Mission Definition Review (MDR)

Mission Concept Academy

L’SPACE Team 19

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Table of Contents

a. Abbreviation Index 4

1. Mission Definition Review 5-57

1.1. Mission Statement 5

1.2. Science Traceability Matrix 5-10

1.3. Mission Requirements 11-12

1.4. Concept of Operations 12-14

1.5. MCA Team Management Overview 14-16

1.6. Project Management Approach 16-19

1.7. Manufacturing and Procurement Plans 19-22

1.8. Risks and Safety 23-32

1.8.1. Risk Analysis 23-28

1.8.2. Failure Mode and Effect Analysis (FMEA) 28-31

1.8.3. Personnel Hazards 31-32

1.9 Schedule 32-37

1.9.1. Schedule Basis of Estimate 32-34

1.9.2. Mission Schedule 34-37

1.10 Budget 37-45

1.10.1. Budget Overview 37-38

1.10.2 Budget Basis of Estimate 38-39

1.10.3. Personnel Budget 39-41

1.10.4. Travel Budget 41

1.10.5. Outreach Budget 42-43

1.10.6. Direct Costs 44-45

1.11 Scope Management 45-49

1.11.1 Change Control Management 45-48

1.11.2. Scope Control Management 48-49

1.12. Outreach Plan 49-52

1.13. Conclusion 52

2. Bibliography 53-57

A. 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. Mission Definition 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. Instruments such as radiometers and thermal sensors will characterize the thermal environment by measuring temperature fluctuations and stable zones. Structural integrity will be evaluated using LiDAR and ground-penetrating radar (GPR) to identify cracks or weaknesses in the pit walls and overhangs. Radiation levels will be assessed using a radiation detector to quantify potential exposure risks. A spectrometer will be utilized to analyze resource availability, such as the presence of volatiles like water and hydrogen, while subsurface composition will be studied using GPR and imaging tools. This data will directly contribute to evaluating the pit's ability to serve as a habitat, with minimal need for artificial environmental regulation. Understanding radiation shielding capabilities and stable temperature zones will also be crucial for assessing the site's suitability for human protection.

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 misson's budgetary and technical constraints

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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. 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	Necessary Condition to	NC- 2.0	-	Inspection	All subsystems	Not Met

	outlined by NASA-STD-8-719.27 and NPR 8715.24.	complete the mission					
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

1.4. Concept of Operations

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

To effectively satisfy all objectives and requirements of this mission [See Science Traceability Matrix], the system architecture will take the form of a Robotic, All-Terrain Rover. The rover will be encapsulated in a thermally shielded compartment of the entry vehicle and will be released upon successful surface touchdown.

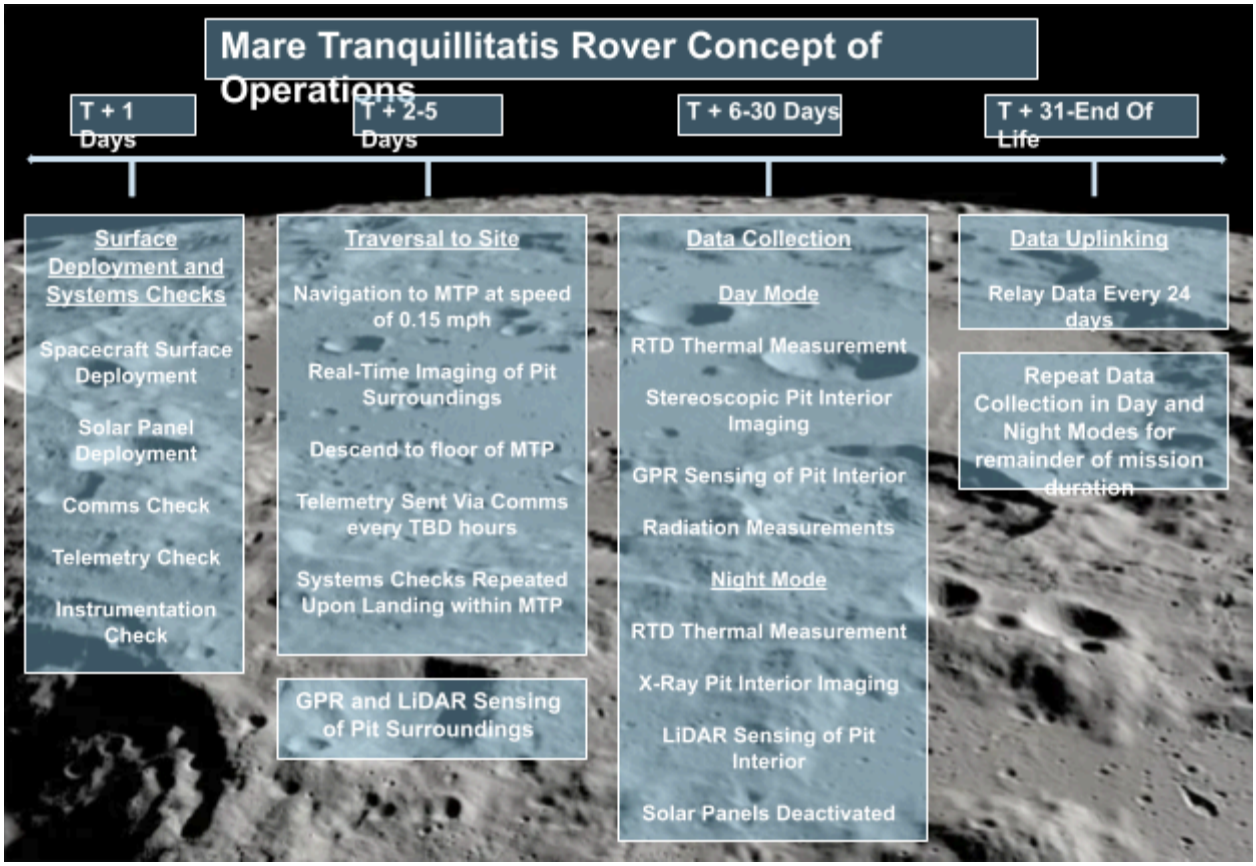
During the launch, travel, and descent stages before the start of the mission, the system will receive auxiliary power from the primary launch vehicle to keep essential systems active. Upon separating from the primary vehicle at the landing site during the surface deployment stage, the system will be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

In the next two to five days, the rover will traverse to the mission location. During traversal, the rover will not exceed speeds of 0.15 mph or 0.24 km/h as per requirement MEC.06. During traversal, the rover will begin real-time imaging of the surface surrounding MTP in order to discern major geological and topographic features of the surrounding region. The rover will also use onboard Ground Penetrating Radar (GPR)

and Light Detection and Ranging (LiDAR) technology to construct models of the surrounding region on the lunar surface and to determine if there are any other lunar lava pits or lava tubes underneath the lunar surface within close proximity to MTP. During the traversal stage, telemetry data will be relayed back to ground operations with a frequency that is to be determined. Upon reaching MTP, the rover will descend into the lunar lava pit and land on the floor of the pit. In order to ensure that the vehicle did not sustain any damages during the traversal and descension stages, the rover will repeat systems checks of communication and telemetry software as well as payload instrumentation.

In the next 24 days, the rover will commence science operations and data collection. The science operation stage is divided into operations to be conducted during the lunar day as opposed to night. During the day, the rover will utilize its Resistance Temperature Detector (RTD) to measure thermal variation within the pit to begin constructing a thermal mapping of the interior of the pit. Secondly, the rover will utilize its Stereoscopic Camera to capture images to begin assessing the structural composition and layout of the interior of the pit. Thirdly, Ground Penetrating Radar will be utilized to determine the structure of the interior of the pit as well as the structure of other lava pits beyond the walls of the pit. The rover will also use a spectrometer to measure the environmental characteristics of the atmosphere of the interior of the pit. Finally, the rover will utilize a UV Radiometer to begin measuring radiation levels within the pit. During the night, the rover will cease power supply to the latter three of the four previously mentioned instruments but continue to perform thermal measurements of the interior of the pit to determine the varying surface temperatures and sunlight levels that ffect temperatures within the pit. During night mode, the rover will utilize an X-ray camera to perform analyses of cracks within the walls of MTP. Secondly, LiDAR will be used to continue analyzing the structure of the interior of the pit. In order to conserve power usage, solar panels will be deactivated during night mode.

Upon completion of this 24-day science operation stage, data will be uplinked to be relayed to the ground station. Upon successful transfer of data, the rover will return to the science operation stage. This cycle will continue to repeat until the rover’s end of life. After descending into MTP in the Traversal stage, the rover will not exit the pit for the remainder of the Mission timeline. Any further traversal required will only be within the volume of the pit itself.



1.5. MCA Team Management Overview

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

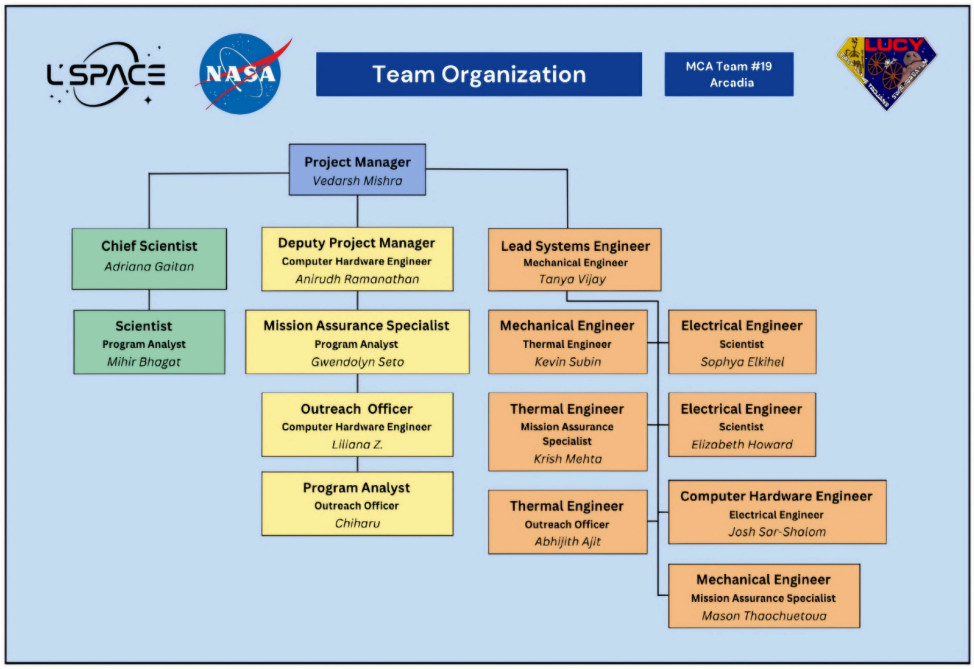
A mission of such specification requires a multidisciplinary team with specialized skills. Mechanical Engineers with expertise in CAD are essential for designing the chassis and structural components to house the mission's elements. Electrical Engineers must develop reliable power systems to ensure a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

Outreach Officers are required to publicize the mission's purpose and provide updates throughout its lifecycle.

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

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

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



1.6. Project Management Approach

The successful execution of the mission objectives for the exploration and evaluation of Mare Tranquillitatis Pit (MTP) requires an extended team beyond the Academy personnel. An estimated 25–30 additional personnel are necessary, covering expertise in engineering, science, operation, and programmatic roles. Each subteam will address specific mission components with clear responsibilities, ensuring alignment with the mission's technical and scientific objectives.

Personnel and Roles

1. Engineering Division
    - Mechanical Subteam:
        - Focus: Design and testing of rover components, including the chassis, mobility systems, and robotic arm.
        - Skills: CAD modeling, materials engineering, structural design, and mobility integration.
        - Team Size: 4–5 engineers.
    - Thermal Subteam:
        - Focus: Development of systems to regulate spacecraft

temperatures in extreme lunar conditions.
        - Skills: Heat transfer analysis, insulation design, and active thermal control.
        - Team Size: 3–4 engineers.
    - Electrical and Power Subteam:
        - Focus: Design of solar panels, battery systems, and power distribution systems.
        - Skills: Solar array design, energy storage optimization, and fault isolation.
        - Team Size: 3–4 engineers.
    - Command and Data Handling (CDH) Subteam:
        - Focus: Management of onboard computing, telemetry systems, and data storage.
        - Skills: Software development, telemetry protocols, and systems integration.
        - Team Size: 3–4 engineers.
2. Science Division
    - Planetary Geology Subteam:
        - Focus: Analysis of the MTP environment, including geological mapping and pit stability.
        - Skills: Remote sensing, geological analysis, and surface characterization.
        - Team Size: 4 scientists.
    - Instrumentation and Data Analysis Subteam:
        - Focus: Operation of spectrometers, radiometers, and other instruments to collect and analyze mission-critical data.
        - Skills: Instrument calibration, data modeling, and interpretation.
        - Team Size: 4–5 scientists.
3. Verification & Validation (V&V) Division
    - Focus: Ensuring all systems meet mission requirements through testing and quality assurance.
    - Skills: Failure analysis, system integration, and subsystem validation.
    - Team Size: 3 engineers.
4. Operations Division
    - Focus: Management of spacecraft activities post-launch, including telemetry monitoring and data collection scheduling.
    - Skills: Mission planning, satellite navigation, and anomaly resolution.
    - Team Size: 5 specialists.
5. Programmatic Division

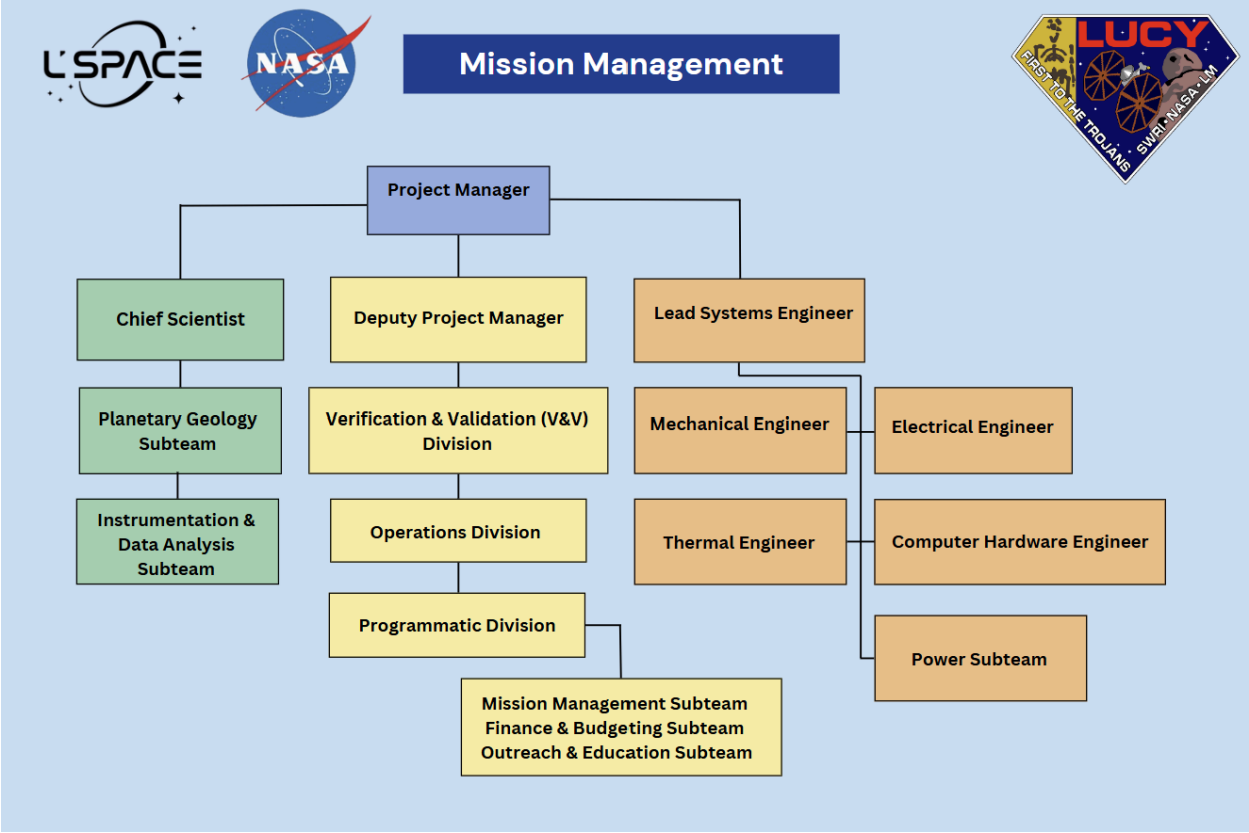
- Mission Management Subteam:
  - Focus: Oversight of mission planning, risk management, and resource allocation.
  - Skills: Leadership, decision-making, and communication.
  - Team Size: 2 program managers.
- Finance and Budgeting Subteam:
  - Focus: Budget tracking and financial management.
  - Skills: Cost estimation, financial planning, and reporting.
  - Team Size: 2 finance specialists.
- Outreach and Education Subteam:
  - Focus: Public engagement and educational content creation.
  - Skills: Marketing, content development, and public speaking.
  - Team Size: 3 specialists.

Team Structure and Responsibilities

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

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

Organizational Chart



1.7. Manufacturing and Procurement Plans

Part/Assembly	Supplier (Contractor/COTS/ In-House)	Estimated Lead Time	Justification
Chassis, Masthead, Robotic Arm: 2000 series Aluminum	In-House @ Jet Propulsion Laboratory	3 years	JPL manufactured the chassis for the Mars Perseverance rover.
Superelastic Tires (nickel-titanium shape memory alloy springs)	In-House @ Glenn Research center	2 years	Superelastic Tires are still being researched by NASA and currently have a TRL of 4. It is likely that more time will be required before manufacturing.
LR-450 Inertial Measurement Unit (IMU)	Contractor: Northrop Grumman	3 months	Supplied by a trusted provider for planetary and deep space missions. LR-450 IMU is resistant to variable radiation levels to be expected within the lunar pit, and has a low weight and power draw. A short lead time can be expected

			since production began in 2023.
Robotic Arm Internal Gears: bulk metallic glass	In-House @ Jet Propulsion Laboratory (JPL)	TBD	Bulk Metallic Glass gears are already being developed through the BMGG Project.
LED Headlights	Contractor: Sierra Space Backup: Leidos	2 months	TRL 9. Low mass and power draw. A short lead time can be expected since Sierra Space has demonstrated short lead time in previous solar array solutions for a 2016 project with the Air Force Research Laboratory. Leidos is also developing external spacecraft lighting, but may have longer lead times since the project is still in the R&D stages.

Part/Assembly	Supplier (Contractor/COTS/ In-House)	Estimated Lead Time	Justification
Gallium Arsenide (GaAs) solar cells	Contractor: Spectrolab (Subsidiary of Boeing)	2 years	Spectrolab manufactured the GaAs solar cells for the Spirit and Opportunity rovers. They are capable of withstanding variable radiation levels and thermal extremes.
Lithium Ion Batteries	Contractor: EaglePicher Technologies	3 years	Yardney Technical Products (now under EaglePicher Technologies) manufactured Lithium Ion batteries for Curiosity and Perseverance rovers. Lead time for Mars rovers was around 5 years, however, a shorter lead time can likely be expected due to a higher TRL.
PMAD	In-House @ Jet Propulsion Laboratory	TBD	JPL managed integration and testing of power sources for Perseverance Rover.

Part/Assembly	Supplier (Contractor/COTS/ In-House)	Estimated Lead Time	Justification
VxWorks Real Time Operating System	COTS: Wind River Systems	6 Weeks	Industry standard for operating systems. Reliable and proven efficient
Rad-Hard CPU (RAD750)	COTS: BAE	1.5 Years	The RAD750 is the current processor

	systems		used on perseverance, and BAE system is there manufacturer and supplier to NASA
Rad-Hard DRAM	COTS: Renesas electronics	4 months	They've been supplying NASA with Rad-Hard ICs along side BAE systems
S-band Antennas and Transceiver	Contractor: Lockheed Martin	5 months	Lockheed specializes in defense and communication with various systems

Part/Assembly	Supplier (Contractor/COTS/ In-House)	Estimated Lead Time	Justification
Multilayer insulation (MLI): Metallized polyimide film	In-House: Goddard Space Flight Center	3 months	NASA has developed and used Multilayer Insulation (MLI) for its spacecraft, such as the James Webb Space Telescope and different Artemis missions. The metallized polyimide film used by NASA has been tested.
Copper thermal straps	In-House: Goddard Space Flight Center	5 months	NASA specialized in thermal designs and has been used in spacecraft such as the James Webb Space Telescope and the Mars Rovers. Their thermal management expertise ensures that copper straps meet space-grade standards, including flexibility and high reliability under vibration. Goddard also specialized in spacecraft thermal management
Radiator	In-House @ Jet Propulsion Laboratory (JPL)	4 months	JPL designs radiators for harsh environments and have been operated in such missions. This will be needed for the moon's temperature fluctuations
Heat Pipes	In-House @ Glenn Research center	4 months	GRC's heat pipes are designed for high-performance and efficient thermal control in space applications. These have been tested and validated.
Thermal Louvers	In-House @ Glenn Research center	4 months	GRC has designed and developed louvers for various space missions. These include satellites and space

			stations
Electrical Heaters	In-House @ Glenn Research center	5 months	GRC specializes in custom electrical heaters for temperature regulation in harsh lunar environments.
Mechanical Pump Fluid Loop	In-House @ Glenn Research center	5 months	GRC's mechanical pumps have been used in several NASA missions, including spacecraft and satellite applications.

Part/Assembly	Supplier (Contractor/COTS/ In-House)	Estimated Lead Time	Justification
Resistance Temperature Detector	In-House @ Glenn Research center	5 months	GRC has experience in designing these detectors for spacecraft thermal management systems.
Stereoscopic Camera	In-House @ Jet Propulsion Laboratory	5 months	JPL developed the stereoscopic cameras used in Mars rovers and has high resolution.
X-ray Camera	In-House: Goddard Space Flight Center	6 months	GSFC has developed several advanced X-ray cameras for missions
Space Qualified Rover Lidar (SQRLi)	In-House @ Goddard Space Flight Center	2.5 years	Project is in progress right now and is projected to end in 2026 with a TRL of 8. Manufacturing for space applications will only begin after this point.
Ground Penetrating Radar	In-House @ Jet Propulsion Laboratory	6 months	JPL offers specialized systems made for planetary exploration, and are used on rovers or landers.
Radiation Dosimeter	In-House: Goddard Space Flight Center	5 months	GSFC develops and deploys radiation dosimeters for deep-space missions and are capable of monitoring high radiation.
Spectrometers (SHERLOC)	In-House @ Jet Propulsion Laboratory	1 year	JPL design and manufacturing SHERLOC to operate onboard Perseverance.
UV Radiometer	In-House: Goddard Space Flight Center	5 months	GSFC has developed UV radiometers for Earth observation and planetary exploration missions. They have high reliability and accuracy.

1.8. Risks and Safety

1.8.1. Risk Analysis

Risk management is crucial for complicated space missions in order to handle various difficulties brought on by the hostile lunar environment. The risk management technique presented here depends on NASA's RIDM approach, aiming to systematically identify, analyze, and manage risks across subsystems to assure vehicle and mission success. In addition to focusing on the vehicle system risks that were first noted in the System Requirements Review (SRR), this analysis also takes programming risks, environmental factors, and planetary protection into account. The team wants to make sure that accepted risks, particularly those connected to vital mission activities, have a strong defense even though lower-cost missions can have higher accepted risks. The risk identification procedure, categorization standard, and mitigation techniques created to preserve mission continuity in unpredictable lunar conditions are described in detail in the parts as follows.

Technical Hazards:

Systems integration difficulties represent a major technological risk. When payload components, surface vehicles, and research instruments are combined, incompatibilities may arise that raise assembly costs and delay the process. The mission team will use modular designs to isolate subsystem concerns, carry out several integration dry runs prior to the Critical Design Review (CDR), and develop a comprehensive integration testing strategy prior to the assembly phase in order to address this. Since dependable transmission between the lunar surface and Earth is essential, communication system failures are another urgent concern. Possible hardware issues or signal deterioration could interfere with data flow and compromise mission goals. Relay satellites are used to provide redundant communication channels, thorough testing is conducted under lunar-like circumstances, and backup systems are tested in advance for quick deployment.

Because any mistake in the guidance, navigation, and control (GNC) systems during descent could lead to a crash or a departure from the designated landing location, failures in the propulsion and landing systems also pose a significant risk. In order to combat this, the team will use autonomous navigation algorithms with fail-safe protocols, incorporate extra fuel reserves to account for trajectory corrections, and perform comprehensive GNC simulations under a variety of failure situations. Furthermore, scientific equipment may operate worse if exposed to the lunar

environment for an extended period of time. Accurate data gathering will continue thanks to radiation-hardened materials, routine diagnostics, and the prioritizing of dependable instrument designs.

Risk 1: Difficulties with Systems Integration
Compatibility problems may arise during the assembly process (Departure) due to the complexity of integrating multiple subsystems and scientific instruments (Condition). This could affect the spacecraft's operational functionality (Asset), causing the mission timeline to be delayed and costs to increase (Consequence).
Mitigation These issues will be resolved by multiple integration rehearsals, modular designs to isolate errors and early subsystem testing.

Risk 2: Failure of the Communication System
There is a chance that signal transmission between the spacecraft and Earth will be disrupted (Departure), affecting the communication subsystem (Asset), and making it impossible to receive scientific data or control the vehicle (Consequence) due to the harsh conditions of the lunar environment and possible hardware malfunctions (Condition).
Mitigation: Reliable signal transmission will be ensured via relay satellites, redundant communication channels, and thorough environmental testing.

Risk 3: Failure of the Propulsion and Landing Systems
There is a chance that the lander will stray from its intended descent trajectory (Departure), which could cause instability in the propulsion and landing systems (Asset) and result in an unsafe or unsuccessful landing (Consequence) due to the intricacy of the guidance, navigation, and control (GNC) systems and possible sensor errors (Condition).
Risks will be reduced by improved GNC algorithms, thorough simulation under different failure situations, and extra fuel reserves for trajectory adjustment.

Risk 4: Degradation of the Instrument
There is a chance that sensor accuracy will deteriorate over time (Departure), decreasing the dependability of data gathered by scientific payloads (Asset), and possibly jeopardizing mission objectives (Consequence) due to the extended exposure of sensitive instruments to lunar radiation and temperature extremes (Condition).
Mitigation: Periodic instrument diagnostics, heat protection systems, and radiation-hardened components will maintain functionality.

Programmatic Hazards:

Because unforeseen expenses during development or manufacturing delays could put a burden on financial resources and necessitate a reduction in mission scope, budget overruns pose a key programmatic risk. This will be lessened by setting up a contingency budget of at least 20% and doing frequent financial audits to make sure costs are being met. Schedule slippage, in which delays in one phase could ripple into later phases, endangering the mission timeframe and driving up costs, is another programmatic risk. This risk can be reduced by creating buffer intervals into the plan, conducting regular project reviews, and strictly adhering to milestone deadlines.

Another programmatic difficulty is supply chain disruptions, such as delays or shortages in acquiring vital parts like propulsion parts or microchips. Development, testing, or assembly may be halted by these interruptions. The development process can be kept continuous by diversifying sources, keeping an inventory of necessary components, and creating in-house substitutes for high-risk products. The mission team hopes to accomplish the mission's scientific goals while staying within budget and schedule by taking proactive measures to mitigate these risks.

Risk 5: Overspending
The risk of going over the mission budget (Departure) due to unforeseen expenses during the development and testing phases (Condition) could put a strain on project resources (Asset), requiring a reduction in the mission scope or implementation delays (Consequence).
Mitigation: To guarantee cost adherence, set up a 20% contingency budget and carry out frequent financial audits.

Risk 6: Schedule slippage
Due to the interdependencies between mission milestones (Condition), delays in one phase may affect the project timeframe as a whole (Asset), cause delays in succeeding phases (Departure), and possibly postpone the launch and other crucial tasks (Consequence).
Mitigation: Scheduling risks can be reduced by implementing buffer periods, regular project reviews, and milestone enforcement.

Risk 7: Interruptions to the Supply Chain
There is a chance of delays or shortages in obtaining essential components (Departure), which could impact the assembly and testing procedures (Asset) and cause disruptions to the mission timetable (Consequence) due to global uncertainties in manufacturing and material availability (Condition).

Mitigation: Reliance on outside variables can be decreased by diversifying providers, accumulating necessary components, and creating internal substitutes.

Hazards to the Environment:
Because of the high radiation levels, harsh dust, and extremely high temperatures, the lunar environment presents significant dangers. Sensitive components will be protected by radiation shielding and dust-resistant seals, and systems must be built to survive temperature swings between -173°C and 127°C. Extended exposure to radiation storms and solar activity can potentially harm electronic systems, resulting in power outages or corrupted data. To mitigate this risk, it is crucial to use radiation-tolerant equipment, keep an eye on solar weather forecasts, and install backup systems in protected areas.

There are more risks due to the rough lunar surface. During surface operations, uneven surfaces at the landing location could cause the vehicle to become unstable or limit its mobility. The mission crew will employ adaptive landing legs to balance the vehicle, perform high-resolution mapping of possible landing sites, and outfit surface vehicles with obstacle detection and avoidance technologies in order to lessen these difficulties. During scientific missions, these tactics are intended to guarantee a smooth landing and enable efficient mobility.

Risk 8: Extreme Temperature Changes
There is a chance that vehicle systems and instruments will experience thermal stress due to the lunar surface's temperature fluctuations, which range from -173°C to 127°C (Condition). This could compromise the operation of temperature-sensitive components (Asset) and result in operational failures or data loss (Consequence).
Mitigation: Resilience will be guaranteed by sophisticated thermal protection technologies and thorough testing in lunar-like environments.

Risk 9: Interference from Lunar Dust
Due to lunar regolith's abrasive and sticky qualities (Condition), dust might potentially contaminate optical and mechanical systems (Departure), deteriorate mobility systems and sensor performance (Asset), and interfere with scientific activities (Consequence).
Mitigation: Interference will be reduced by regolith-resistant materials, dust-resistant seals, and routine system diagnostics.

Risk 10: Storms and Solar Radiation
Mission objectives may be hampered (Consequence), electronic components may be damaged (Departure), and the operational lifespan of vital systems may be shortened

(Asset) due to the high levels of solar radiation and the possibility of solar storms (Condition).
Mitigation: Systems will be protected by shielding, radiation-tolerant architecture, and real-time solar weather monitoring.

Risks to Planetary Protection:

There are particular difficulties in maintaining international treaty compliance and safeguarding the lunar environment. One significant worry is biological contamination, in which germs from Earth can inadvertently reach the moon, jeopardizing scientific integrity and going against planetary protection regulations. This danger will be reduced by strict sterilization procedures, contamination analysis, and compliance with COSPAR regulations. Future exploration efforts may also be hampered by the environmental effects of mission trash, such as remaining lander or surface vehicle materials. The proper disposal of mission materials will be ensured by controlled decommissioning, debris minimization, and tracking features.

Risk 11: Biological Contamination
There is a risk of contaminating the lunar environment with terrestrial life forms (Departure), jeopardizing the integrity of scientific investigations (Asset), and breaking international planetary protection agreements (Consequence) due to the strict planetary protection guidelines and the possibility that Earth-origin microorganisms will survive the journey (Condition).
Mitigation: Compliance will be guaranteed by sterilization procedures, contamination analyses, and adherence to COSPAR regulations.

Risk 12: Impact of Debris
There is a chance that mission materials will impede future exploration efforts (Departure), affect the sustainability of lunar operations (Asset), and result in long-term environmental issues (Consequence) given the long-term ramifications of leaving debris on the lunar surface (Condition).
Mitigation: Plans for trash tracking and controlled decommissioning will reduce the negative effects on the ecosystem.

Risk Observation and Reduction:
Throughout the mission lifespan, a strong Risk Management Plan (RMP) will be put into place to properly handle these risks. Because this plan incorporates ongoing risk assessment, the team can modify mitigation tactics in response to emerging obstacles. A cohesive approach to risk management will be ensured via integrated communication

between the science, engineering, and program management teams. Regular briefings that keep everyone updated on developments and possible changes will also prioritize stakeholder alignment.

The mission is in a strong position to accomplish its goals while negotiating the challenges of lunar exploration by tackling these programmatic, technical, environmental, and planetary protection concerns. Within the limitations of the Discovery-Class framework, the mission team aims to optimize the scientific return and guarantee mission success by early planning, ongoing assessment, and a dedication to strict risk mitigation techniques.

Given the inherent difficulties of lunar exploration and the difficulty of carrying out a Discovery-Class endeavor under limited financial and schedule constraints, effective risk management is crucial to the mission's success. The mission team has created focused methods to deal with any problems by methodically identifying risks using NASA's RIDM framework and classifying them into technical, programmatic, environmental, and planetary protection domains. By taking these precautions, vital resources like communication systems, scientific payloads, and mission schedules are protected from known uncertainties and erratic lunar conditions.

Additionally, incorporating mitigating techniques like redundancy, thorough testing, and backup plans strengthens mission resilience, and adhering to planetary protection guidelines demonstrates a dedication to sustainable development and ethical exploration. In addition to reducing the possibility of failures, this thorough and proactive approach encourages innovation in resource management, operation, and design.

Following these guidelines and being adaptable in the face of unforeseen difficulties will put this mission in a strong position to optimize its scientific return, preserve stakeholder trust, and provide important insights to the larger objectives of lunar exploration and beyond.

1.8.2. Failure Mode and Effect Analysis (FMEA)

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Power	Solar power reduction in efficiency	Greatly reduces power available to the spacecraft's systems.	7	Dust accumulation over the solar panels from lunar regolith.	7	Special dust repellent coating, or using electrostatic devices to prevent dust particles from building up.	2	98	Dus needs to be cleaned off (repelled) using electrostatic devices.

	Lithium Ion battery capacity reduction	Increases risk of current power not being sufficient when solar panels cannot be used. Lifespan of battery can also be reduced due to cold temperatures. Lithium plating can also occur which is dangerous to the components.	7	Cold temperatures on lunar surface.	6	Proper temperature control such as heating during cold conditions as well as proper insulation, proper UV protection.	3	126	Battery needs to be warmed in case of cold temperature. If lithium plating occurs, the only solution is to rely on a secondary battery.
	PMAD fault	Loss of power regulation causing damage to components and loss of data. Also affects efficiency.	8	Temperature changes	2	Proper temperature control such as heating during cold conditions as well as proper insulation, proper UV protection.	5	80	Identify the cause of the issue, but needs a redundant system to rely upon in case of failure.
CDH	Computer Failure	Vehicle unable to operate.	9	Dust, radiation, temperature changes, power fluctuations, memory failure.	4	Proper temperature control such as heating during cold conditions as well as proper insulation, proper UV protection. Dust protection is also needed.	2	72	A backup computer is needed in case the primary one fails. Once the system is stable on the secondary computer, the issue can be troubleshooted and solved.
	Data Failure	Data potentially lost, extremely negative to the science objectives of the mission with the loss of collected data.	9	Radiation, temperature changes, debris, collisions, software glitch.	4	Data needs to be regularly backed up and system must be protected from environmental conditions.	2	72	Troubleshoot system and see what the error is and if the system can be repaired.
	Telecommunications failure	Unable to transmit data back to Earth which is detrimental to the mission's science objectives. Furthermore, can leave the whereabouts of the vehicle unknown, and unable to troubleshoot other problems.	8	Radiation, interference from other celestial bodies, data failure	3	Needs protection from radiation. Frequencies must be chosen specifically to reduce the impact of other bodies in space from affecting transmissions.	4	96	Issue needs to be diagnosed and repaired.
Thermal	Loss of thermal protection	Damage of sensitive components and even destruction of spacecraft.	10	Degradation of passive insulation over time due to lunar temperature cycling.	2	Needs a protective layer to prevent damage from physical/environmental damage. Cannot be subject to excessive compression.	4	80	Needs redundant layer of thermal insulation in case of breach.
	Radiator fault	Increased energy consumption, loss of efficiency, reduction in heat	10	Dust accumulation over the radiator	2	Needs protection from dust.	3	60	Dust needs to be cleaned from panels. Can also have a redundant system/backup if a failure

		transfer.		panels. The dust acts as a layer of insulation trapping heat.					occurs.
	Thermal strap fault	Can cause sensitive systems to overheat, damaging them.	7	Improper installation, excessive vibration, deformation due to loads or extreme temperature changes.	2	Needs adequate sensors to detect the status of thermal straps.	6	84	Needs multiple thermal straps in case of a failure in one due to fatigue.
Mechanical	Tether fault	Possibly mission ending due to the possibility of destruction of the vehicle from free fall.	10	Overloading/ fatigue	1	Extensive testing is needed to prove that tether can withstand the load of the vehicle and more. Otherwise a second cable can be used.	4	40	If tether fails, then the mission is most likely a failure, as vehicle will be damaged into a non performing state.
	Gyroscope failure	Can lead to incorrect orientation data, leading to a loss of direction and control for the vehicle.	5	Bearing failure due to fatigue/wear, dust contamination, physical damage.	5	Gyroscope must be calibrated regularly. It must be thermally regulated, and needs to be protected from dust via electrostatic devices.	2	50	Gyroscope needs to be calibrated. Multiple gyroscopes are needed on the vehicle.
	Structural failure	Compromises structural integrity of vehicle, hindering mobility of vehicle. Possibly mission ending due to the rough driving conditions on the lunar surface.	9	Improper manufacturing, collision/physical damage.	1	Hardening of structure is needed. Redundant systems need to be in place for vital structural components in case of failure. Careful handling is a must in order to prevent collisions with terrain.	4	36	No action is required as the vehicle cannot repair itself in case of structural damage.
	Rocker-bogie fault	Vehicle unable to traverse required terrain to acquire data, cannot offer stability to instruments and other systems.	8	Extremely rough terrain, debris, collision, fatigue/wear on joints. Differential failure.	1	Careful monitoring is needed to ensure no damage is sustained during travel. Cautious handling of vehicle is needed to prevent damage to differential.	3	24	Check to see if differential can be adapted to via software.
	Rollover	Mission will be terminated if vehicle cannot be recovered from a rollover. Can cause damage to solar panels, mast, and other instruments.	10	Extreme terrain.	1	Terrain needs to be deemed safe to traverse to prevent a rollover case.	1	10	Vehicle has the means to flip itself upright incase of a rollover.

	Motor failure	Effect depends on type of motor. Mobility of vehicle will be hampered if a motor fails, each wheel has its own individual motor. If motors for robotic arm fails, arm will lose mobility depending on which joints fail.	8	Fatigue/wear, dust accumulation, temperature changes. Issues with power management can cause a motor failure.	3	Needs protection from dust, proper thermal protection and surge protection.	3	72	Identify if the issue can be solved via software. If not power can be rerouted to different systems, and the mission can still continue due to the vehicle having multiple motors.

1.8.3. Personnel Hazards

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

Machining Hazards

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

Integration Hazards

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

1.9. Schedule

1.9.1. Schedule Basis of Estimate

The following presents the basis for the mission's schedule and follows the chronological order of the mission lifecycle. The mission schedule presented in this document assumes Phase C and the beginning of this mission; however, this section also defines the basis for previous phases. As a preface, the schedule has built a margin for unforeseen circumstances. Several factors were considered when creating a schedule for Operation Lunar Descent**,** such as staff, facilities, and other resources that the mission requires.

Pre-Phase A:

Pre-phase A is the preliminary mission concept development phase, and activities include identifying top-level system requirements, identifying and procuring stakeholders, and drafting program/project proposals. Given these activities, sufficient staff (science, engineering, programmatics, etc.) are readily available for this preliminary planning stage. In addition, it’s estimated that project/program proposals are not delayed and are approved in a moderate time span. Facilities and additional resources required for the project proposal are readily available during Pre-Phase A.

Phase A:

Phase A is still in the mission concept development phase; however, its goal is to develop a verification and validation plan, determine the scope of the mission, and finalize the mission concept. The previous basis also applies to Phase A activities; however, it is assumed that if more personnel are brought on board, they are hired within 1-2 months after the Pre-Phase A closeout. Since this phase may begin the fabrication of systems designs and/or engineering units, breadboards, models, etc., to verify the scope of the mission, it is assumed that the proper facilities/cleanrooms are ready and available. In addition, if parts are procured from external sources, they arrive in an appropriate amount of time that does not delay approval of the System Requirements Review (SRR) and System Definition Review (SDR).

Phase B:

Key decision point (KDP) B marks the transition from Phase A to Phase B, where initial designs are made, and the required technology is finalized for mission launch. Activities

in Phase B include developing the preliminary design, improving models and prototypes, and updating risks, baselines, and ConOps. Assumptions for the schedule estimate include the following: subcontractors are identified and hired within 2-3 months, both PDR and Safety Review are not delayed, and top-level requirements from the SRR are finalized and unchanged.

Phase C:

By the end of Phase C, a complete system built from parent and child-level system requirements should be finalized. Moreover, major assembly and subsystem architecture is finalized. It is assumed that during Phase C, the Critical Design Review (CDR) is not delayed, and no significant changes to the system design are made after Phase C closeout. This mission also assumed that parts/components are ordered immediately after Phase B, ensuring that if delays occur, there is no significant delay until the start of Phase D. Furthermore, the mission assumes that software fabrication is completed before the start of Phase D.

Phase D:

The goal of Phase D is to integrate the system to meet the top-level requirements and begin testing and other forms of verification to ensure confidence in the final system. In addition, launch operations are started in preparation for mission launch. It is assumed that activities dealing with launch operations, such as training staff, baseline handbooks (i.e., maintenance, operations, etc.), and contingency planning have begun after Phase C closeout. Other assumptions include that integration and test facilities are ready and available to integrate the system and that components have arrived when Phase D begins so that fabrication can begin immediately. Materials and components are also assumed to be in supply and the mission assumed no shortage of material required for system assembly. Instrumentation design is assumed to be finalized and tested/calibrated for payload integration. In addition, the launch vehicle is assumed to be identified before Phase D and is available for the launch window, and launch resources are readily available. For example, the launch site should be identified after Phase C closeout.

Phases E & F:

Operations, sustainment, and closeout of the mission assume that sufficient science/engineering data is collected and ensures mission success. In Phase E, it is assumed again that staff are available to maintain and upgrade the system. In addition,

the mission schedule assumes no catastrophic failure occurs, resulting in mission failure. The schedule also assumes that no mission extensions are approved, thus marking the end of mission operations.

The basis also assumed that critical positions are filled with experienced personnel, no significant staff turnover resulting in delays, and adequate staff are always available.

1.9.2. Mission Schedule
Major Milestones:

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

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

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

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

Milestone	Phase	Maximum Time from Previous (months)	Maximum Time from Start of Phase C

			(months)
Begin Phase C of Mission Lifecycle with Key Decision Point (KDP) C	C	0	0
Critical Design Review (CDR)	C	6	6
Production Readiness Review (PRR)	C	2	8
System Integration Review (SIR)	C	7	15
Key Decision Point (KDP) D	C-D	1	16
System Acceptance Review (SAR)	D	3	19
Operational Readiness Review (ORR)	D	20	39
Mission Readiness Review (MRR)	D	13	52
Safety and Mission Success Review (SMSR)	D	5	57
Key Decision Point (KDP) E	D	4	61
Launch	D	1	62
Post-Launch Assessment Review (PLAR)	D-E	1	63
Lunar Landing		0	63
Critical Events Readiness Review (CERR)	E	2	65
Pit Entry	E	1	66

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

Gantt Chart

MCA Mission Schedule

Team Number: # 19

Project Team Members: Project Team Members: Abhijith Ajit, Mihir Bhagat., Chiharu, Sophya Elkihel, Adriana Gaitan, Elizabeth Howard, Krish Mehta, Vedarsh Mishra, Anirudh Ram, Josh Sar-Shalom, Gwendolyn Seto, Kevin Subin, Mason Thaochuetoua, Tanya Vijay, Liliana Z.

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
1	**Concept Development**		100%	9/10/24	10/7/24	28	8
1.1	Identify scope and customer requirements	Entire team	Complete	9/10/24	9/16/24	7	
1.2	Identify team roles and responsibilities	Entire team	Complete	9/17/24	9/20/24	4	
1.3	Baseline Concept of Operations	Engineering, Science	Complete	9/21/24	9/30/24	10	
1.4	Baseline Science Traceability Matrix	Entire team	Complete	9/30/24	10/7/24	8	
1.5	Schedule Margin	Programmatics	Complete	9/30/24	10/7/24	8	
1.6	◆ Complete Mission Concept Review (MCR)	Entire Team	Complete	9/10/24	10/7/24	28	
2	**Preliminary Design and Technology**		100%	10/7/24	10/28/24	22	3
2.1	Outline Mission Schedule and Budget	Programmatics	Complete	10/7/24	10/11/24	5	
2.2	Create trade studies for subsystem components	Engineering	Complete	10/12/24	10/23/24	12	
2.3	Refine Science Traceability Matrix	Science	Complete	10/14/24	10/18/24	5	
2.4	Lay Out Interface Control and Block Diagrams	Engineering	Complete	10/12/24	10/21/24	10	
2.5	Schedule Margin	Programmatics	Complete	10/24/24	10/26/24	3	
2.6	◆ Complete Systems Requirements Review	Entire Team	Complete	10/7/24	10/28/24	22	
3	**Final Design**		0%	11/1/24	12/9/24	39	7
3.1	Create final CAD models	Engineering	Not complete	11/1/24	11/20/24	20	
3.2	Document final design	Engineering	Not complete	11/18/24	11/24/24	7	
3.3	Update risk	Engineering, Science	Not complete	11/25/24	11/28/24	4	
3.4	Update verification and validation plans	Engineering, Science	Not complete	11/25/24	11/28/24	4	
3.5	Schedule Margin	Programmatics	Not complete	12/1/24	12/7/24	7	
3.6	◆ Complete Preliminary Design Review	Entire Team	Not complete	11/1/24	12/9/24	39	

1.10. Budget

1.10.1. Budget Overview

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

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

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

1.10.2. Budget Basis of Estimate

A structured set of ground rules, assumptions, and cost drivers have been taken for the cost estimation of the mission. These measures allow for transparency between advisory boards and the project team while also staying consistent with price quotes and estimates.

Inflation Rate

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

Team Size

We assume that the project team is not limited to the amount of MCA team members. The amount of team members may vary depending on the project phase. The budget is built in enough salary to accommodate varying team sizes over a 5-year time period.

Instrumentation Costs Estimate

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

Mission Travel

Throughout the life cycle of the mission, team members must travel to certain sites to advance the project. Travel estimates are used to calculate the discounted ticket rate for U.S. government officials from the hub of New York City to several locations ranging from Cleveland, Ohio, to Washington D.C., to Cape Canaveral, Florida. The highest economy ticket cost is used in the estimate as airline ticket prices are highly variable. Lodging and Food costs are embedded in the budget, as the highest cost per person is used, per the U.S. General Administration Services per Diem.

Risk Mitigation and Compliance

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

1.10.3. Personnel Budget

Personnel Budget Chart

Mission Phase	Phase A-B	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
PERSONNEL							
Science Personnel	$ 1,200,000	$ 1,231,200	$ 589,120	$ 603,680	$ 441,600	$ 904,000	$ 4,969,600
Engineering Personnel	$ 800,000	$ 984,960	$ 1,262,400	$ 1,293,600	$ 706,560	$ 723,200	$ 5,770,720
Technicians	$ 180,000	$ 369,360	$ 946,800	$ 1,617,000	$ 993,600	$ 1,017,000	$ 5,123,760
Administration Personnel	$ 240,000	$ 246,240	$ 378,720	$ 323,400	$ 198,720	$ 203,400	$ 1,590,480
Project Management	$ 240,000	$ 492,480	$ 631,200	$ 776,160	$ 397,440	$ 406,800	$ 2,944,080
Total Salaries	$ 2,660,000	$ 3,324,240	$ 3,808,240	$ 4,613,840	$ 2,737,920	$ 3,254,400	**$ 20,398,640**
Total ERE	$ 742,406	$ 927,795	$ 1,062,880	$ 1,287,723	$ 764,153	$ 908,303	**$ 5,693,260**
Personnel Margin	$ 1,000,000	$ 3,000,000	$ 4,000,000	$ 4,000,000	$ 1,500,000	$ 1,000,000	**$ 14,500,000**
TOTAL PERSONNEL	$ 4,402,406	$ 7,440,588	$ 9,332,418	$ 10,673,885	$ 5,522,289	$ 5,833,854	$ 43,205,441

Rationale

A diversified team with specialized knowledge is required to successfully carry out the Mare Tranquillitatis Pit (MTP) exploration mission. To guarantee that all mission objectives are fulfilled, 20–25 more employees are needed in addition to the Academy's core staff. Because each subteam is organized to manage particular mission components, technical and scientific milestones are met effectively.

Breakdown of Subteam Roles and Responsibilities

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

2. Science Team: Four scientists make up the Planetary Geology Subteam, which performs geological analysis of MTP and significantly contributes to subsurface mapping and pit stability assessment during Phases D–F.

Six scientists make up the Instrumentation and Data Analysis Subteam, which manages and analyzes data from LiDAR, spectrometers, and other sensors. As data collecting starts in Phases E and F, their role becomes more important.

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

4. Verification & Validation (V&V) Team: The team of four engineers, primarily contributed during Phase D, ensures all the systems meet design and mission requirements via thorough testing and quality control.
5. Operations Team: Five specialists comprise the operations team: oversees post-launch operations, such as anomaly resolution and telemetry. Phases E and F are when their workload peaks.

1.10.4. Travel Budget

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

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

Mission Launch: Mission team members who may be key to launch preparations or

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

For All Travel: The team should plan for commercial coach flights using government rates from the City Pair Program (CPP). The cost of these flights should be determined using the high fare from a variety of cities flying into the necessary location. The team should also plan for lodging (one room per person) at a partnered hotel from Fedrooms, ground travel using car rentals with consideration for varying schedules and travel needs, and a meal per diem rate for the duration of the stay. Per diem rate, allowances for food and lodging can be found using the U.S. General Services Administration Per Diem Website.

1.10.5. Outreach Budget

In the outreach plan, the team wanted to dedicate much of the mission to astronaut-related engagements. The total budget for just the outreach is USD $4,210,188. The team decided to dedicate this to several components, such as astronaut engagements, in-person learning experiences, virtual learning opportunities, and other costs necessary to engage the audience to ensure their success in the efforts.

Astronaut engagements are the top strategy for outreach to ensure that the team captures the public's attention and interest. The team plans to produce a high-quality video that will interview fellow NASA astronauts and express interest in the mission for the Mare Tranquilities exploration mission (Professional services to produce a high-quality video ($12,000)). The budget for this would include professional filming of the high-quality video, editing of the video, interviews with NASA Astronauts, and NASA information The team approximated this engagement to be a total of USD $21,000 due to recruiting NASA astronauts to speak and providing a small stipend for their participation (Logistics, scheduling, and securing participation ($3,000)). This will ensure the astronaut will be motivated to speak on their behalf and stay the extended time necessary to complete the video. Because this video is intended to be Nationwide and distributed along social media platforms (Adapting the video for multiple platforms,

including subtitled and translated versions to ensure inclusivity ($3,000)). The team wants to ensure that the video can reach many backgrounds and demographics to encourage everyone interested in the mission. The team would also like to have a DEI panel of NASA's astronauts; this video will be essentially designed to reach many audiences with various age groups (Panel recordings, preparation, and integration into the video ($2,000)).

The outreach team wants to include Lunar Science Nights in the engaging in-person activity. For this dedication, the team has the budget for school transportation within the area of teams' locations (location provision zones), funds to pay scientists and engineers who are attending and operating events, and grants for schools outside the teams' locations, which can apply. The team wants to provide school transportation to the Lunar Science Nights to bring the schools to those who cannot afford to travel. The team set aside a total transportation budget of USD $30,000 annually for schools, with USD $10,000 from the total transportation budget being towards grants for schools that are in need of transportation and do not meet the boundaries of these zones. Having scientists and engineers come to speak and present, including engaging with students with activities and resources, comes with a cost. The team are able to compensate the members of the Lunar Science Nights for their time and efforts, which are approximately USD $3,500 monthly, with bi-weekly pay per working member. Hosting these in-person activities includes activity set-ups, venues, and materials for students. If events are hosted once a week, these annual costs will become a total of USD $12,000 (USD $1,000 per month). The total annual cost of the in-person Lunar Science Nights would be about USD $52,000, not including wages for each scientist and engineer.

Finally, due to understanding various difficulties that may arise for schools and the members, the team is transparent and understanding of these circumstances that may occur if the Lunar Science Nights were in person. To address this, the team wants to ensure equality across locations and accessibility for everyone. To achieve this goal, the team decided to include virtual options so that schools and staff can still be educated if they desire. These virtual meetings will include live virtual events, recorded versions of the presentations taught by scientists and engineers, interactive activities, and worksheets for students that they can use to take notes. The team estimated the live virtual events to be about $12,000 for annual platform subscriptions such as Zoom Premium to ensure good quality and be able to provide good content nationwide. The interactive activities and worksheets are included in the materials budget mentioned in the in-person Lunar Science Nights. In addition to these materials, they will be provided in kits for students and schools if requested. Once requested in the form, it will be sent to anyone wanting to attend the meeting. The team could have volunteers to package

and ship out these kits. The shipping and handling costs annually, if delivered to schools for their students to pick up, would be around USD $500 per packaged kit of 150 each time the team sends supplies to these schools.

The mission is to make sure the outreach resources and engagement are open to each and every student despite any challenges that may occur. With the thoughtful, engaging activities the team plans to provide, the overall budget for outreach is well over what the team actually uses. With the extra money coming from the overall budget for outreach, the team intends to use that for any miscellaneous materials and grants for schools to bring their students to the activities. The team aims to make the Mare Tranquillitatis exploration mission an engaging and educational experience for all.

1.10.6. Direct Costs

Direct Costs Budget Chart

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

Mechanical

[View Mechanical Subsystems Row of Direct Costs Chart]

Power

[View Power Subsystems Row of Direct Costs Chart]

CDH

[View CDH Subsystems Row of Direct Costs Chart]

Thermal

[View Thermal Subsystems Row of Direct Costs Chart]

Instrumentation

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

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

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

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

RAD	0.6	0.1	12

1.11. Scope Management

1.11.1. Change Control Management

Throughout the mission planning process, unforeseen constraints or shifts in priorities may emerge from potential issues or improvements in the current plan. This could result from new data, unexpected challenges, feedback from internal 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.

Change Request Process

1. Initiation of Change Request:

- The change request process is initiated when a team member submits a formal request to their subteam lead. This request must include:
    - A description of the proposed change.
    - Justification for the change (e.g., addressing new data, correcting an issue, or incorporating feedback).
    - Potential impacts on costs, timelines, and interdependencies.
    - Initial resource assessment for implementation.

2. Review Process:

- Once the change request is submitted, the team leads organize a meeting to discuss and evaluate the proposal. This review includes:
    - Impact Analysis: Assessment of how the change will influence mission objectives, costs, and timelines, as well as interactions with other subsystems.
    - Feasibility Check: Ensuring the change is achievable with current resources and constraints.
    - Risk Assessment: Identification of new risks introduced by the change and potential mitigation strategies.
- The Project Manager (PM) and Deputy Project Manager (DPM) oversee the review process, collaborating with the Lead Systems Engineer (LSE) to ensure alignment with the overall mission goals.

3. Approval and Action Plan:

- If the change is approved, an action plan is developed to implement it. The action plan details:
    - Task assignments for responsible team members.
    - Updated timelines reflecting the change's integration.
    - Allocation of any additional resources required.
- Changes are tracked using a centralized change log, which documents:
    - Change description.
    - Justification and expected outcomes.
    - Team members responsible for execution.
    - Current status (proposed, under review, approved, implemented).
- The change log is maintained in a shared project management tool to ensure all team members can access the latest updates.

4. Implementation and Monitoring:

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

5. Final Review and Documentation:

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

Academy-Mandated Change Request Procedures

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

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

Communication and Decision-Making

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

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

Stakeholder Feedback

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

- Regular meetings with stakeholders to clarify feedback and expectations.
- Immediate assignment of RFAs or ADVs to relevant subteams for analysis.

- Timely updates are provided to stakeholders on the progress and resolution of their feedback.

1.11.2. Scope Control Management

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

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

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

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

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

Mission Life Cycle Effects

a. Concept/Design Phase
    i. Requires a cost and schedule estimate to determine a baseline to work off of in the event of a change in scope. Furthermore, there needs to be an emphasis on flexible systems to account for future changes in scope.
b. Manufacturing

        i. Scope changes need to be assessed in terms of how they will impact the mission. These changes need to be communicated with potential manufacturers.
    c. Testing
        i. Focus on schedule changes, such as the bloated testing procedures, rather than changes to components/instruments or software.
    d. Operations
        i. Need to ensure that scope changes do not compromise the integrity of the mission.

1.12. Outreach Plan

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

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

The “Astronaut Engagement” portion of the outreach can be used multiple times, including being incorporated into the mission countdown and launch day coverage. Additionally, participant astronauts will be invited to present the “Astronaut Engagement” video and an informational clip about the mission’s development and science goals at their alma mater universities. When presenting these clips, the students will be given the opportunity to engage in person at the astronaut's comfort level, whether that be taking student questions about the mission’s importance or further giving their insights on the relevance of developing sustainable habitability. An alternative option to this

would be for participating astronauts to record a short message to students at their alma mater, which would be shown with the regular engagement clips. The “Astronaut Engagement” and “Informational Science” clips will be publicly available for all educational entities to show their students, allowing schools at every level of education and funding to engage their students with the mission’s purpose.

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

Additionally, local “lunar science” nights will be held near the teams’ locations, and families from the area will be encouraged to participate in learning and science engagement activities for multiple age levels. This part of the outreach effort will allow students and adults alike to engage with scientists and engineers from the team and will target the goal of engaging with underserved communities. The team intends to set aside a designated amount of money from the allotted outreach budget, which can be used to provide transportation capabilities to schools that cannot afford to bring students to a lunar science night near them. The ability of the team to provide this service will be determined by allowing schools within a certain radius (determined by the available funding) to apply for a transportation grant. Reception of the grant will be non-competitive; any school within the budget-defined radius that cannot provide transportation to interested students will have their transportation covered by the outreach budget. Schools outside of the “transportation provision zone” will be allowed to apply for the grant should there be leftover funds in the outreach budget, and if available, these grants will be provided on a first-come, first-serve basis.

In order to engage with as much of the community as possible, team members available to attend and operate activities at the lunar pit science nights will be distributed amongst multiple activities. This will allow for different activities geared towards people of different age groups and knowledge of the mission. Lunar pit science nights will be held once data has started being collected from the Mare Tranqillitatis pit so that novel information about the pit can be shared, and activities can be based on real, new science the mission has provided. For example, one activity could be using a scale Mare Tranquililtatis pit and lava tube model where students can plan habitation “developments” for astronauts. More advanced or scientifically informative activities,

such as structural or material findings from the mission, could be incorporated into activities for older students or adults.

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

One weakness of the outreach plan is its contingency regarding team members' physical availability and willingness to attend and run outreach events. The team intends to gauge its members' willingness or interest in carrying out lunar science nights pro bono. While it is possible that scientists and engineers will be interested in carrying out these activities purely in the interest of engaging the community in novel science and fostering a passion for their mission in the future workforce, the programmatics group acknowledges the time and energy that this would take and the possibility that team members will have commitments to their families or otherwise. For willing team members, every effort will be made to coordinate lunar pit science nights around their convenience. Should team members lack interest in carrying out lunar pit science nights pro-bono, funding allotted to the "transportation provision" will be diverted to offering overtime pay for team members participating in lunar pit science nights to the necessary extent. Funding left in this category will still be used to provide transportation to schools that apply for the grant, and the radius of noncompetitive opportunities will be decreased to accommodate the funding shift.

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

Another potential weakness of the outreach efforts planned for the Mare Tranqillitatis pit exploration mission is that its official in-person events are mostly located near locations

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

1.13. Conclusion

This Mission Definition Review overviews the detailed requirements for subsystem design and mission definition for a discovery-class mission to the lunar pit Mare Tranquillitatis. The systems and subsystems remain closely aligned with the science objectives outlined in the Mission Concept Review (MCR). Several sections, including the Science Traceability Matrix (STM), cost estimates, and schedule projections, have been updated and refined from the SRR to ensure the mission remains achievable within the defined parameters. If additional time were allocated towards developing the MDR, the team would focus on further refining instrumentation selection and enhancing subsystem requirements to better align with mission objectives.

The next milestone for the team is the Preliminary Design Review (PDR). For this document, the team plans to expand upon the foundational work of the MDR by advancing subsystem designs and ensuring seamless integration across all mission components. Responsibilities will continue to be divided among sub-teams, with clearly defined tasks assigned to each member. Enhanced communication methods will support the development of a cohesive and comprehensive mission design as the team prepares for the PDR.

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