibilities

1. Engineering Team**:** Five engineers comprise the Mechanical Subteam, responsible for developing the robotic arm, testing the chassis, and designing the

rover's structure. Vital for design integration and validation in Phases C–D. The mechanical subteam would utilize structural engineering, CAD modeling, materials analysis, and systems integration. To ensure the spacecraft's operation under extreme lunar conditions throughout Phases C and D, the Thermal Subteam, consisting of three engineers, must concentrate on thermal management systems. They will use heat transfer analysis, insulation design, and the radiator and heater implementation. Four engineers make up the Electrical and Power Subteam, primarily involved in Phases C and D, and manage solar panels, batteries, and power distribution systems. Four engineers make up the Command and Data Handling (CDH) Subteam, which handles the management of data processing, onboard computation, and telemetry systems. Their duties are maintained throughout Phases C–E to guarantee data integrity and real-time communication.

2. Science Team**:** Four scientists make up the Planetary Geology Subteam, which performs geological analysis of MTP and significantly contributes to subsurface mapping and pit stability assessment during Phases D–F. Six scientists make up the Instrumentation and Data Analysis Subteam, which manages and analyzes data from LiDAR, spectrometers, and other sensors. As data collecting starts in Phases E and F, their role becomes more significant.

3. Programmatic Team: Two program managers comprise the Mission Management Subteam, which oversees project timelines, resource allocation, and risk management during every mission stage. Two finance specialists from the Finance and Budgeting Subteam oversee the $425 million budget, essential for upholding financial restraint throughout the mission. Three specialists comprise the Outreach and Education Subteam, which creates educational materials and encourages public participation. As mission outcomes are communicated, their roles become more intense in Phases D–F.

4. Verification & Validation (V&V) Team: The team of four engineers, primarily contributed during Phase D, ensures all the systems meet design and mission requirements via thorough testing and quality control.

5. Operations Team: Five specialists comprise the operations team: oversees post-launch operations, such as anomaly resolution and telemetry. Phases E and F are when their workload peaks.

5.3.4. Travel Budget

TRAVEL							
Total Flights Cost	$ 2,400	$ 9,600	$ 10,000	$ 14,000	$ 9,600	$ 3,000	$ 48,600
Total Hotel Cost	$ 3,000	$ 12,000	$ 13,000	$ 16,000	$ 12,000	$ 4,500	$ 60,500
Total Transportation Cost	$ 3,600	$ 14,400	$ 15,000	$ 16,000	$ 14,400	$ 4,500	$ 67,900
Total Per Diem Cost	$ 4,800	$ 19,200	$ 20,000	$ 21,500	$ 19,200	$ 5,500	$ 90,200
Travel Margin	$ 400,000	$ 700,000	$ 700,000	$ 700,000	$ 700,000	$ 500,000	$ 3,700,000
Total Travel Costs	$ 413,800	$ 774,835	$ 797,416	$ 827,365	$ 833,741	$ 584,775	$ 4,231,932

System Testing: A portion of the team will need to travel for any necessary Earth analog testing and drop testing. This testing will occur at either a remote location (analog testing) or at the NASA Glenn Research Center in Cleveland, Ohio (drop testing). The mission team must determine the exact locations and durations of this testing based on the spacecraft design and identified mission risks.

Key Decision Points (KDPs): Before missions can transition to the next phase in the NASA mission life cycle, a Key Decision Point (KDP) must occur. These KDPs are considered phase gates for the mission. Missions with a cost allocation greater than $250M are Category 2 NASA projects. For Category 2 projects, the Decision Authority that signs off on the mission proceeding to the next phase is the Mission Directorate Associate Administrator (MDAA). KDPs, where the MDAA is the decision-making authority, are conducted in Washington, D.C., at NASA Headquarters. While KDPs A and B will be completed during the academy, the team must account for the travel of key personnel to NASA Headquarters for KDPs C, D, and E.

Mission Launch: Mission team members who may be key to launch preparations or required for pre-launch meetings will need to travel to Cape Canaveral, Florida, for the mission launch. Many groups expanded this travel to include all team members who had worked on the mission. For this trip, the team will want to plan to travel to the Orlando, Florida airport for a stay of 5 days, arriving 2 days prior to the provided launch date and departing two days after. This travel schedule will also build in some margin in case the launch does not occur on the first day of the launch window opening.

Budget Determination: The team should plan for commercial coach flights using government rates from the City Pair Program (CPP). These costs can be compared to the Bureau of Transportation's average rates to cross-check [1]. The cost of these flights should be determined using the high fares from a variety of cities flying into the necessary location. The team should also plan for lodging (one room per person) at a partnered hotel from Fedrooms, ground travel using car rentals with consideration for varying schedules and travel needs, and a meal per diem rate for the duration of the stay. Per diem rate, allowances for food and lodging can be found using the U.S. General Services Administration Per Diem Website [2].

5.3.5. Outreach Budget

OUTREACH							
Total Outreach Materials	$ 18,000	$ 20,000	$ 25,000	$ 28,000	$ 26,000	$ 18,000	$ 135,000
Total Outreach Venue Costs	$ 30,000	$ 35,000	$ 40,000	$ 50,000	$ 45,000	$ 30,000	$ 230,000
Total Outreach Travel Costs	$ 7,500	$ 10,000	$ 12,500	$ 15,000	$ 10,000	$ 7,500	$ 62,500
Total Outreach Services Costs	$ 138,000	$ 160,000	$ 200,000	$ 240,000	$ 215,000	$ 138,000	$ 1,091,000
Total Outreach Personnel Costs	$ 7,500	$ 10,000	$ 12,500	$ 15,000	$ 10,000	$ 7,500	$ 62,500
Outreach Margin	$ 300,000	$ 150,000	$ 200,000	$ 800,000	$ 800,000	$ 100,000	$ 2,350,000
Total Outreach Costs	$ 501,000	$ 395,010	$ 515,480	$ 1,237,544	$ 1,221,024	$ 340,130	$ 4,210,188

In outreach plan, we wanted to dedicate a large portion of the team's mission to astronaut-related engagements. Our total budget for just the outreach is USD $4,210,188. We decided to dedicate this to several components such as astronaut engagements, in-person learning experiences, virtual learning opportunities, and other costs that will be necessary to engage the team's audience to ensure their success in the team's efforts.

Our Astronaut engagements are the team's top strategy for the team's outreach to ensure that we capture the public's attention and interest. We plan to produce a high quality video that would interview fellow NASA astronauts and express interest in the team's mission for the Mare Tranquilities exploration mission (Professional services to produce a high-quality video ($12,000). Our budget for this would include professional filming of the high-quality video, editing of the video, interviews with NASA Astronauts, and NASA information. We approximated this engagement to be a total of USD $21,000 due to recruiting NASA astronauts to speak and providing a small stipend for their participation (Logistics, scheduling, and securing participation ($3,000)). This will ensure the astronaut will be motivated to speak on the team's behalf and stay the extended time necessary to complete the video. Because this video is intended to be Nationwide and distributed along social media platforms (Adapting the video for multiple platforms, including subtitled and translated versions to ensure inclusivity ($3,000)). We want to ensure that the team's video can reach many backgrounds and demographics to encthe team'sage everyone who has an interest in the team's mission. We would also like to have a DEI panel of NASA’s astronauts; this video will be essentially designed to reach many audiences with various age groups as well (Panel recordings, preparation, and integration into the video ($2,000)).

In the team's engaging in-person activity, the team's outreach team wants to include Lunar Science Nights. For this dedication we have budgets for transportations for schools within the area of teams’ locations (location provision zones), funds to pay scientists and engineers that are attending and operating events, and grants for schools outside the team's location in which that can apply for. Our team wants to provide transportation for schools to the team's Lunar Science Nights in order to bring the team's schools who are not able to afford traveling. We set aside a total transportation budget of USD $30,000 annually for schools with USD $10,000 from the team's total

transportation budget being towards grants for schools who are in need of transportation and do not meet the boundaries on these zones. Having scientists and engineers come to speak and present, including engaging with students with activities and resources comes with a cost. We are able to compensate the team's members of the Lunar Science Nights for their time and efforts of approximately USD $3,500 monthly with bi-weekly pay per working member. Hosting these in-person activities include activity set-ups, venues, and materials for students. These costs annually if events are hosted once a week would become a total of USD $12,000 (USD $1,000 per month). The total cost of the in-person Lunar Science Nights annually would be about USD $52,000 not including wages for each scientist and engineer.

Finally, due to understanding various difficulties that may arise for schools and the team's members, we are transparent and understanding of these circumstances that may occur if the team's Lunar Science Nights were in person. To address this, we want to ensure that there is equality all across locations and all accessibility for everyone. To achieve this goal we decided to include virtual options for schools and staff to still have the opportunity to be educated if they desire. These virtual meetings will include live virtual events, recorded versions of the presentations taught by scientists and engineers, interactive activities, and worksheets for students in which they can use to take notes. We estimated the team's live virtual events to be about $12,000 for annual platform subscriptions such as zoom premium to ensure good quality and be able to provide good content nationwide. The interactive activities and worksheets are included in the materials budget mentioned in the in-person Lunar Science Nights. In addition to these materials they would be provided in kits for students and schools if requested. Once requested in the team's form that would be sent out to anyone who wants to attend the team's meeting. We would be able to have volunteers to package and ship out these kits. The shipping and handling costs annually if delivered to schools for their students to pick up would be around USD $500 per packaged kit of 150 each time we send supplies to these schools.

Our mission is determined on making sure the team's outreach resources and engagement is open to each and every student despite any challenges that may occur. With the team's thoughtful engaging activities that we are planning to provide the team's overall budget for outreach is well over what the team's team actually uses. With the extra money that is coming from the team's overall budget in outreach we intend to use that for any miscellaneous materials and grants for schools to bring their students to the team's activities. Our goal is to make the Mare Tranquillitatis exploration mission an engaging and educational experience for all. We referenced reputable sources, including Amazon Business, Flinn Scientific, the Bureau of Labor Statistics (BLS), Rev,

NASA's learning resources, and TechSmith, to estimate the average costs associated with professional services, materials, and tools for the team's outreach initiatives.

5.3.6. Direct Costs

Direct Costs Budget Chart

DIRECT COSTS							
Mechanical Subsystem	$ 2,272,000	$ 32,376,000	$ 5,452,800	$ 22,152,000	$ -	$ -	$ 62,252,800
Power Subsystem	$ 1,348,000	$ 19,209,000	$ 3,235,200	$ 13,143,000	$ -	$ -	$ 36,935,200
Thermal Control Subsystem	$ 572,000	$ 8,151,000	$ 1,372,800	$ 5,577,000	$ -	$ -	$ 15,672,800
Comms & Data Handling Subsystem	$ 604,000	$ 8,607,000	$ 1,449,600	$ 5,889,000	$ -	$ -	$ 16,549,600
Guidance, Nav, & Control Subsystem	$ 532,000	$ 7,581,000	$ 1,276,800	$ 5,187,000	$ -	$ -	$ 14,576,800
Science Instrumentation	$ 3,524,000	$ 50,217,000	$ 8,457,600	$ 34,359,000	$ -	$ -	$ 96,557,600
Spacecraft Cost Margin	$ 1,000,000	$ 2,000,000	$ 2,000,000	$ 500,000	$ -	$ -	$ 5,500,000
Total Spacecraft Direct Costs	$ 9,852,000	$ 131,472,666	$ 24,453,530	$ 93,577,946	$ -	$ -	$ 259,356,142
Manufacturing Facility Cost	$ 1,327,800	$ 18,921,150	$ 3,186,720	$ 12,946,050	$ -	$ -	$ 36,381,720
Test Facility Cost	$ 1,327,800	$ 18,921,150	$ 3,186,720	$ 12,946,050	$ -	$ -	$ 36,381,720
Facility Cost Margin	$ 500,000	$ 1,000,000	$ 1,000,000	$ 100,000	$ -	$ -	$ 2,600,000
Total Facilities Costs	$ 3,155,600	$ 39,852,200	$ 7,756,859	$ 28,019,484	$ -	$ -	$ 78,784,142
Total Direct Costs	$ 13,007,600	$ 171,324,866	$ 32,210,388	$ 121,597,430	$ -	$ -	$ 338,140,284
Total MTDC	$ 9,852,000	$ 131,472,666	$ 24,453,530	$ 93,577,946	$ -	$ -	$ 259,356,142

Instrumentation

According to the STM in section 1.2, this robotic mission will carry 5 instruments: Thermal Infrared Sensor (TIS), Close-Up Imager (CLUPI), Ultra-wide-band Ground Penetrating Radar (UGPR), Radiation Assessment Detector (RAD), and Alpha Particle X-Ray Spectrometer (APXS). Parametric cost-estimating relationships (CERs) were used to address the approximate costs associated with the fabrication of these instruments. By category, the mission requires one optical instrument, three passive microwave instruments, one active microwave instrument, and one particle planetary instrument. The System Model CERs used to calculate the costs are as follows.

- CLUPI
  - 392 * TotalMass^0.45 * TotalMaxPwr^0.49 * DsgnLife^0.32
- TIS, UGPR
  - 1,686 * TotalMass^0.39 * TotalMaxPwr^0.38
- APXS
  - 1,244 * TotalMass^0.36 * TotalMaxPwr^0.50
- RAD
  - 223 * TotalMass^0.31 * TotalMaxPwr^0.44 * DsgnLife^0.52

The intended design life for all instruments falls under the timeline for the operations and sustainment phase in the mission project lifecycle, which is approximately one year for this mission. The extra 6 months of extension time for mission operations the team plans to request was not included in the CER calculations. The following table outlines the specifications used for the cost-estimating calculations. Most of these specifications are derived from the previous missions that flew the instruments; however, if previous

missions did not explicitly state the specifications, estimations were made based on other instruments in the same performance class.

	Total Mass (kg)	**Total Max Power (W)**	**Design Life (months)**
CLUPI	0.932	15	12
TIS	0.8	5	12
UPGR	0.8	5	12
APXS	0.57	0.3	12
RAD	0.6	0.1	12

5.4. Scope Management

5.4.1. Change Control Management

Throughout the mission planning process, unforeseen constraints or shifts in priorities may emerge from potential issues or improvements in the current plan. This could result from new data, unexpected challenges, feedback from internal reviews, or direction from external sources such as RFAs or ADVs. At this point, changes to the original mission plans are necessary to ensure effective operation within the mission's costs, timelines, and objectives.

The team follows a set of procedures to ensure all changes are evaluated, implemented, and communicated effectively, minimizing disruption and preserving mission integrity. A process for change is typically initiated by a subteam member who reports a change request to the team lead. The team member proposing the changes is responsible for creating a formal change request, which outlines the nature of the change, its justification, potential impacts on other subsystems or mission aspects, and an initial assessment of the resources and time needed for implementation.

Change Request Process

<u>Initiation of Change Request:</u>

The change request process is initiated when a team member submits a formal request to their subteam lead. This request must include:

- A description of the proposed change.

- Justification for the change (e.g., addressing new data, correcting an issue, or incorporating feedback).
- Potential impacts on costs, timelines, and interdependencies.
- An initial resource assessment for implementation.

Review Process:

Once the change request is submitted, the team leads organize a meeting to discuss and evaluate the proposal. This review includes:

- Impact Analysis: Assessment of how the change will influence mission objectives, costs, timelines, and interactions with other subsystems.
- Feasibility Check: Ensuring the change is achievable with current resources and constraints.
- Risk Assessment: Identification of new risks introduced by the change and potential mitigation strategies.

The Project Manager (PM) and Deputy Project Manager (DPM) oversee the review process, collaborating with the Lead Systems Engineer (LSE) to ensure alignment with the overall mission goals.

Approval and Action Plan:

If the change is approved, an action plan is developed to implement it. The action plan details:

- Task assignments for responsible team members.
- Updated timelines reflecting the change's integration.
- Allocation of any additional resources required.

Changes are tracked using a centralized change log, which documents:

- Change description.
- Justification and expected outcomes.
- Team members responsible for execution.
- Current status (proposed, under review, approved, implemented).

The change log is maintained in a shared project management tool (e.g., Google Sheets), ensuring all team members can access the latest updates.

Implementation and Monitoring:

Subteam leads oversee the implementation, ensuring all affected team members are informed and able to adapt their work as needed. Regular progress updates are provided during team meetings and through subteam Discord channels to keep all stakeholders informed.

Final Review and Documentation:

Once the change is implemented, a final review is conducted to verify that it achieves the intended objectives and integrates seamlessly with other mission components. The results, lessons learned, and any adjustments made during the process are documented and shared with the team to inform future decision-making.

Academy-Mandated Change Request Procedures:

The team adheres to Academy guidelines for handling changes, particularly for RFAs and ADVs issued by external stakeholders. For Academy-mandated changes:

- RFAs are assigned to the relevant subteams for analysis and resolution.
- ADVs are evaluated to determine their impact on mission objectives, resources, and timelines.
- Once the Academy reviews and approves a proposed resolution, the team incorporates the required changes and updates internal documentation and the change log.

Communication and Decision-Making:

Effective communication is essential for managing changes and ensuring alignment across the team. The team employs the following methods:

- Meeting Frequency: Weekly team meetings are held to review change requests, discuss progress, and address challenges. Subteam-specific meetings occur as needed for focused discussions.
- Communication Tools: Discord channels are used for real-time updates and collaboration among subteam members. Major updates are shared with the entire team to maintain transparency.
- Consensus Building: Subteam leads facilitate discussions addressing differing perspectives for decisions requiring team agreement. If consensus cannot be reached, the PM and DPM mediate the decision-making process, ensuring it aligns with mission priorities.

Stakeholder Feedback:

Stakeholder feedback, including RFAs and ADVs, is treated as a high priority. The team has implemented the following practices to address stakeholder input:

- Regular meetings with stakeholders to clarify feedback and expectations.
- Immediate assignment of RFAs or ADVs to relevant subteams for analysis.
- Timely updates provided to stakeholders on the progress and resolution of their feedback.

5.4.2. Scope Control Management

Reduction in Scope :

In the event of descoping, non-critical deliverables need to be identified for further discussion to determine whether the function is redundant, overly complex, or unnecessary for the mission's objectives. This can be accomplished via a prioritization analysis, ranking systems and elements by their complexity, relation to scientific objectives, and necessity to the completion of the mission itself.

Since descoping generally means reducing budget and time, manufacturing in-house components is exponentially more difficult with these restrictions. Due to these constraints, the design of the spacecraft and its necessary components must be analyzed thoroughly and compared to the specifications of commercially available parts. For components being acquired from vendors, these vendors need to be notified of the schedule change and cost reductions, and the status of the parts needs to be verified. Furthermore, there will be less time for the completion of critical tasks. Said tasks will need to be completed in parallel/overlapped, resulting in more resources used and running the risk of mission failure.

In a worst-case scenario, the team needs to analyze the whole system to determine which components critical to the science objectives (i.e., science instruments) can be removed without compromising the entire integrity of the mission itself.

Increase in Scope:

With increased scope, the team can have extra room regarding schedule and budget. With increased resources, there is more time to develop technologies to optimize the vehicle's performance and mission. This includes protecting components, more instruments, and expanding scientific objectives. Furthermore, there is more time to thoroughly investigate risk and other factors affecting the mission's success.

However, the team needs to evaluate if the additions to the mission can be accomplished in the given time and budget or risk the possibility of a reduction in scope.

Mission Life Cycle Effects

Concept/Design Phase: Requires a cost and schedule estimate to determine a baseline to work off of in the event of a change in scope. Furthermore, flexible systems need to be emphasized to account for future changes in scope.

Manufacturing: Scope changes need to be assessed to determine how they will impact the mission. These changes need to be communicated with potential manufacturers.

Testing**:** Focus on schedule changes, such as the bloated testing procedures, rather than components/instruments or software changes.

Operations**:** We need to ensure that scope changes do not compromise the integrity of the mission.

5.5. Outreach Summary

In order to increase public awareness and appreciation for lunar pit exploration, the team intends to emphasize both the importance of planetary science as well as lean into public interest in astronauts and human space exploration. Although this mission itself is an unmanned scientific mission, one of the main goals being to develop methods of sustainable lunar habitation for astronauts is an aspect the team wants to emphasize in its public outreach efforts. The outreach efforts related to the Mare Tranquillitatis exploration mission will be comprised of two portions: a virtual outreach effort as well as in-person opportunities to learn about the mission.

One aspect of the mission that the team anticipates will appeal to students is its applicability to the livelihood of current and future astronauts. In order to emphasize this, the programmatics team will work to create a short video speaking with astronauts about the importance of developing habitation abilities for lunar missions. Due to the close timing of the Mare Tranquillitatis mission with the Artemis program, the team anticipates high public interest in lunar exploration. It will reach out to professionals at the Johnson Space Center to discuss the availability of astronauts to participate. Participating astronauts will be asked to record an answer to questions regarding the relevance of this mission to themselves and to the future of manned space exploration. Answers will be spliced together to allow viewers to get an idea of how this mission connects with the current cohort of astronauts.

The “Astronaut Engagement” portion of the outreach will be able to be used multiple times, including being incorporated into the mission countdown and launch day coverage. Additionally, participant astronauts will be invited to present the “Astronaut

Engagement” video along with an informational clip about the mission’s development and science goals at their alma mater universities. When presenting these clips, the students will be given the opportunity to engage in person at the astronaut's comfort level, whether that be taking student questions about the mission’s importance or further giving their insights on the relevance of developing sustainable habitability. An alternative option to this would be for participating astronauts to record a short message to students at their alma mater to be shown with the regular engagement clips. The “Astronaut Engagement” and “Informational Science” clips will be publicly available for all educational entities to show their students, allowing schools at every level of education and funding to engage their students with the mission’s purpose.

In-person watch opportunities aside from astronaut engagement with alma mater programs will include engagement with scientists and engineers at school and community programs local to sites the team’s workforce is located at. For this section of the outreach, K-12 schools and community programs such as astronomy or community science clubs will be reached out to. Participating schools will be able to watch the “Astronaut Engagement” clip and hear about the visiting scientist’s or engineer’s personal role in the Mare Tranquillitatis mission success, as well as ask questions about the mission’s development and operation.

Additionally, local “lunar science” nights will be held near the teams’ locations in which families from the area are encouraged to participate in learning and science engagement activities for multiple age levels. This part of the outreach effort will allow students and adults alike to engage with scientists and engineers from the team and will target the goal of engaging with underserved communities. The team intends to set aside a designated amount of money from the allotted outreach budget, which can be used to provide transportation capabilities to schools that are unable to afford to bring students to a lunar science night near them. The ability of the team to provide this service will be determined by allowing schools within a certain radius (determined by the available funding) to apply for a transportation grant. Reception of the grant will be non-competitive; any school within the budget-defined radius that is unable to provide transportation to interested students will have their transportation covered by the outreach budget. Schools outside of the “transportation provision zone” will be allowed to apply for the grant should there be leftover funds in the outreach budget, and if available, these grants will be provided in order of a first-come, first-serve basis.

In order to engage with as much of the community as possible, team members available to attend and operate activities at the lunar pit science nights will be distributed amongst multiple activities. This will allow for different activities to be geared towards people of different age groups and knowledge of the mission. Lunar pit science nights will be held once data has started being collected from the Mare Tranqillitatis pit so that novel information about the pit can be shared, and activities can be based on real, new

science that the mission has provided. For example, one activity could be the use of a scale Mare Tranquililtatis pit and lava tube model where students can plan habitation “developments” for astronauts. More advanced or scientifically informative activities, such as structural or material findings from the mission, could be incorporated into activities for older students or adults. Custom made stickers will be printed to hand out to students to generate sustained interest in the mission.



Figure 1: Custom sticker design for mission outreach events

Additionally, the team will dedicate an outreach programmatics member to make a website detailing the ongoing activities and findings of the mission. One of the pages on this site will be devoted to giving information about the activities setups from lunar pit science nights. This way, schools not located in areas where the team is distributed are able to access the information that was used to develop the outreach efforts for the Mare Tranqillitatis pit mission.

One weakness of the outreach plan is its contingency on team members’ physical availability and willingness to attend and run outreach events. The team intends to gauge its members willingness or interest in carrying out lunar science nights pro bono. While it is possible that scientists and engineers will be interested in carrying out these activities purely in the interest of engaging the community in novel science and fostering a passion for their mission in the future workforce, the programmatics group

acknowledges the time and energy that this would take and the possibility that team members will have commitments to their families or otherwise. For willing team members, every effort will be made to coordinate lunar pit science nights around their convenience. Should team members show a lack of interest in carrying out lunar pit science nights pro-bono, then funding allotted to the “transportation provision” will be diverted to offering overtime pay for team members participating in lunar pit science nights to the necessary extent. Funding left in this category will still be used to provide transportation to schools that apply for the grant, and the radius of noncompetitive opportunities will be decreased to accommodate the funding shift.

An alternative option to having the lunar pit science nights run entirely by team members, the programmatics team is considering having the lunar pit science nights attended by a couple of available scientists and engineers who can present interesting information and answer community members’ questions. In lieu of the activities being fully fun by the team’s scientists and engineers, schools in the community can be contacted to request volunteers to run events. One possible way of further incorporating underserved communities into this event is to ask participating communities if they have groups for underrepresented groups in STEM that could help run the event. For example, universities that have programs for groups such as SWE (Society of Women in Engineering) sometimes offer university-funded opportunities for their members to help at local events. Such participation could help alleviate the financial requirements of team member engagement in lunar pit science nights.

One other potential weakness of the outreach efforts planned for the Mare Tranqillitatis pit exploration mission is, again, that its official in-person events are mostly located near locations where the team is. While it is not possible to fund nationwide lunar pit science nights, the programmatics team has and continues to work to develop public access to information about the mission and outreach events. The purpose of creating virtual versions of applicable engagement events, informational clips, and outreach activity development is to remove geographic proximity to the mission as a barrier to entry in learning about novel lunar pit and lava tube science. The team intends to gauge in-person and virtual engagement with the planned activities and assess how successful the virtual engagement opportunities are for future reference.

6. Conclusion

This Preliminary Design Review (PDR) overviews the detailed requirements for subsystem design and mission definition for a discovery-class mission to the lunar pit Mare Tranquillitatis. The systems and subsystems have been refined and enhanced from the Mission Definition Review (MDR), System Requirements Review (SRR) and

the Mission Concept Review (MCR) to address the mission's scientific objectives, engineering constraints, and stakeholder priorities. Key updates include the incorporation of advanced subsystem designs, refined cost estimates, detailed schedule projections, and a more comprehensive Science Traceability Matrix (STM). These developments ensure the mission remains on track for its planned objectives and deliverables. If additional time were allocated toward developing the PDR, the team would focus on further integration of subsystems and advanced prototyping to ensure seamless performance in the lunar environment.

The next milestone for the team is the Critical Design Review (CDR). For this document, the team will advance the detailed designs into finalized configurations, ensuring all components are optimized for integration and testing. Plans include verifying the compatibility of subsystems, implementing advanced risk mitigation strategies, and addressing any gaps identified during the PDR process. Enhanced collaborative tools and tracking systems will be utilized to maintain alignment across all subteams, ensuring that the mission progresses efficiently and effectively toward its next milestone.

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Appendix

Updated Budget Version:

Item	**Cost**
Personnel	$30,000,000
Travel	$2,500,000
Outreach	$2,500,000
Direct Costs	$250,000,000
F&A	$15,000,000
Total Project Cost	$300,000,000

Note: The mission cost exceeds the $300 million constraint, as noted in the feedback provided. Due to time constraints and the delayed submission of the MDR, the feedback regarding the budget was received later in the process. By that point, significant progress had already been made on the budget, and efforts were focused on

completing other critical sections. As a result, revisiting and updating the budget within the given timeframe was not feasible. However, if an updated budget were to be created, it would reflect the necessary adjustments to align with the cost constraint. Despite this, the current submission utilizes the original budget due to these limitations.

Trade Studies:

Thermal Straps						
Criteria	**Explanation**	**Grade**	**Weight**	**Copper**	**Graphene**	**Aluminum**
Weight	SYS.02	10 = Low Weight, 5 = medium 1 = High Weight	25%	5	10	7
Cost	TH-3	10 = Low Cost, 5 = medium 1 = High Cost	25%	7	3	9
Thermal Conductivity	TH-1.2	10 = high, 5 = medium 1 = low	25%	9	10	4
Durability	0.1 (Ability to withstand thermal cycling, and withstand impact)	10 = high, 5 = medium 1 = low	25%	10	6	6
		TOTALS:	**100%**	77.50%	72.50%	65.00%

Batteries Trade Study						
Criteria	**Explanation**	**Grade**	**Weight**	**Nickel-cadmium**	**Lithium Ion Batteries**	**Nickel-hydrogen**
Ampere-hour Capacity	MEC.04.1	10 = high, 5 = medium 1 = low 0 = Fail	30%	8	9	5
Rechargebility	SYS.07	10 = high, 5 = medium 1 = low 0 = Fail	25%	2	8	6
Lifetime	SYS.07	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	8	8
Weight	SYS.07	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	6	9
		TOTALS:	**100%**	65.50%	79.00%	68.00%

MLI Type						
Criteria	**Explanation**	**Grade**	**Weight**	**Kapton**	**Polyester**	**Mylar**
Insulation	TH1.2	10: Able to trap heat very well 1: Unable to insulate, great heat loss	30%	9	3	6
Weight	Sys.02	10: Lightweight 1. Heavy	25%	8	4	9
Cost	TH.3	10: Cheap per weight 1: Very expensive per weight	20%	4	9	6
Durability	0.1	10: Durable against extreme temperatures 0: Material failure in extreme temperatures	25%	8	4	5
		TOTALS:	**100%**	75.00%	47.00%	65.00%

Suspension					
Criteria	**Explanation**	**Grade**	**Weight**	**4-Wheel Suspension; All-Wheel Drive**	**6-Wheel Suspension; 4 Wheel Drive (Rocker-Bogie Suspension)**
Shock Absorption	MEC.04.1	10 = high, 5 = medium 1 = low 0 = Fail	30%	8	8
Slope Climbing Performance	SYS.07	10 = high, 5 = medium 1 = low 0 = Fail	20%	8	8
Maneuverability	SYS.07	10 = high, 5 = medium 1 = low 0 = Fail	30%	9	8
Traction	SYS.07	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	9
		TOTALS:	**100%**	81.00%	82.00%

Chassis Material						
Criteria	**Explanation**	**Grade**	**Weight**	**2000 series Aluminum**	**UD Carbon Fiber**	**S97 Steel**
Weight	MEC.09.2	10: Very lightweight 1: Very heavy	25%	8	10	2
Tensile Strength	MEC.04.2, MEC.05	10: High tensile strength 1. Low tensile strength	25%	7	10	9
Cost	MEC.10	10: Very cheap 1: Very expensive	25%	6	2	8
Temperature Tolerance	MEC.02	10: Falls within the required temperature range 5: Falls within the required temperature range but is +/- TBD degrees from the max/min 0: Does not fall within the required temperature range	25%	8	7	9
		TOTALS:	**100%**	72.50%	72.50%	70.00%

Wheels					
Criteria	**Explanation**	**Grade**	**Weight**	**Conventional Solid Aluminum Wheels**	**Nickel Titanium Spring Wheels**
Weight	MEC.09.2	10: Very lightweight 1: Very heavy	25%	5	10
Performance	SYS.07	10: Excellent performance over rough terrain 1. Poor performance over rough terrain	25%	8	9
Cost	MEC.10	10: Very cheap 1: Very expensive	25%	8	5
Durability	0.1	10: Very durable 1: Not durable	25%	8	9
		TOTALS:	**100%**	72.50%	82.50%

Robotic Arm Gear Material					
Criteria	**Explanation**	**Grade**	**Weight**	**Steel**	**Bulk Metallic Glass**
Temperature Resistance	MEC.02	10: Resistant to extreme temperatures 1: Loses durability in extreme temperatures	25%	4	10
Strength:Weight Ratio	MEC.04.2	10: Very strong requiring moderate mass 1: Very weak requiring extensive mass	25%	6	8
Cost	MEC.10	10: Very cheap 1: Very expensive	25%	8	5
Durability	0.1	10: Very durable 1: Not durable	25%	7	9
		TOTALS:	**100%**	62.50%	80.00%