System Requirements Review (SRR)

Mission Concept Academy

L’SPACE Team 19

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1. Abbreviation

a. GPR - Ground-Penetrating Radar
b. ISRU - In-Situ Resource Utilization
c. KDP- Key Decision Point
d. LADEE - Lunar Atmosphere and Dust Environment Explorer
e. LIDAR - Light Detection and Ranging
f. LRO - Lunar Reconnaissance Orbiter
g. MCR - Mission Concept Review
h. MTP - Mare Tranquillitatis Pit
i. NASA - National Aeronautics and Space Administration
j. RTG - Radioisotope Thermoelectric Generator
k. SRR - System Requirements Review
l. TRL - Technology Readiness Level
m. SSR - Solid State Recorder

1. System Requirements Review

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. This instrument will be utilized to characterize the pit's stability and detect any hazardous materials or supporting essential resources. 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.

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>

The overarching goal of this mission is to find a place where humans and technology can exist on the lunar surface. Reasons for this objective include utilizing the moon as a gateway to the outer parts of the solar system. An aim that stems from this goal is to identify where these places are located and how NASA might use them. Based on the team's LRO image analysis, Lunar Pit Tranquillitatis is an exceptional candidate for exploration. Considering this, 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 STM. The motivation behind this mission is to analyze these parameters and verify a sustainable location to progress to a stage where future pit exploration is confirmed.

The central science goal of this mission is to evaluate the habitability potential and geophysical characteristics of the Mare Tranquillitatis Pit. This goal is derived from the customer's goal of characterizing the features of the lunar pit/cave in an effort to determine the potential for safety and habitability. Furthermore, the team's mission objective is to provide lunar astronauts with significant data samples that provoke further investigation/experimentation on the lunar surface. This will include activities related to in-situ resource utilization, quantification of radiation and its implications for the protection of both humans and technology and determination of the feasibility of Mare Tranqullitatis as a potential future base of operations.

Derivation from Stakeholder Requirements:

According to the Mission Task Document, the primary focus is on surface operations post-landing with a budget of $425M for a Discovery-Class mission. The goal is to conduct geological, structural, and environmental investigations to assess the feasibility of using the pit as a long-term habitat. 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).

Science Traceability Matrix:

The following science traceability matrix (STM) establishes a clear link between the mission's overarching science goal, the specific objectives, and the necessary observables that will be analyzed back on Earth. This matrix will serve as a baseline for the mission's science plan.

Rationale for the STM Components

- *Science Goal:*
    - This goal addresses the need to evaluate the selected pit's habitability potential. It ties directly to future human exploration, aligning with NASA's Artemis program and stakeholder expectations for sustainable lunar exploration.
- *Science Objectives:*
    - Each objective is derived from specific requirements in the Mission Task Document, focusing on characterizing the pit's geological stability, thermal environment, and resource availability.
- *Measurements:*
    - The selected measurements are focused on producing quantifiable data that directly informs the mission's objectives. These include mapping thermal profiles, assessing structural integrity, and detecting subsurface features.
- *Measurement Methodology:*
    - The methodologies are chosen to ensure the measurements are accurate, reliable, and feasible within the mission's budgetary and technical constraints.

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 resources for in-situ use for future explorers? *(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 on MTP floor	Observe stable floor and wall temperatures ~ 290 Kelvin	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 structual instability through imaging	Image cracks, fractures, deformations, and debris piles near MTP entryway, walls, and floor.	Spectral Range:	Visible	400-700 nm	Close - Up Imager (CLUPI)	Vehicle shall maintain at most a 100 cm distance from 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 radar signatures of MTP subsurface and surface	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. The scientific community is interested in these remnants due to their potential for lunar habitation, as they experience less extreme temperature fluctuations and radiation exposure compared to the lunar surface, 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 with a consistent line-of-sight for orbiter communications and data downlinking. This eliminated lunar pits on the moon's far side, 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 considered when selecting a pit location. The pit has an inner diameter of approximately (100 x 88) meters and a funnel diameter of approximately (146 x 140). 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.

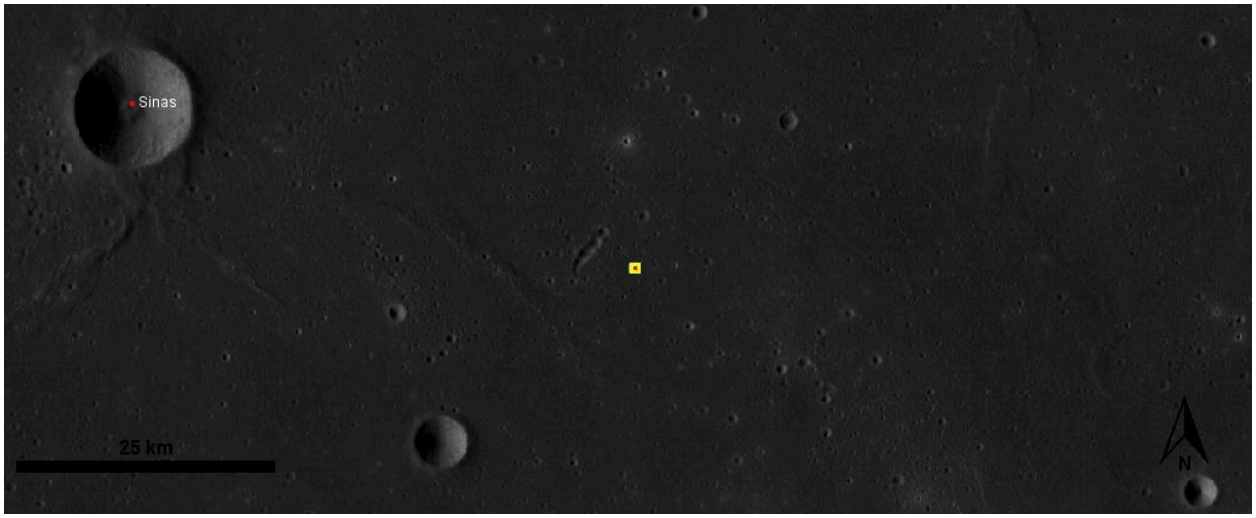


Figure 1: JMARS image showing the Mare Tranquillitatis pit's location within the Sea of Tranquility at (8.3355 degrees N, 33.222 degrees E) close to the Sinas crater

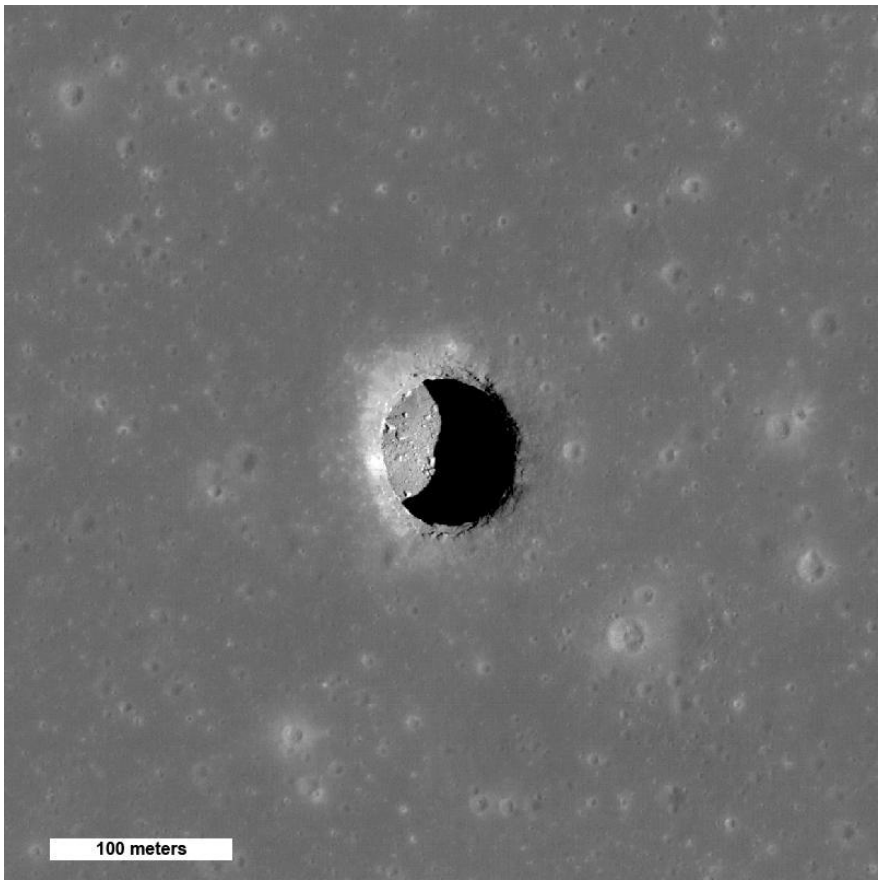


Figure 2: Lunar Reconnaissance Orbiter Camera (LROC) image of the Mare Tranquillitatis pit, NASA/GFSC/Arizona State University 2012

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	Not 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	Not 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	Not 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	Not 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	Not 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	Not 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	Not 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	Not 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	Not Met

NC-2.3	The system should be able to mitigate lunar dust buildup so that all subsystems remain operational.	Necessary Condition to complete the mission	NC- 2.0	-	Test	Mechanical	Not Met
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	Not 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	Not Met

1.5. System Definition

1.5.1. Spacecraft Overview

The spacecraft is designed to meet the mission of exploring and assessing the habitability and geological characteristics of the Mare Tranquillitatis Pit (MTP) on the lunar surface. It integrates multiple subsystems to ensure successful data collection and analysis while maintaining functionality in lunar conditions.

Top-Level Subsystem Requirements

Operational Conditions:

Must operate within the extreme temperature range of -170°C to 120°C.

Capable of surviving and functioning during the long lunar night cycle.

Communication:

Equipped with a radio frequency (RF) communication system using S-band or X-band frequencies for data transmission.

Includes a high-gain antenna (HGA) for focused, long-distance communication to Earth and a low-gain antenna (LGA) for omnidirectional backup communication.

Internal connections using coaxial cables or fiber optics for efficient data transfer between the CDH unit and communication components.

Power and Energy:

Utilizes GaAs solar panels with an integrated electrostatic dust removal system for efficient energy collection.

Lithium-ion batteries to store energy for use during the lunar night.

A Power Management and Distribution (PMAD) system for stable voltage regulation and fault isolation.

Mobility and Navigation:

A 4-wheel rocker-bogie suspension system for maneuverability on uneven lunar surfaces.

Superelastic wheels are designed for traction and durability.

Mass and Power:

Total mass not exceeding 350 kg.

Maximum power draw limited to 300 W.

Science Data Collection:

Equipped with instruments for temperature measurement, spectrometry, LiDAR mapping, and radiation detection.

Includes a robotic arm for sample collection, extendable up to 1.2 m.

Mission Duration:

Designed to last a minimum of 12 months to fulfill data collection and analysis objectives.

Subsystem Narrative 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 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.

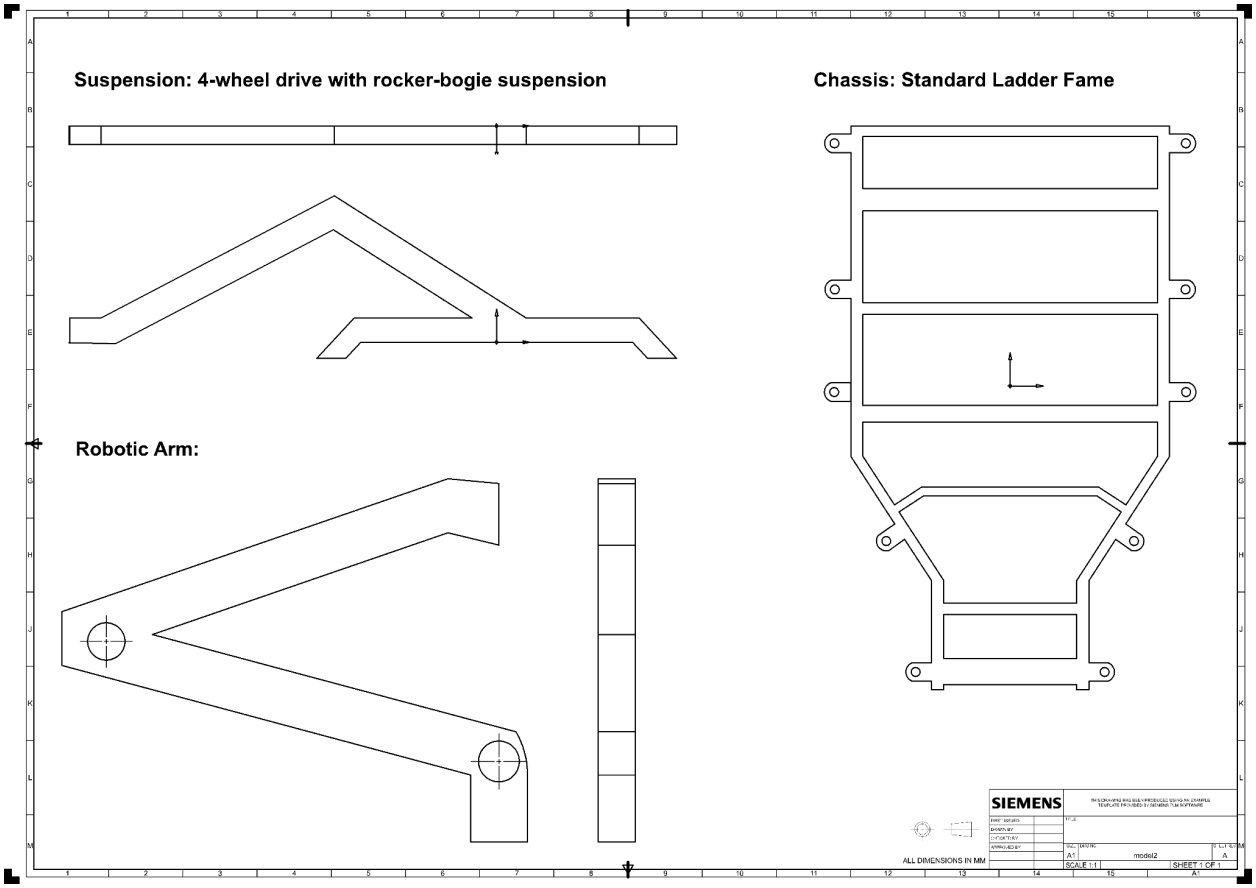
Command and Data Handling (CDH) Subsystem: Centralized control hub for the spacecraft, managing data acquisition, processing, and communication. The CDH unit features a radiation-hardened CPU, memory modules, and interfaces with the communication system to send data back to Earth.

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.

Science Instrumentation 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.

CAD Drawings

The CAD sketches represent the preliminary design layout of the spacecraft. These diagrams include the main structure, robotic arm, and suspension system. Detailed subassemblies and more intricate design elements will be added in future deliverables.



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	TBR	16.2 W
CDH	34	TBR	86 W
Power	17.5	TBR	310 W
Payload	14.52	TBR	70 W
Total	274.82	N/A	110 W

Below are the engineering requirements for the spacecraft.

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 instrumention 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.1	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

1.5.2. Mechanical Subsystem

1.5.2.1. Mechanical Subsystem Requirements

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		Inspection	Blank
MEC.02	The system shall maintain structural integrity within the temperature range of 103 K to 395 K	Structure expands and contracts due to temperature changes	SYS.03		Test	Blank
MEC.03	The system shall be able to recover from an inverted position in case of a roll over	Uneven terrain will be encountered in MTP	SYS.07		Demonstration	Blank
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	Blank
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		Test	
MEC.04.2	The structure shall support the weight of all required instruments	Needs to transport all instruments to target area	MEC.04		Analysis	
MEC.04.3	The system shall protect instruments from debris, dust, etc.	Instruments are vital to the mission and need to be protected	MEC.04		Test	

		from damage				
MEC.05	The system shall be able to withstand a collision at speeds up to TBD mph	Needs to operate and be able to recover on its own	SYS.07		Analysis	Blank
MEC.06	The system should travel at speeds not exceeding 0.15 mph	Ensures safe operation and limits power usage	SYS.07		Demonstration	Blank
MEC.07	The system shall be able to be located regardless of position. (GNC)	Needed to control the vehicle	SYS.09	MEC.07.1	Blank	Blank
MEC.07.1	The system should include a gyroscope	Necessary to identify the orientation of the vehicle	MEC.07		Inspection	
MEC.08	The system should use a tether system	Needed to descend MTP if adequate route to the bottom is not found	SYS.06		Test	Blank
MEC.08.1	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	MEC.08		Analysis	
MEC.08.2	The tether should be TBD feet in length and TBD inches in diameter	Ensures structural integrity of the cable as well as giving enough length to not hinder movement of vehicle	MEC.08		Analysis	
MEC.09	The mechanical subsystem shall be no more than TBD kgs in weight	Need to allocate a set amount weight for the weight "budget"	SYS.02	MEC.09.1, MEC.09.2	Inspection	Blank
MEC.09.1	The suspension of the systelm shall be no more than TBD kgs in weight	Need to allocate a set amount weight for the weight "budget"	MEC.09		Inspection	
MEC.09.2	The chassis of the system shall be no more than TBD kgs	Need to allocate a set amount weight for the weight "budget"	MEC.09		Inspection	
MEC.10	The system shall cost no more than $TBD	Cannot exceed given budget	Customer		Blank	Blank

1.5.2.2. Mechanical Subsystem Overview

The mechanical subsystem allows continuous wheeled mobility when entering MTP and navigating within the pit. The mechanical subsystem comprises 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 aluminum panels facing the exterior will protect it from the elements.

- **Structural Design**: The rover will utilize a standard ladder frame chassis. This 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.

- **Technology Readiness Level 7:** An aluminum chassis/body has been used multiple times on Martian rovers. The system has been proven on the Martian surface. However, how it will perform in a lunar cavern is unknown, granting the system a TRL of 7.

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 weight distribution 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 system's load 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 climb or dismount uneven surfaces more easily. 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 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 instead of 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 toward the direction of the cave with an algorithm that the rover will follow. However, it will develop a route using the scanners and sensors from the navigation system. 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 to help determine the rover's movement and orientation. This will provide continuous data on the rover's pitch, roll, and yaw. 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 wheel's rotational movement, showing how far the rover has traveled from the starting point and how fast it moves. A stereo camera will be added to the rover to capture 3D images of the lunar surface and 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 to scan the environment and 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, stability control will be implemented based on the suspension chosen. On rough terrain, the wheels will remain on the ground. If uneven forces are 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 guide the rover.

- **Technology Readiness Level 8:** The GNC system of the rover mentioned above has been used in multiple missions on the moon. Additionally, engineers implement this same technology and processes to ensure the rover's guidance, navigation, and control are successful.

Masthead

- **Structural Design:** The rover will utilize a fixed masthead, which will help mount the camera for imaging and provide headlights for vision. The method will provide plenty of stability. A fixed masthead is also a good idea because it is a simple design, and implementing it 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, which makes 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.

- **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 reduces power consumption since additional heating is unnecessary 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, optimizing space and reducing the necessity for heat shielding between mechanisms.

- **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 rover's base to illuminate a broader area; however, this will be at a lower 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 proven efficient and effective. These LED lights have been tested in similar environments to the moon to ensure functionality in such dark environments. A NASA rover will use These exact lights to explore the moon. Thus, a TRL level of 8 was assigned.

[max mass = 350 kg]

Subsystem	Mass (kg)	Dimensions (m)	Max Power Draw (W)
Chassis	100	2m x 1.5m x 1.5m	
Suspension	23.5		
Wheels	12		
GNC	10		
Masthead	2		
Robotic Arm	30		
Headlights	0.5		
Total	178		110

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.

1.5.2.3. Mechanical Subsystem Trade Studies

The following trade study compares a 4-wheel all-wheel drive suspension and a 6-wheel suspension 4-wheel drive. Shock absorption and maneuverability were weighted 30% each as rover movement is crucial to complete science objectives. The rover will likely encounter various kinds of terrain, so the suspension is critical for mission success.

Both suspensions were seen to be similar in performance; however, since traction is a major factor that will keep the rover stable in case of high slopes, the 6-wheel suspension was chosen for this mission.

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%

1.5.3. Power Subsystem

1.5.3.1. Power Subsystem Requirements

Requirement ID	Requirement Description	Rationale	Parent Requirement	Verification Method	Relevant Subsystem
P.S - 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	Simulation, Analysis	Power Generation
P.S - 1.1	Solar panels will achieve at least 25% efficiency under lunar illumination	Ensures adequate energy generation with constrained lunar light levels.	PS-1.0	Testing, Analysis	Power Generation

	conditions.				
P.S - 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
P.S - 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	Testing, Analysis	Power Storage
P.S - 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
P.S - 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	Simulation, Testing	PMAD
P.S - 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
P.S - 4.0	Solar panel dust mitigation will achieve 90% dust removal efficiency during lunar day cycles	Ensures sustained power output and efficiency in dusty lunar conditions.	PS-1.0	Testing, Analysis	Power Generation

1.5.3.2. Power Subsystem 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%) and radiation resistance, making them optimal for lunar missions. GaAs cells offer a robust alternative to silicon-based cells, which are less efficient under harsh lunar conditions.
- **Dust Mitigation Technology:** An electrostatic dust removal system is incorporated to counter the effects of lunar dust, which can reduce panel efficiency by up to 50%. 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
    - This area is rounded up to 1.1 m² to ensure consistent energy generation.

Structural Design:

- **Deployment Mechanism:** Solar panels are stored compactly during transit and deployed 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): 8

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 7**.

<u>Power Storage</u>

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. 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): 9

- 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 9** 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 from damaging sensitive scientific instruments or disrupting communication links.
- **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.

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	7	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	9	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 the 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.

1.5.3.3. Power Subsystem Trade Studies

Solar Panel Trade Study: Solar panels are the sole mechanism powering the rover. Different types of solar panels have been used in space applications. A Germanium Arsenide solar panel has been chosen through meticulous research. The category with the most weight is capacity, as the rover will not function without enough power. The GeAs solar panels can achieve a higher power output within a smaller area than traditional panels. This high capacity means that less surface area is needed for the same power output, so it is given a higher score than Silicon panels or hybrid panes. The next highest weighted category is deterioration, as generating enough power throughout the life cycle of the mission is important. Unlike other materials, Germanium and arsenic-based materials demonstrate good resilience against the radiation and high-energy particles found in space. Reliability and efficiency have been given the same weight, and GaAs panels are superior in both categories. Germanium arsenic panels have a wider range of bandgap options, allowing them to capture a broader spectrum of solar radiation than the others. This makes them particularly efficient in converting sunlight into electricity. Thus, our selection will be Germanium Arsenic solar panels.

Spacecraft Solar Panel						
Criteria	**Explanation**	**Grade**	**Weight**	**GaAs Solar Cell**	**Silicon Solar Cell**	**Multi-junction cells**
Efficiency	DEP-3	10: No supporting systems needed 1: Complicated supporting system	20%	9	8	7

Deterioration	DEP-1, DEP-2	10: Solar Panel capabilities deteriorate at a slow rate per year <3% 5: Solar Panels deteriorate at an increased rate per year <10% 1. Solar Panels deteriorate very quickly >10%	25%	9	8	5
Reliability	DEP-1, DEP-2	10: Very reliable 1: Minimally reliable	20%	10	9	10
Capacity	MAT-4	10: Solar Panels generate more than enough power /hr for the rover 5: Solar Panels generate just enough to power rover 0:Solar panels do not produce sufficient power	35%	7	4	5
		TOTALS:	**100%**	85.00%	68.00%	64.00%

1.5.4. Command and Data Handling (CDH) Subsystem

1.5.4.1. CDH Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Req met?
CDH-1	The rover shall transmit information to 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 satellite within [TBD] km rate of range	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 [TBD] to communicate output information at a frequency of [TBD]	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 retrieve and stored	CDH-2	CDH-2.1.1	Inspection	Not Met
CDH-2.1.1	The system shall have a storage capacity of [TBD] 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 [TBD] km rate of range
Frequency Rate: The system shall use [TBD] to communicate output information at a frequency of [TBD]

Objective 2: Transmission and Scheduling of Rover Data
Transmission: The rover shall transmit [TBD] information to the 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 [TBD] 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

1.5.4.2. CDH Subsystem Overview

1.5.4.2. Command and Data Handling 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 facilitates 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 of the CDH subsystem designed to ensure mission success because of the harsh conditions, software and hardware components are made to meet strict thermal stability and radiation resistance standards. This strategy protects data integrity and system functionality while guaranteeing that the CDH subsystem can adjust to communication failures.

I. **Data Computing Module**
   A. **Real-Time Operating System - VxWorks (RTOS)**
      1. A mission control software is needed 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 compared to modern-day CPUs on Earth. Processing speeds can range from 100 MHz to 1 GHz.

(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. 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) Technology 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 with mission control and track the location of the rover, a telecommunications subsystem is needed to receive and transmit signals to the LRO and Earth through the deep space network. With the use of S-band Antennas and transceivers, the rover can communicate with mission control GNSS(Global Navigation Satellite System) antennas to track the rover's coordinates on the moon

a) Technology Readiness Level: 6 ~ S-Band Antennas and Transceivers have 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 communication network configuration 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.

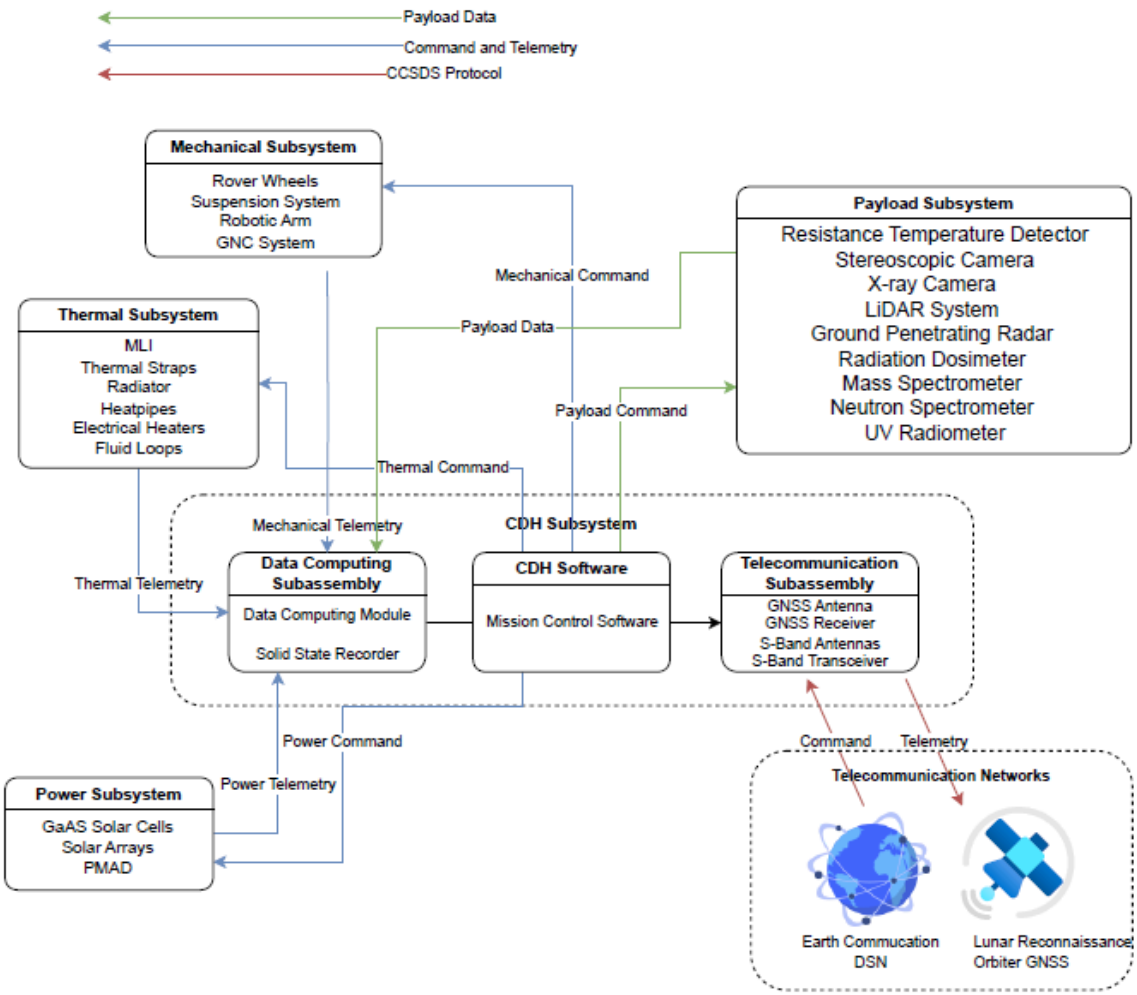
4. Technology Readiness Level (TRL) Analysis

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 subsystem's CPU and RAM data modules. 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 yet been defined or established.

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 connects with the Deep Space Network and the LRO and only gets inputs from the Data Computing Module.

CDH Overview Conclusion

Its interconnecting hardware and software components define the current state of the CDH subsystem. 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 subassembly. The CDH subsystem hosts a TRL score of 6, the lowest rating of the whole subsystem; the operating system dictates the overall score.

1.5.4.3. CDH Subsystem Trade Studies

The CDH subsystem enables data management and communication between the rover and mission control. It should be able to successfully transmit data, process the collected data received from other subsystems, and maintain communication with the Lunar Reconnaissance Orbiter. The components are selected to have high radiation resistance and thermal stability.

Spacecraft Command and Data Handling system						
Criteria	**Explanation**	**Grade**	**Weight**	**Direct-to-Earth(DTE)**	**Relay via Orbiter**	**Inter-Rover**
Rover Communication Environment	DEP-3	Grading: - 10: Communication does not require additional support systems, ensuring simplicity and reliability. - 1: Communication requires complex support systems, increasing the risk of failure.	25%	10	7	5
Transmission and Scheduling	DEP-1, DEP-2	- 10: Position is fully secure during launch and adjustable after, ensuring flexibility in orientation. - 5: Position is secure during launch and adjustable afterward, providing moderate flexibility. - 1: Position is fixed both during and after launch, limiting adaptability	15%	10	8	5

Data Processing	DEP-1, DEP-2	- 10: Data processing is highly reliable, ensuring minimal errors in operation. - 1: Data processing is minimally reliable, with a higher potential for operational issues.	35%	10	9	6
Data Storage and Management	MAT-4	- 10: Storage remains within the required temperature range, ensuring data integrity. - 5: Storage operates within the range but may exceed by a defined margin (± TBD), which could affect performance. - 0: Storage does not meet temperature requirements, risking data loss.	25%	8	7	6
		TOTALS:	**100%**	95.00%	78.50%	56.00%

Direct-to-Earth (DTE) communication capacity, transmission and scheduling, data processing, and data storage and management were among our CDH subsystem trade research requirements. Each criterion was given a weight depending on how important it was to the mission's success, and scores were given to different choices based on how well they performed in these areas. Each criterion, the rationale behind the weights allocated, the scoring rubric, and the outcomes for each configuration are broken down here.

Communication via Direct-to-Earth (DTE) (25%)
Justification: A strong communication link is essential to guarantee a direct connection between the rover and Earth. By minimizing reliance on extra support structures, an ideal DTE system would increase simplicity and lower the likelihood of failure. Because DTE communication is crucial for direct communication with mission control and for guaranteeing vital data relays without the assistance of middlemen, we gave it a 25% weight.
Because it enabled simple, less complicated communication, our investigation revealed that the DTE option offered the maximum reliability. Relying on a relay through an orbiter, however, provided flexibility at the expense of a minor increase in complexity.

Scheduling and Transmission (15%)
Justification: The CDH system must be able to safely deploy and retain communication devices while having the adaptability to make necessary adjustments after launch. Since flexibility is necessary to ensure dependable communication at different mission stages but less important than data reliability and storage, transmission and scheduling were given a 15% weight.
Because it was the most flexible and reliable, a system with a secure and customizable transmission arrangement (rated 10) was preferred. Relay through the orbiter was somewhat

flexible, but the fixed configuration of the inter-rover communication system made it less flexible.

Processing Data (35%).
Justification: Because the CDH's capacity to process data reliably is essential to the rover's operations, data processing skills were given the greatest weight (35%). Effective data processing improves communication effectiveness, prevents mistakes, and preserves mission continuity.
According to our findings, the DTE option (10) provided the maximum processing dependability necessary for precise data handling. Inter-rover communication (6) demonstrated poorer reliability, making it a lower priority for this criterion, although relay via the orbiter (9) was nearly as effective.

Management and Storage of Data (25%)
Justification: Data storage reliability was a crucial criterion with a 25% weight because of the drastic temperature swings on the lunar surface. Long-term data integrity and the prevention of data degradation depend on systems that can sustain temperature stability.

With the highest score of (8), DTE demonstrated excellent temperature management capabilities with little danger to data integrity. The inter-rover option (6) had the lowest thermal stability, while the orbiter relay (7) performed similarly but was marginally less stable.
With the highest overall score (95.00%) across all categories, the Direct-to-Earth communication option was determined to be the best configuration for the CDH subsystem based on the findings of our trade research. This option is the most reliable alternative for guaranteeing continuous and precise contact with mission control because of its great reliability, versatility, and secure data processing capabilities. The final design is the best option for the mission's CDH subsystem since it prioritizes thermal stability, data integrity, and system simplicity.

1.5.5. Thermal Management Subsystem

1.5.5.1. Thermal Management 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	-	SYS.01, SYS.03, SYS.04	All	Demonstration	Met

		of lifetime as defined by the client					
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 instrumention 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	0.1	TH.1.0	All	Test	Met

		pose challenges to instrument operability					
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

1.5.5.2. Thermal Management Subsystem Overview

The extreme temperatures on the surface of the Moon make an efficient thermal management system imperative. System requirement .03 (SYS .03) requires the spacecraft to operate between a temperature of 103 K to 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. Combining the two technologies provides the most optimal, cost-effective route.

I. Passive Systems

A. Passive Heating Systems

1. **Multilayer insulation (MLI)** is utilized on the rover to protect sensitive instruments against freezing temperatures. The layered insulation consists of layers of low-emittance films. We will specifically use aluminized Kapton film, as studies have shown a 19% improvement in insulation performance compared to Mylar films. 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. Metalized 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.
    a) **Technology Readiness Level: 6** - The technology has been used in the past, and many manufacturers diversify present rovers, spacecraft, and products. Due to different shapes, dimensions, and specifications, the technology is tailored to the mission's specific needs, thus driving up the price and time required to design and manufacture.
2. **Thermal straps** are flexible, thermally conductive connectors that 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 enables the rover to use its own heat and distribute it to maintain a regulatory temperature throughout the rover. The straps are made of flexible, copper “ropes” that dismiss any concern about additional structural

load. This keeps the payload light yet increases thermal conductivity.

a) **Technology Readiness Level: 5 -** The technology has been used on many different CubeSats and larger vehicles such as the Orion capsule.

B. Passive Cooling Systems

1. 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.
    a) **Technology Readiness Level: 5 -** Common technology used in a space application
2. **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.
    a) **Technology Readiness Level: 5 -** Common convection methods used in space applications. It can be expensive and very involved due to the specifications of the mission
3. **Thermal Louvers** are heat-activated shutters that control how much heat a louvered surface can dissipate by adjusting infrared emissivity. The louvers operate without drawing power from the spacecraft when utilized in a CubeSat-adapted design.
    a) **Technology Readiness Level: 4 -** Integration on smaller spacecraft is challenging and more cost-heavy.

C. Active Heating Systems

1. **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.

a) **Technology Readiness Level: 4 -** Although technology is common in the space industry, the extreme conditions of the Moon leave little precedent.

D. Active Cooling Systems

1. **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.
    a) **Technology Readiness Level: 6 -** Widely used on both smaller satellites and larger vehicles such as the Mars rover *Curiosity*

E. 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 source 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				

1.5.5.3. Thermal Management Subsystem Trade Studies

Thermal Straps						
Criteria	**Explanation**	**Grade**	**Weight**	**Copper**	**Graphene**	**Aluminum**
Weight	SYS.02	10 = Low Weight, 5 = medium 1 = High Weight 0 = Fail	25%	5	10	7
Cost	TH-3	10 = Low Cost, 5 = medium 1 = High Cost 0 = Fail	25%	7	3	9
Thermal Conductivity	TH-1.2	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	10	4
Durability	0.1 (Ability to withstand thermal cycling and withstand impact)	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	6	6
		TOTALS:	**100%**	77.50%	72.50%	65.00%

The above trade study outlines how the thermal straps were chosen. The team decided on copper due to its durability and high conductivity. For this trade study, all factors were equally weighted as they all play a key role in determining the correct part for a thermal strap.

1.5.6. Payload Subsystem

1.5.6.1. Payload Subsystem Requirements

Objective 1: Characterize the thermal environment of Mare Tranquillitatis Pit (MTP)

Temperature sensors

- Temperature Sensitivity: The temperature sensor should detect temperature fluctuations between 100-300 K.
- Stability: The temperature sensor should not change by more than 1 degree per year.
- Spatial Resolution: The temperature sensor should observe an area of less than 10 square meters

Objective 2: Assess the structural integrity of the walls and overhangs of MTP

Stereoscopic and X-ray cameras

- Stereo Camera: The stereo camera should have a field of view of at least 100 degrees
- Stereo Camera: The stereo camera should have a root-mean-square correlation accuracy of no greater than 0.2
- Stereo Camera: The camera should have a spectral range in the visible part of the electromagnetic spectrum
- Stereo Camera: The camera should have a resolution of less than 2.5 mm/pixel
- X-ray: The X-ray camera should have a modulation transfer function (MTF) of greater than 0.7
- X-ray: The X-ray camera should have a spatial resolution of at least 2.5mm
- X-ray: The X-ray camera should have a signal-to-noise ratio of at least 40:1

Objective 3: Investigate and characterize potential cave networks and terrain in and around MTP, respectively

LiDAR and GPR

- LiDAR: The LiDAR system should operate at a 1550 nm wavelength
- LiDAR: The LiDAR system should achieve 1m per 100m (1%) of error
- LiDAR: The LiDAR system should have a detection range of at least 200 m
- GPR: The GPR should use dual-frequency scanning
- GPR: The GPR should have a resistivity of at least 100 Ohm-m
- GPR: The GPR should have an antenna center frequency of 100 MHz
- GPR: The GPR shall have a frequency range greater than 100 Mhz

Objective 4: Quantify the radiation environment in and around MTP to understand its effect on humans and instrumentation

Radiation dosimeters, UV radiometer, spectrometers

- Energy range: Spectrometers should measure the energy range of radiation between 100 keV - 10 MeV.
- Exposure time: The particle detector should take exposures of around 1 hour
- Sensitivity: The detector should be sensitive to less than 10^4 erg/s, UV flux should be less than 124 eV/s/m^2

Objective 5: Map the distribution of volatiles and hydrogen concentrations found in and around MTP

Neutron spectrometer, X-ray spectrometer

- The spectrometer shall be rated for measurements in the 780 nm to 4 μm range
- The spectrometer shall be rated for measurements in the 100 - 700 nm range
- The spectrometer should have a resolution of 1-2 nm

1.5.6.2. Payload Subsystem Overview

The current instrumentation 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.

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 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 [1]. Currently, the team is working to come to a conclusive decision between RTDs and thermocouples. RTDs measure 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 [2]. RTDs can take measurements in the desired temperature range and are more accurate and stable than thermocouples but less robust.

On the other hand, thermocouples operate by taking a temperature change-induced voltage across two distinct metals joined together [3]. The robust nature of thermocouples lends itself to pit entry but introduces the drawback of less accuracy and stability than RTDs. Most likely, system-level requirements such as size or budget will play a role in the final selection along with instrument performances.

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. For the pit to be reasonably viable for further habitation considerations, it should be structurally sound and ideally will include some lava tube network. The first instrument that will contribute to structural characterizations of MTP is 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 [4]. Stereoscopic cameras are of interest for similarly demanding scientific missions, such as underwater cave mapping [5], 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, 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). Another method that will be employed to investigate MTP’s structural integrity is the use of X-ray imaging. X-rays are often used in the medical field to examine the internal state of a body's physiological structure. Frequently, X-rays are used to assess bone health or diagnose broken and fractured bones, somewhat analogously to what the X-ray on the spacecraft will do. Using electromagnetic radiation, X-rays create contrast in images that include different materials due to the differing amounts of energy lost as the X-rays pass through those materials [6]. While the team has developed standards to ensure that the X-ray imaging carried out during the mission will have sufficient contrast visibility and signal-to-noise ratio to ensure a thorough analysis of structural cracking in MTP, the use of this instrument is still under consideration due to mission restrictions on activities involving radiation. Should X-ray imaging be deemed acceptable by the team, this instrumentation will be included as part of the structural characterization during the mission.

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 are commonly used for geological assessments, making it a well-tested instrument for this mission objective. GPR has interested the

science community for Martian missions because of its ability to penetrate well enough below the planetary surface 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 so as to get as much imaging depth as possible near the pit [8], which is estimated by some scientists to have a depth of around 100 meters [9], a relatively high depth for a GPR application. The last tool to be used for structural characterizations is a Light Detection and Ranging (LiDAR) system. LiDAR is a remote sensing method similar to radar for environmental mapping [10]. A LiDAR system sends light in the form of laser beam pulses and creates mappings by measuring how long it takes for the light beam to return after bouncing back off of an object. One advantage of using a LiDAR system over a radar system is its spatial resolution. Because LiDAR tends to have better spatial resolution than radar [10], the mapping of MTP will ascertain more thorough and reliable structural characterizations.

On the other hand, a potential drawback of selecting LiDAR over radar is its increased sensitivity to environmental conditions, which may not always be ideal in the pit. To try and mitigate the potential for this to affect the LiDAR system’s performance, the team has developed standards regarding the system's allowable error. Additionally, the team has opted to employ a 1550 nm LiDAR instead of a 905 nm LiDAR since the performance of LiDAR systems operating at 1550 nm is less environmentally sensitive.

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, which 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. One potential issue with this instrumentation is that the payload will also employ an X-ray, which could interfere with the accuracy of measurements taken by the dosimeter. Currently, the team is considering two options for mitigating this issue. Firstly, using the dosimeter and X-ray at different times may help avoid data interactions between the instruments. Alternatively, post-processing could be set up to take the effect of X-ray imaging into account when performing data analysis of the dosimeter. Another instrument the team has opted to employ, the spectrometer, will be used for two purposes: working in tandem with the dosimeter to characterize the radiation environment in MTP and including a specific instrument called a neutron spectrometer

will be used to check the pit for volatile compounds and hydrogen. 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 [12]. This information and 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. A neutron spectrometer is specifically good for detecting the presence of hydrogen [13]. It will thus be employed to assess the potential for any in-situ resource utilization requiring hydrogen to be carried out near and in MTP. Finally, UV radiometers filter radiation sources detected by the device to make UV spectrum characterization [14]. Spectrum irradiance measurements will help the other instruments to provide a holistic initial assessment of the pet's environment.

1.5.6.3. Payload Subsystem Trade Studies

As a brief overview, most of these trade studies were similar because the criteria were mostly based upon baseline things like cost/mass and volume. There are also supporting criteria that pertain to each instrument, and how these criteria are described in the following section:

The cost of these instruments is difficult to estimate, so a very basic estimate is utilized to score this section. A general guideline was used to score this section: greater mass = costlier. This is not necessarily always the case; however, it is the basis for the following trade studies that were scored.

The volume of these instruments was a simple criterion to apply to every trade study due to the customer's constraint on payload size. Given the constraint, a larger volume resulted in a lower score, as most of the volume cannot be allocated to instruments only.

Power consumption is an essential part of every mission. A very costly instrument in terms of power consumption may jeopardize the mission lifespan and the instrument's ability to conduct valuable science for a long period of time, potentially even after mission completion.

The previous three criteria were used for most, if not all, of the trade studies due to the complexity of each instrument and how they may serve different purposes. At the very least, these criteria provide a baseline for any modifications that may and will occur when developing this mission's instrumentation. These criteria will not discussed again; however, the following is the rationale for the weighting of each trade study. Cost should be paramount in a discovery class mission, as the team has many science objectives. These criteria were weighted an appropriate amount greater than the others to provide a greater margin to the total mission cost. Volume falls into a similar category as the

customer's constrain must be taken into account; however, was not weighted significantly because most of these instruments do not exceed 10,000 cm^3. Power consumption is a vital aspect of day-to-day operations; instrumentation is allowed to take a significant portion of the daily power budget; however, lower power consumption was taken into significant consideration to provide a margin.

Imager

To identify markers of structural integrity in MTP, an optical imager was chosen as per the instrument performance requirements. The trade study associated with this instrument is a comparison of a few instruments that were flown in past missions on Mars. Naturally, these instruments were made for a Martian environment, so a certain amount must decrease the TRL of these instruments. Still, these instruments were chosen because they were responsible for capturing the environment around their respective rovers, similar to how this mission plans on identifying features in the pit's floor, walls, and overhang. The weighting is as follows:

- Cost: 25%
- Volume: 20%
- Resolution: 30%
- Power Consumption: 25%

Resolution was given a weight of 30%, a considerable amount. A good imager is necessary to identify any signal of structural instability within the pit. If any markers are identified, future exploration of this pit may not be necessary if MTP is not stable enough to provide long-term habitation.

When scoring the instruments, the basic criteria were sourced from reliable sites that overviewed the technical specifications of each instrument, as these missions have been flown before. There were some instances where an imager was not suitable for the mission's requirements thus, a score of 0 was given. For this section, CLUPI was chosen as the final imager and will be a safe option to characterize MTP's walls, floor, and overhand.

Ground Penetrating Radar

Two criteria were a part of this trade study that were not chosen as baseline criteria. The frequency bandwidth of a ground-penetrating radar is weighted 25% as a higher range of frequencies will allow the rover to identify various structures, large and small. Although an important criterion determining the depth the instrument can see, the central frequency was weighted 15%. Since an aspect of the performance requirements of this instrument is rated to at least 50 meters and it is understood that the rover will be able to descend into the pit, a larger weight was not required. The Under-Rover Ground Penetrating Radar Antenna was chosen as it is a viable instrument for detecting subsurface features

Radiation Detector

The three baseline criteria were used for this trade study. In addition, the energy coverage of the radiation detector was weighted 25%. The reasoning behind this weight is due to a mission science objective to quantify the radiation environment around MTP, which has implications for humans and technologies alike. A significant weight was given since a larger coverage will better understand the variety of high-energy particles that bombard the mission's operational area. The Radiation Assessment Detector was chosen for this trade study, as it has shown success in the Martian environment.

Spectrometer

For a spectrometer instrument, calibration time was an important factor to consider when conducting day-to-day operations. A long time to analyze and/or calibrate the sensor will take time away from other activities. As such, this criterion was weighted at 20%, which was a little low compared to the baseline but an important factor nonetheless. The Alpha Particle X-Ray Spectrometer (APXS) was chosen for this science objective since it has flown more than once and is a reputable instrument. Furthermore, it fits most, if not all, of the requirements that the mission needs to identify the chemical compounds that the science team would like to identify. It can identify the chemical compounds that the STM lists with proper modifications.

Temperature Sensor

The range over what the sensor can see is crucial for a temperature sensor. A larger range will determine hotspots or cold spots on the lunar surface and subsurface, which is crucial when creating a heat map of the inner pit and surrounding environment. The instrumentation choice for this trade study was slightly unorthodox as two contending instruments had different forms of conducting measurements: one with contact and one without. An infrared sensor aboard MEDA on the Perseverance rover was chosen to characterize the temperature in MTP.

Imager						
Criteria	**Explanation**	**Grade**	**Weight**	**Mastcam-Z**	**CLUPI - Close - UP Imager**	**Pancam**
Cost	Using paramatric estimates, costs are closely related to mass of intrsument, Generally, higher mass = more costly to launch	10 = Cheap, easy to manufacture 5 = Cheap, but costs are justified 1 = Extremely Expensive, greater than budget constraint	25%	4	7	8
Volume	In cubic centimeters; volume is an essential criteria to stay within customer's constraints	10 = Relatively small, with no sacrifice to performance 5 = Average in size, doesn't take up significant % of vehicle size 1 = Relatively large, doesnt not fit w/in the scope of vehicle size 0 = Simply too large given custom constraints	20%	4	5	9
Resolution	Detailed images are critical since they provide the highest amount of information of the site	10 = High microns/pixel count at TBR distance 5 = Medium microns/pixel count at TBR distance 0 = Poor resolution	30%	8	6	0
Power consumption	Wattage of instrument, efficient power consumption is integral for performance (e.g., thermal management, instrument lifespan)	10 = Not a signifianct impact towards total vehicle power budget 5 = Slight impact 1 = Significant impact 0 = Exceeds vehicle power consumption constraints	25%	8	8	9
		TOTALS:	**100%**	62.00%	65.50%	60.50%

Radar Device						
Criteria	**Explanation**	**Grade**	**Weight**	**WISDOM - Water Ice and Subsurface Deposit Observation On Mars**	**Radar for Icy Moon Exploration (RIME)**	**Under-Rover Ground Penetrating Radar Antenna**
Frequency Bandwidth	The greater the bandwidth of frequencies available, the more features that are able to be identified	10 = High range, 5 = Not a signifiacnt range, but fits within requirements 1 = Barely meets range requirements	25%	4	4	8
Central Bandwidth	The center frequency of a sensor is critical, it determines the maximum depth the instrument see, and governs the resolution of the features that are identified.	10 = Meets central bandwidth requirements, 5 = Falls within +/- 10 central bandwidth requirements 1 = Barely meets central bandwidth requirements	15%	2	4	9
Cost	Using paramatric estimates, costs are closely related to mass of intrsument, higher mass = more costly to launch	10 = Cheap, easy to manufacture 5 = Cheap, but costs are justified 1 = Extremely Expensive, greater than budget constraint, or unknown cost	35%	1	6	8
Power Consumption	Wattage of instrument, efficient power consumption is integral for performance (e.g., thermal management, instrument lifespan)	10 = Not a signifianct impact towards total vehicle power budget 5 = Slight impact 1 = Significant impact 0 = Exceeds vehicle power consumption constraints/Unknown	25%	0	7	0
		TOTALS:	**100%**	16.50%	54.50%	61.50%

Radiation Detector

Criteria	Explanation	Grade	Weight	Radiation Assessment Detector (RAD)	AGILE: Advanced enerGetic Ion eLectron tElescope	Radiation Hard Diamond Particle Detector for Heliophysics
Volume	In cubic centimeters; volume is an essential criteria to stay within customer's constraints	10 = Relatively small, with no sacrifice to performance 5 = Average in size, doesn't take up significant % of vehicle size 1 = Relatively large, doesnt not fit w/in the scope of vehicle size 0 = Unknown, or too large	20%	9	0	0
Cost	Using paramatric estimates, costs are closely related to mass of intrsument, Generally higher mass = more costly to launch	10 = Cheap, easy to manufacture 5 = Cheap, but costs are justified 1 = Extremely Expensive, greater than budget constraint	30%	8	4	2
Energy Coverage	A broader energy range that the detector can cover will be beneficial towards understanding the various kinds of energetic particles that bombard the rover, thus providing key information towards implications of human and technological health overtime	10 = Falls into power coverage requirements, 5 = Is within +/- ~5 MeV of energy coverage requirements 1 = Energy coverage is unknown 0 = Does not meet energy coverage requirements/ Unknown	25%	10	3	3
Power Consumption	Wattage of instrument, efficient power consumption is integral for performance (e.g., thermal management, instrument lifespan)	10 = Falls within power requirements 5 = Is within +/- ~1 W power requirements 1 = Power requirements is unknown 0 = Does not meet power requirements/Requirements unknown	25%	8	3	3
		TOTALS:	100%	87.00%	27.00%	21.00%

Spectrometer						
Criteria	**Explanation**	**Grade**	**Weight**	**Alpha Particle X-Ray Spectrometer (APXS)**	**Instrument for X-Ray Lithochemistry (PIXL)**	**Near Infrared Spectrometer (NIRS3)**
Cost	Using paramatric estimates, costs are closely related to mass of intrsument, higher mass = more costly to launch	10 = Cheap, easy to manufacture 5 = Cheap, but costs are justified 1 = Extremely Expensive, greater than budget constraint	35%	10	8	9
Power Consumption	Wattage of instrument, efficient power consumption is integral for performance (e.g., thermal management, instrument lifespan)	10 = Not a signifianct impact towards total vehicle power budget 5 = Slight impact 1 = Significant impact 0 = Exceeds vehicle power consumption constraints	20%	10	8	4
Volume	In cubic centimeters; volume is an essential criteria to stay within customer's constraints	10 = Relatively small, with no sacrifice to performance 5 = Average in size, doesn't take up significant % of vehicle size 1 = Relatively large, doesnt not fit w/in the scope of vehicle size 0 = Simply too large given custom constraints	25%	10	8	2
Calibration Time	Spectrometers have to be calibratied in order to conduct good science, how many calibration tasks are needed to done before taking measurements. Generally more tasks = more time	10: Takes little time to calibrate (small # of tasks) 5: Takes a medium amount of time 0: Many tasks, a lot of time towards calibration	20%	4	8	8
		TOTALS:	**100%**	88.00%	80.00%	60.50%

Temperature Sensor

Criteria	Explanation	Grade	Weight	Chandra's Surface Thermo physical Experiment (ChaSTE)	Thermal IR Sensor aboard Mars Environmental Dynamics Analyzer (MEDA)	Europa Thermal Emission Imaging System (E-THEMIS)
Volume	In cubic centimeters; volume is an essential criteria to stay within customer's constraints	10 = Relatively small, with no sacrifice to performance 5 = Average in size, doesn't take up significant % of vehicle size 1 = Relatively large, doesnt not fit w/in the scope of vehicle size 0 = Simply too large given custom constraints	15%	4	9	7
Cost	Using paramatric estimates, costs are closely related to mass of intrsument, higher mass = more costly to launch	10 = Cheap, easy to manufacture 5 = Cheap, but costs are justified 1 = Extremely Expensive, greater than budget constraint	30%	10	9	4
Temperature Range	Defines the sensitivity of the sensor, whether or not it can measure the temperatures that are constrained in STM	10 = Falls w/in temperature range requirements 5 = Falls w/in temperature range but is short +/- 20 K 1 = Does mot meet temperature range requirements	30%	3	7	6
Power consumption	Wattage of instrument, efficient power consumption is integral for performance (e.g., thermal management, instrument lifespan)	10 = Not a signifianct impact towards total vehicle power budget 5 = Slight impact 1 = Significant impact 0 = Exceeds vehicle power consumption constraints	25%	4	6	4
		TOTALS:	100%	55.00%	76.50%	50.50%

1.5.7. 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.

Mechanical Subsystem

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. When it comes to the wheels, having spare wheels on hand that can be easily swapped out can be useful. In addition, it can also be helpful to have a tire repair kit so that wheels can be patched up due to surface damage or inflated if any punctures occur. 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 source can be helpful 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.

Power Subsystem

Overall, the main idea for the power subsystem is to use solar panels. This can come with some recovery and redundancy measures. Solar panels may potentially break or malfunction. To prevent this, automated cleaning systems can help remove any debris on top of the solar panels that may accumulate over time. This way, the solar panels' energy efficiency would be reduced. In addition, there can also be a backup battery that could hold energy in case of solar panel malfunction or when there is a low level of light.

Thermal Management Subsystem

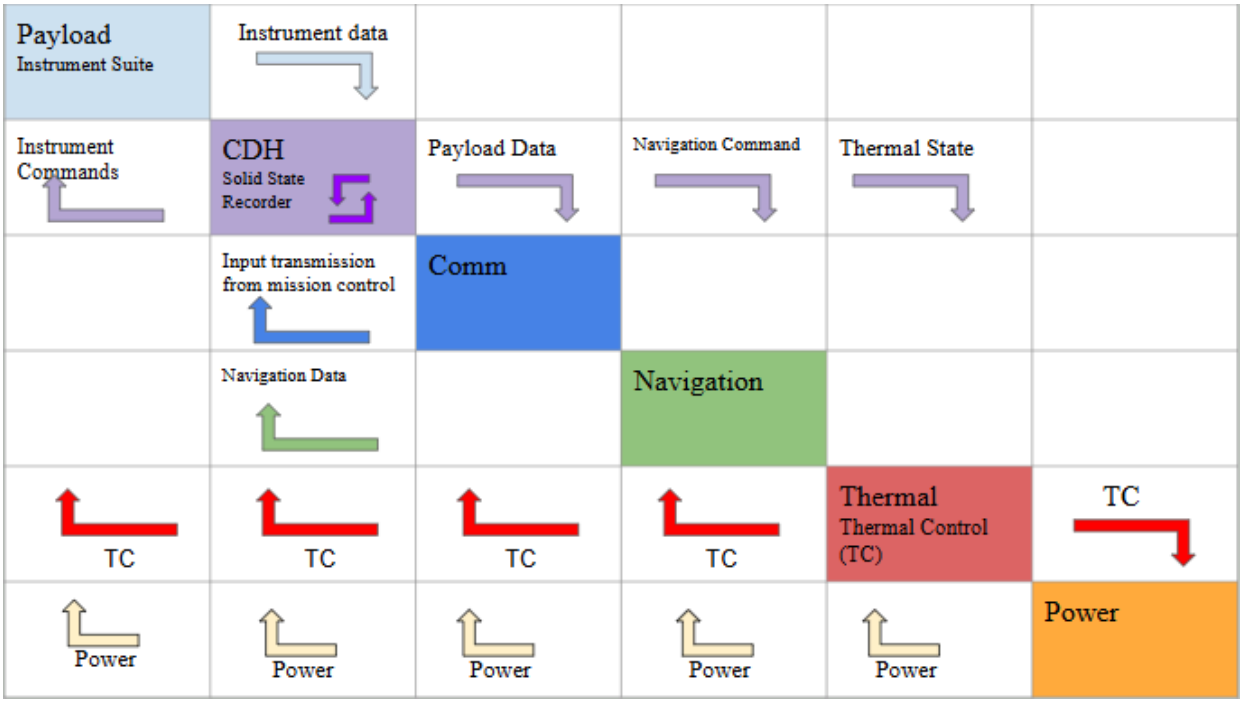
Thermal management is imperative for maintaining optimal temperatures. Ideas for redundancy would include backup radiator panels and thermal blankets that can help retain heat in emergencies. There can also potentially be chambers created for emergency heating storage to prevent overheating.

Payload Subsystem

In regards to the payload subsystem, being able to recover from potential malfunctions concerning temperature sensors and spectrometers can be important. If the potential issue is within these units, having backup detectors and shielding for environmental protection can be helpful.

1.5.8. Interface Control

N^2 Chart

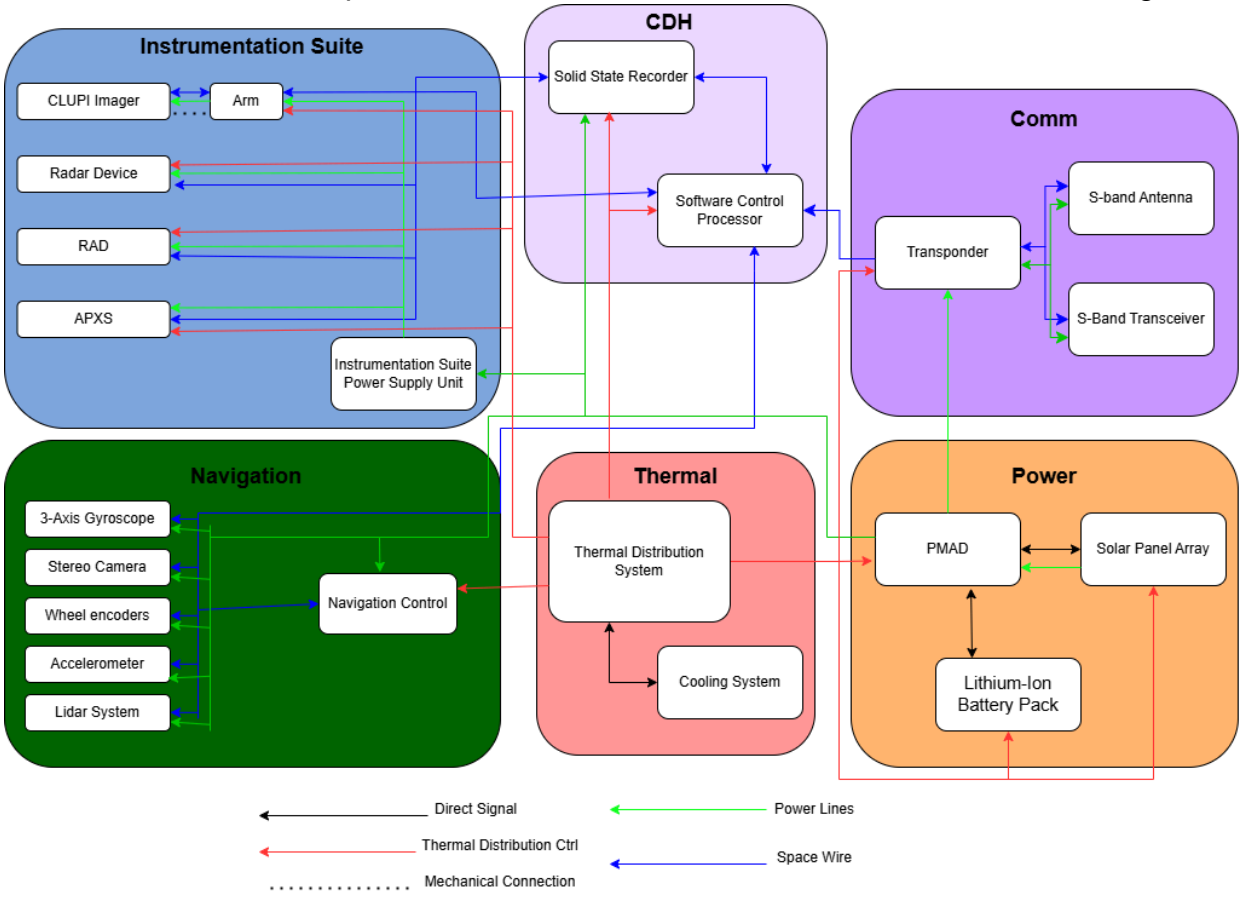


The MTP rover comprises 6 subsystems: Payload, Command & Data Handling (CDH), Communications, Navigation, Thermal Control, and Power. The N^2 diagram outlines high-level relationships between various subsystems. The power subsystem enables the operation of all other subsystems, as indicated by the yellow 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.



1.6. Risk Analysis

To identify and manage risks across the spacecraft's primary subsystems, including mechanical, power, command, and data handling (CDH), thermal, and instrumentation, the team has employed a systematic approach during the design process. On a scale of 1 to 5, each identified risk is defined by its likelihood (L) and consequence (C). A trend with arrows indicates whether the risk level is rising, falling, or staying the same. We established mitigation techniques for every risk to handle any possible effects due to the failure or malfunction of the systems. In order to adjust to new developments, the team will regularly monitor and update this risk profile throughout the project. This will ensure each subsystem has a controllable and defendable degree of risk for project succession.

The team has used a combination of historical data examinations and predictive analysis approaches to foresee possible risks. Risks were assessed according to how they would affect the mission's success, with an emphasis on mitigating errors. The team has also evaluated the cost-effectiveness and viability of mitigation strategies, acknowledging that missions with smaller budgets might take on greater risks in particular domains.

Risk Matrix:

1	Power	3	4	↑	M	Accumulation of dust reduces solar panel efficiency by about 50% which impacts power generation	Active
2	Power	2	5	→	M	Extreme lunar weather conditions (coldness) reduce lithium-ion battery capacity, which increases the risks of insufficient power at night	Active
4	Thermal	3	3	↑	M	Passive insulation (MLI) may degrade with time caused by lunar temperature cycling which leads to loss of thermal protection	Active
6	Thermal	3	4	↑	M	Thermal straps may undergo reduced heat transfer efficiency which impacts the overall thermal regulation within the rover	Active
7	Communication	3	5	↑	M	The rovere may experience difficulty in establishing stable connection with the satellite within the required range	Active
8	Communication	2	4	→	A	Communication frequency or power may be too low/small to penetrate lunar terrain, causing issues with data transfer	Active
11	Budget	4	4	↑	M	Personnel costs may come out higher than expected due to inflation or increased staffing needs which	Active

						may exceed the project budget	
15	Mechanical	3	4	↑	M	The system may exceed 2m × 1.25m × 1.25m which impacts storage and transportation	Active
17	Mechanical	3	3	↑	M	The inability to recover from an upside position may cause immobility	Active
21	Mechanical	4	5	↑	M	T,ether may fail to support system weight increasing risk of vehicle fall or loss,	Active

Risk Mitigation Strategies:

- Power Subsystem:
    - The risk of dust accumulation on solar panels will be addressed by adding a mechanical dust removal and anti-dust coating that will be used to clean the panels on a regular basis. Efficiency will be tracked, and cleaning frequency will be adjusted through ongoing monitoring. In terms of extreme coldness and battery, insulating batteries and providing brief warmth during low-temperature cycles will help reduce capacity loss. In order to prevent power shortages, power simulations will take night requirements into account.

- Thermal Subsystem:
    - To ensure the insulation layers can tolerate anticipated temperature ranges, routine inspections and pre-mission thermal cycle tests will be implemented. Additionally, real-time monitoring in conjunction with materials for thermal straps that are more resilient to temperature changes could aid in finding efficiency losses early on.

- Communication Subsystem:
    - Signal boosters and additional power for communication will help keep connections steady within the necessary range. In the event that the primary system fails, backup communication systems are prepared. As for terrain-related communication barriers, placing relay stations at strategic points will facilitate more reliable data transfer, and signal testing will identify the best communication frequencies.

- Mechanical Subsystem:
    - Modifications to the component arrangement and compact design decisions will keep the stowed configuration from going over available space. The system will be subjected to regular dimension assessments throughout the design process. The rover will be able to continue operating after rolling over because of improved suspension and shock-absorbing parts, and automatic recovery procedures will help it start up again. The tether system will be tested for maximum bed capabilities with sizable safety margins to ensure it can sustain the weight

of the complete system under adverse circumstances.

1.7. Programmatics

1.7.1. Team Organization

For developing a mission concept at such a high level, high productivity, effective collaboration, and organization will be crucial and essential to the team's success in this mission. Starting with delegating the workload, the team will do its best to ensure all work is distributed evenly and fairly throughout. Furthermore, the team will check in with each member to ensure that there are no problems working on the assigned section or task.

Team Members	Primary Roles	Availability (hours/week)	Preferred working time
Abhijith Ajit	Thermal Engineer	**2-3**	**Night**
Mihir Bhagat	Scientist	**6-10**	**Night**
Chiharu Mamiya	Program Analyst	**4-7**	**Morning/Afternoon**
Sophya Elkihel	Electrical Engineer	**2-6**	**Evening/Night**
Adriana Gaitan	Chief Scientist	**3-5**	**Night**
Elizabeth Howard	Electrical Engineer	**2-7**	**Night**
Krish Mehta	Thermal Engineer	**4-8**	**Afternoon/Night**
Vedarsh Mishra	Project Manage	**7-9**	**Afternoon/Night**
Anirudh Ram	Deputy Project Manager of Resources	**5-8**	**Evening/Night**
Josh Sar-Shalom	Computer Hardware Engineer	**4-5**	**Afternoon/Night**
Gwendolyn Seto	Mission Assurance Specialist	**3-5**	**Evening/Night**
Kevin Subin	Mechanical Engineer	**3-5**	**Night**
Mason Thaochuetoua	Mechanical Engineer	**2-6**	**Night**
Tanya Vijay	Lead Systems Engineer	**7-10**	**Morning/Night**
Liliana Z.	Outreach Officer	**2-5**	**Afternoon/Night**

In addition, the workload distribution will also be based on each member's role. Assigning roles that are best suited for each specific team member will be decided based on the strengths and experience of each individual.

Members will also provide updates on progress with the assigned tasks and communicate about completing or any struggles with the designated position. Additionally, at least one team meeting each will be placed into the schedule so that everyone is up to date with everything that needs to be worked on.

Mandatory team meetings are held every Monday from 9 to 11 PM EST based on availability surveys to review key updates, address challenges, and align on upcoming deliverable deadlines. In addition to mandatory meetings, regular working sessions are scheduled throughout the week based on availability data collected from the When2Meet surveys. Members' availability and capacity will be re-assessed weekly using the meeting turnout from previous weeks. Attending these working sessions is not mandatory, but team members are encouraged to join. Each team member must participate in at least one weekly working session.

When the team assigns each member a task to work on during the week, allocating these tasks to their respective individual will be listed on a Google document and Google sheet for the required parts of the mission concept. Each member will update this Google document or sheet when it's completed. Throughout this project, different opinions will be expected. This will be discussed respectfully, and the entire group will assess all the pros and cons to make a decision that aims toward a consensus among the whole group. If needed, the team will seek guidance and advice from the assigned team mentor. Time-sensitive decisions are also expected to happen, and in these cases, every team member will meet and discuss the best way to move forward, given that everyone puts some input into making a collective decision.

This brings up the point that though delegation of the workload is essential, the team has a collective understanding that it's vital to help each other during the entire mission concept development to reduce being overworked and overwhelmed. The team has already agreed that everyone will empathize with each person's situation and understand that there will be differences in ideas and opinions. Moving forward, these situations will be handled well-mannered and respectfully, and everyone's ideas and opinions will be heard. This will allow for open discussion and allow for everyone to contribute and give some input to the team. If conflict within the team arises, efforts will be taken to discuss it in a civilized manner to resolve it, and if needed, will bring up these issues to the team mentors and student advisors.

Finally, with the implementation and consistency of good team organization, the team is ready to carry out this project with driven commitment and good collaboration.

However, there may be some areas where the team will need some guidance. In cases like this, the team plans to seek advice and guidance from mentors or specific role mentors to gain insight on what can be done with the particular part the team is struggling with. The member seeking guidance will update the team on what was explained to keep the whole team informed.

1.7.2. Cost Estimate

This section overviews the rough cost estimate for a discovery class mission with a budget of $425 million and a launch readiness date of March 1st, 2030. A rough cost estimate is sufficient as these estimates need to be further refined.

With every mission comes costs associated with travel, personnel, and outreach. As a rough estimate, expenses related to travel and outreach shall be at most 1% of the aggregate mission cost. This ensures that most of the funding is allocated to critical mission components, such as surface operations, scientific instrumentation, and mission operations. As a result, travel expenditures (i.e., flights, hotels, and other necessary accommodations) and outreach (i.e., workshops, literacy campaigns, and seminars to promote the education of the mission's science objectives) amount to approximately $8.5 million.

Personnel costs are derived from a projected team size consisting of several Scientists, Engineers, Technicians, Administrators, and Managers, all across the different Phases of the mission. Travel costs are calculated based on factors such as average flight costs, gas mileage/rental fees, and general costs associated with necessities. Outreach costs are based on expected modes, including demos, talks, summer programs, internships, scholarships, and university-wide events. Additionally, the team will maintain cost margins to address unforeseen technical challenges and risks.

	Phase A-B	Phase C	Phase C-D	Phase D	Phase E	Phase F	Total Cost Per Phase
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 Cost	$ 4,402,406	$ 7,440,588	$ 9,332,418	$ 10,673,885	$ 5,522,289	$ 5,833,854	**$ 43,205,441**

	Phase A-B	**Phase C**	**Phase C-D**	**Phase D**	**Phase E**	**Phase F**	**Total Cost Per Phase**
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**

	Phase A-B	**Phase C**	**Phase C-D**	**Phase D**	**Phase E**	**Phase F**	**Total Cost Per Phase**
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**

Preliminary Cost Breakdown:

Since the mission budget only covers post-landing activities, the cost estimate reflects surface operations and scientific exploration phases. The NASA Cost Estimation handbook and the L'SPACE Project Management Skill Module outline the cost structure for a general Discovery Class Mission. The specific mission cost structure is organized as follows:

Cost Category	**Estimated Cost ($M)**	**Percentage of Total Budget**

Project Management and Systems Engineering	35	8%
Surface Vehicle Development	130	31%
Scientific Instruments and Payload Development	60	14%
Mission Operations (Surface)	40	9%
Ground Data Systems and Communications	25	6%
Testing and Analog Research	10	2%
Travel and Logistics	5	1%
Outreach, Education, and Public Engagement	5	1%
Contingency (15%)	63.75	15%
Total Estimated Mission Cost	425	100%

Rationale for Cost Allocation:

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. Below is a detailed explanation for each cost category and the rationale for the budgetary allocation:

Project Management and Systems Engineering ($35M, 8%):

- Includes costs related to mission oversight, planning, and risk management. Project management ensures that all mission components are aligned with the goals and constraints. Systems engineering focuses on integrating all systems, verifying requirements, and managing technical risks, which are essential for a complex mission involving lunar pit exploration. Similar costs were seen in LADEE, where systems engineering was critical in managing the mission's limited resources.

Surface Vehicle Development ($130M, 31%):

- As one of the most significant cost drivers, this category includes designing, developing, and testing a surface vehicle that can safely navigate and explore the Mare Tranquillitatis pit. Due to the pit's challenging terrain and environmental conditions, this vehicle must have advanced descent and mobility systems,

power management, and a thermal control system to survive extreme lunar temperatures.

Scientific Instruments and Payload Development ($60M, 14%):

- This category includes the cost of scientific instruments necessary to achieve the mission's objectives. Instruments like high-resolution cameras, ground-penetrating radar (GPR), seismic sensors, and thermal and radiation detectors are essential for characterizing the pit's geology, subsurface structure, and environmental conditions.

Mission Operations (Surface) ($40M, 9%):

- Covers all activities related to surface operations, including command and control, data collection, and troubleshooting. It encompasses mission control personnel, rover operations, and scientific data analysis for the mission's duration.

Ground Data Systems and Communications ($25M, 6%):

- Covers the development and maintenance of ground communication systems, including data transmission infrastructure, relay station support, and secure data storage. Since the lander and rover will communicate through an orbiting relay satellite, this category ensures continuous communication for real-time command and data acquisition.

Testing and Analog Research ($10M, 2%):

- As part of NASA's risk mitigation strategy, the mission requires extensive testing in analogous environments. This includes drop testing at the NASA Glenn Zero Gravity Research Facility and analog research at Black Point Lava Flow in Arizona, which resembles the terrain of lunar pits.

Travel and Logistics ($5M, 1%):

- This budget covers team travel for system testing, reviews, and key decision point (KDP) meetings. Major travel events include system integration at NASA facilities and participation in the launch readiness reviews at Cape Canaveral, following the NASA City Pair Program for travel and lodging to minimize costs.

Outreach, Education, and Public Engagement ($5M, 1%):

- While a more minor component, this allocation ensures that the mission actively engages the public, provides educational content, and disseminates scientific results. Outreach is crucial for maintaining public interest and support for lunar exploration missions.

Contingency ($63.75M, 15%):

- This category is set aside to address unforeseen technical, operational, or environmental challenges. Given the complexity of pit exploration, a 15% contingency is appropriate to account for potential delays or design changes.

1.7.3. Schedule Estimate

The mission will begin in January 2025 and last approximately 4 to 4.5 years, following NASA Mission Lifecycle Phases C-F from detailed design to mission closeout.

Phase 1: Preliminary Design and Systems Engineering (January 2025 – December 2025)

The mission starts with Phase 1, which focuses on preliminary design and systems engineering tasks. The team will complete initial design reviews, choose scientific instruments, and finalize the mission architecture. By July 2025, the Preliminary Design Review (PDR) will confirm that the mission design satisfies the necessary standards. The mission concludes in December 2025, which marks the transition from NASA Lifecycle Phase B to Phase C.

Phase 2: Development and Testing (January 2026–June 2027)
Development and Testing The mission will enter the development and testing phase in Phase 2, during which the scientific payload and surface vehicle will be assembled, tested, and manufactured. In order to ensure that the final design satisfies all mission criteria, the Critical Design Review (CDR) is planned for June 2026. After development and environmental testing, final assembly and testing will start in April 2027. This phase is anticipated to conclude in June 2027, marking the completion of NASA Phase C and the beginning of Phase D.

Phase 3: Integration and Launch Readiness (July 2027–December 2027)
Phase 3 includes preparing the mission for launch; testing, integration, and final vehicle assembly are planned between July and December 2027. The vehicle should be

prepared for launch by December 15, 2027. After a successful launch, this phase brings NASA Phase D to a close and moves the mission into the operational phase.

Phase 4: First Surface Activities (January 2028)
After launch, the spacecraft will land on the moon by around January 10, 2028. Deployment, system inspections, and connection with Earth will be among the first activities, which should be finished by January 15, 2028. NASA Phase E, which marks the start of operational activities on the lunar surface, begins during this one-month timeframe.

Phase 5: Operations for Primary Science (January 2028–December 2028)
The principal science goals of the mission will be carried out in Phase 5. The crew will carry out core research, such as environmental measurements and geological mapping, for a duration of 12 months. Mission progress and accomplishments will be assessed through quarterly science reviews in April, July, and October 2028. The mission team will evaluate the vehicle's condition and suitability for longer-term operations once primary science missions end in December 2028.

Phase 6: Extended Science Operations (January 2029–June 2029)
Phase 6 will enable prolonged science operations in other areas of scientific interest if the vehicle continues functioning. In March 2029, there will be a mid-point assessment during this six-month phase to evaluate mission accomplishments and make any necessary target adjustments. By June 2029, the mission is expected to be completed, and it will go into Phase F for decommissioning and closeout procedures.

In accordance with NASA Mission Lifecycle Phases C–F, this mission timetable, which runs from January 2025 to June 2029, ensures that important dates like the beginning of Phase C, the launch date, and the arrival on the lunar surface are clearly included in the timeline. Within the Discovery-Class framework, the organized phases and milestone reviews will maximize scientific return, facilitate stakeholder alignment, and give project management clarity.

1.7.4. Change Control

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 review, 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 usually initiated by a sub-team member, who reports a change request to the team lead. The team member proposing the changes is responsible for creating a formal change request, outlining 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.

Once a change request is submitted and the scope of the change request is assessed, the team leads organize a meeting to discuss further and review the proposed changes. The review process would include an impact analysis to assess how the change will affect the mission's objective, costs, timeline, and interaction with other subsystems. A feasibility check is performed to ensure the change is possible given current resources and constraints, followed by a risk assessment to identify any new risks introduced and potential mitigation strategies.

If the change is approved, an action plan is developed to implement it. The plan details task assignments, updated timelines, and the allocation of any additional resources needed. Team leads oversee the implementation, ensuring all affected team members are informed and prepared to adapt their work. Changes are tracked using a centralized change log or project management tool, including a detailed description of the change, its reason, status updates, and the team members responsible for its execution. Progress on the change is communicated through regular updates in meetings and via sub-team discord channels. This communication ensures the entire team stays informed and aligned on managing changes.

Once the change has been fully implemented, a review is conducted to confirm that it meets the intended objective and integrates smoothly with other mission components. Document the outcome and integrate smoothly with other mission components. Documentation of the outcome and any lessons learned or necessary adjustments made during the process are shared with the team to inform further session-making.

1.8. Conclusion

This System Requirements Review overviews the top-level requirements for subsystem design for a discovery class mission to the lunar pit Mare Tranquillitatis. The systems and subsystems are derived from the science objectives. Trade studies were used to identify the critical aspects that the mission will utilize to close out the mission with all science objectives completed. Several sections were derived from the Mission Concept Review (MCR) and updated in this document, including STM, cost estimate, schedule estimate, etc. If extra time were allocated towards developing the SRR, the team would use the time to define instrumentation requirements more succinctly and

further refine the overall requirements that the mission needs to successfully carry out the science objectives.

The next milestone for the team is the Mission Definition Review (MDR). Plans for this document include drafting a plan outlining the responsibilities of each sub-team and its members. Sections will be broken down into fundamental parts and assigned to each team member. Members will communicate more effectively to provide a holistic and complete mission definition in the next milestone.

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