System Requirements Review (SRR)

“CHILLY”

(MCA Team 09)

Commanded Harvesting of Ice Lunar Lander Yield

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Table of Acronyms

Acronym	Definition
ADV	Advisory
CCB	Change Control Board
CDH	Command & Data Handling System
CDR	Critical Design Review
CER	Cost Estimating Relationship
CMOS	Complementary Metal Oxide Semiconductor
CNSA	China National Space Administration
ConOps	Concept of Operations
CRF	Change Request Form
CSSL	Communication Systems Simulation Laboratory
GNC	Guidance, Navigation and Control
GPR	Ground Penetrating Radar
MCR	Mission Concept Review
MDR	Mission Definition Review
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
NCIM	NASA Instrument Cost Model
NIRVSS	Near-Infrared Volatiles Spectrometer System
PCM	Phase Change Material
PDR	Preliminary Design Review
PDU	Power Distribution Unit
PSR	Permanently Shadowed Region
RFA	Request For Action
RTG	Radioisotope Thermoelectric Generator
SEE	Single Event Effect
SRR	System Requirements Review
STM	Science Traceability Matrix
TBD	To Be Determined
TBR	To Be Resolved
TRN	Terrain Relative Navigation
TRL	Technology Readiness Level
VIPER	Volatiles Investigating Polar Exploration Rover
WBS	Work Breakdown Structure

1. System Requirements Review

1.1. Mission Statement

The goal of this mission is to study the composition of water-ice and other volatiles within the permanently shadowed regions of the southern pole on the moon. This is being done to measure the viability of long-term settlements on the moon that would use these resources to survive. The main resources that will be tested for will be water, hydrogen, and oxygen. The mission requires the team to collect data on several metrics of lunar water-ice behavior. Each science goal has different objectives, meaning the team will need to measure temperature, pressure, and flow rate measurements made during liquefaction and condensation; ice density, surface tension, and temperature during phase transitions of the water-ice; and the concentration and composition of water-ice in the first meter of regolith on one of the permanently shadowed regions. The data for this mission will be collected using instruments aboard a rover. Using a rover for the mission will increase the area of water-ice deposits that can be tested and allow for a wider range of the permanently shadowed region to be analyzed. Ultimately, this will allow for a breadth of data to be collected, allowing the mission to include research for the multiple aspects of the water-ice mentioned previously. By measuring the proportion and properties of water-ice at the Moon's South Pole, this mission aims to significantly advance our understanding of the Moon's formation and possible geological history, with potential for enrichment, especially drinking water, oxygen production, and fuel for future missions. This not only contributes advanced learning to scientific knowledge but also supports the long-term goal of putting man on the moon.

1.2. Science Traceability Matrix

Determining the presence and composition of water-ice deposits within the lunar regolith is the top priority of this mission. However, studying the ice itself presents an entirely new subset of challenges and introduces additional goals for this mission. The lunar ice-water deposits in PSRs will be studied to examine how partial-g and various particles held within the ice may affect the normal matter phases (solid, liquid, gas). Due to the majority of PSRs being unexplored, it is a goal to determine water ice abundance within the top meter of the regolith as well as other volatiles that may be found in these regions. Additionally, the effects of partial-g on the condensation of hydrogen and oxygen will also be studied during the liquefaction process. All of these goals and how they will be achieved is outlined in the Science Traceability Matrix (see *Table 1*). Accomplishing these goals will give insight into the moon's past as well as potential uses for the lunar ice in future missions and settlements.

These goals will be achieved through the use of two instruments, a strata ground penetrating radar (GPR) and a Near-Infrared Volatiles Spectrometer System (NIRVSS). When combined, these two will be able to allow the mission goals to be met with high precision in every required aspect. The GPR will allow the rover to make a two or three dimensional map of the undergrowth regolith inside the mission area.[6] This is done by sending high frequency radiation into the regolith and measuring the attenuation of the reflected waves. This allows for the GPR to measure the depth and lateral distance of any differing materials in the ground. The NIRVSS is a suite of instruments that include 2 spectrometers of differing wavelength spectrometers, high definition CMOS sensor, LED’s for said sensor, and a longwave calibration sensor.[9] With these, the NIRVSS will be able to monitor changes in surface reflectance, composition, volatile content, and temperature with high precision.

Table 1. *Science Traceability Matrix (STM)*

<table>
<tr><th rowspan="2">Science Goals</th><th rowspan="2">Science Objectives</th><th colspan="2">Science Measurement Requirements</th><th rowspan="2" colspan="2">Instrument Performance Requirements</th><th rowspan="2">Predicted Instrument Performance</th><th rowspan="2">Instrument</th><th rowspan="2">Mission Requirements</th></tr>
<tr><th>Physical Parameters</th><th>Observables</th></tr>
<tr><td rowspan="5">Artemis Science Goal 6n: Study the conversion of water-ice to gaseous hydrogen and oxygen, and liquefaction of gasses for propellant storage</td><td rowspan="2">Identify impact of environment, temperature; material composition; ect, on the condensation of hydrogen, oxygen, and water during the liquefaction process of water-ice.</td><td rowspan="2">Measure gas and liquid temperatures, ambient temperature (during condensation), system pressure, partial pressures, gas and liquid density, and flow rates of different gasses.</td><td rowspan="2">Measure gas and liquid temperatures, ambient temperature (during condensation), system pressure, partial pressures, gas and liquid density, and flow rates.</td><td>Spectral Resolution:</td><td>~ 50 nm</td><td>~20 nm</td><td rowspan="2">Near-Infrared Volatiles Spectrometer System (NIRVSS)</td><td rowspan="2">Mission shall measure physical parameters of gas condensation.</td></tr>
<tr><td>Temperature Ranges:</td><td>From 0°C To 100°C</td><td>Above -173°C</td></tr>
<tr><td rowspan="3">Examine the influence of gravity on solid-liquid phase change of water ice including sedimentation of regolith in the liquid water.</td><td rowspan="3">Identify changes in sedimentation processes of regolith in liquid water in lunar gravity compared to earth gravity.</td><td rowspan="3">Measure composition of liquid water and location of solid regolith over time as regolith particles separate.</td><td>Spectral Resolution:</td><td>~ 50 nm</td><td>~20 nm</td><td rowspan="3">Ground Penetrating Radar (GPR) & Near-Infrared Volatiles Spectrometer System (NIRVSS)</td><td rowspan="3">Mission shall record physical details of sedimentation process of lunar regolith in liquid water</td></tr>
<tr><td>Temperature Ranges:</td><td>+/- 5°C from 0°C</td><td>Above -173°C</td></tr>
<tr><td>Distance Resolution:</td><td>< 5 cm</td><td>~ 3 cm</td></tr>
</table>

Artemis Science Goal 2a: Determine the Compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions.	Determine the water ice abundance of the Leibnitz Beta Plateau in or near a PSR, within the top 1 meter of regolith to at least +/- 5% accuracy	Identify presence and concentration of ground water-ice in the first meter of lunar regolith.	Measure concentration and distribution of water-ice in the first meter of regolith in a permanently shadowed region within an accuracy of +/- 5%.	Wavelength Range:	100 - 1000 MHz	25 - 1500 MHz	**Ground Penetrating Radar (GPR) & Near-Infrared Volatiles Spectrometer System (NIRVSS)**	Mission shall measure water-ice content in first meter of lunar regolith
				Distance Resolution:	Below 5 cm	< 1 cm		
				Lateral Resolution:	Below 5 cm	~ 1.8 cm		

1.3. Summary of Mission Location

Out of the 13 Artemis III Landing Sites (see *Fig. 2*), the Leibnitz Beta Plateau (see Fig 3) will be the mission location and landing site. Multiple factors have been considered when making this decision, such as terrain, permanently shadowed regions, illumination, and communication conditions. The topography of the Leibnitz Beta Plateau is favorable to the proposed rover mission due to its minimal slope changes, >8° [12]. The relatively flat terrain will allow the rover to move around easily and conduct scientific experiments without navigating extreme elevation changes. Along with the favorable terrain, the Leibnitz Beta Plateau is rich in permanently shadowed regions (PSRs) and has PSRs near it (see Fig 4). This is a key characteristic that was considered when choosing the mission location as PSRs are likely to host ice deposits, which is the focus of this mission. In fact, 78% of the PSR area located in the Liebnitz Beta Plateau is favorable to water-ice [13]. The chosen center for the 100m landing radius for this mission will be (-85.203°N, 33.258°E) due to this area covering some of a large PSR where water ice can be examined and samples can be collected to be further analyzed (see Fig 5). However, the western half of the 100m landing radius is a non-PSR area where the rover can possibly analyze the water ice and sediment samples in relatively warmer temperatures as well as recharge in the sunlight using solar panels. A crucial third aspect that has been evaluated when choosing this location is the illumination of the selected area. As previously stated, the rover will use solar power as an energy source to conduct the proposed water-ice deposit experiments. Therefore, illumination of the mission location needs to be analyzed to ensure that enough sunlight can be harnessed to fulfill the needs of the rover. Although the Leibnitz Beta Plateau is a PSR-rich area, it also has areas of high illumination, partially due to its high elevation [13]. The chosen 100m radius covers both the PSR and the areas of high elevation where enough illumination is present to power solar panels (see Fig 5). Arguably the most important consideration relates to the communication conditions, specifically between the mission and Earth. A vast amount of data will be collected in this mission and due to its complexity, good communication is vital to mitigate any issues that occur over the duration of the mission and ensure success. The Leibnitz Beta Plateau is one of the best candidates for mission location when specifically considering its communicability as some areas of this region even reach maximum communication conditions of 100% (see *Fig. 1*). The chosen 100m radius landing site at the Leibnitz Beta Plateau hosts reliable communication conditions along with fulfilling the mission's needs for ideal terrain, PSRs and high illumination areas, making it an ideal candidate for this mission and its experiments as seen by the data collected in the lunar south pole (see *Table 2*).

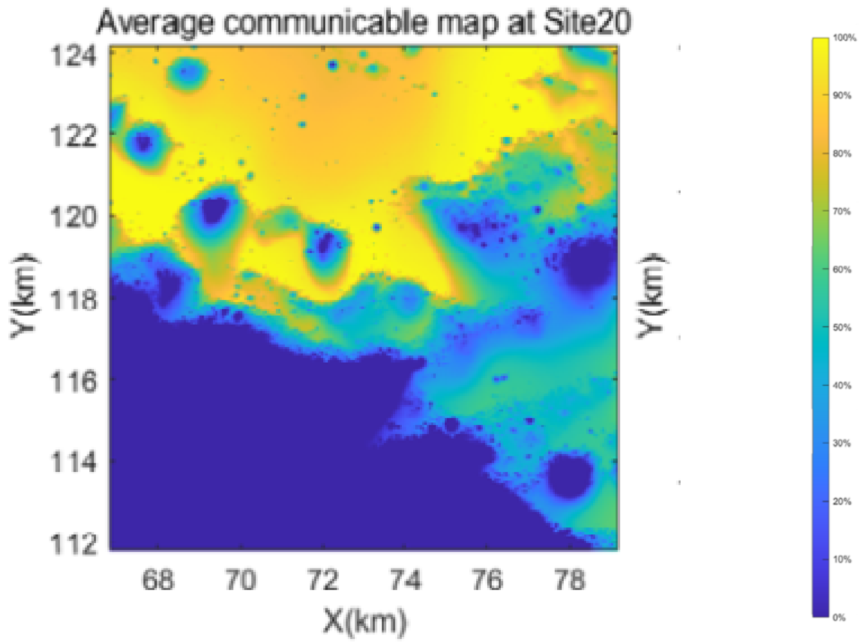

Figure 1. *Communicable Map of Leibnitz Beta Plateau* [9]

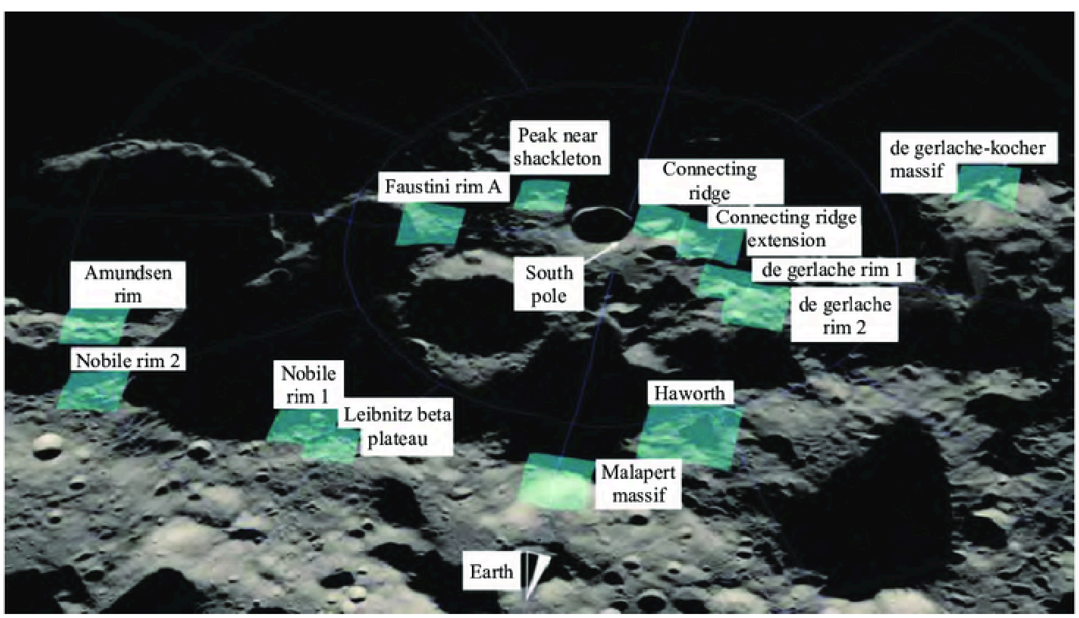

Figure 2. 13 pre-selected landing zones for the Artemis III landing mission [23]

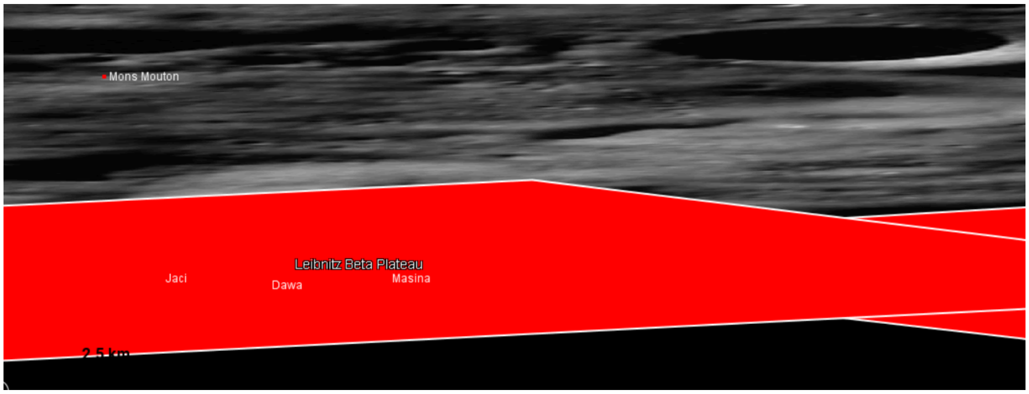

Figure 3. JMARS Map of Leibnitz Beta Plateau

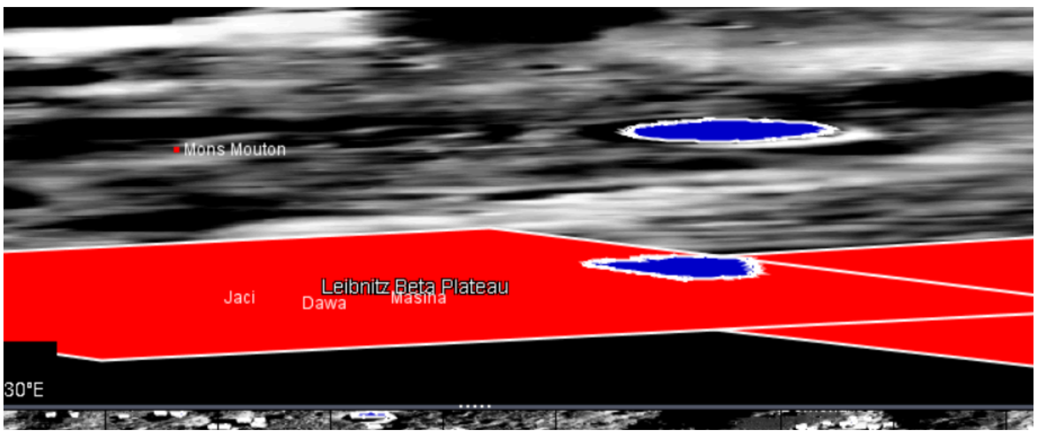

Figure 4. Large PSRs (in blue) in or near the Leibnitz Beta Plateau

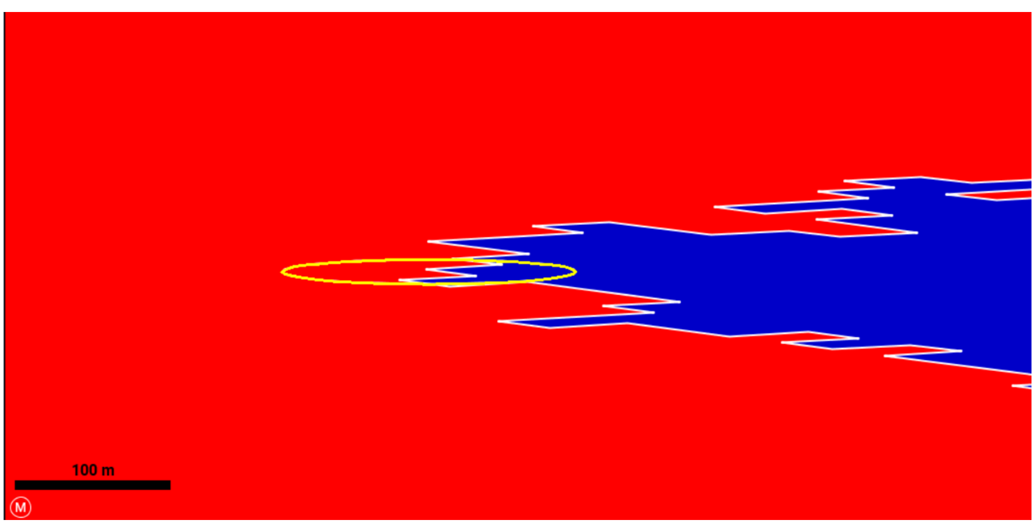

Figure 5. 100m Radius Landing Region (circle in yellow)

Table 2. *Data of Leibnitz Beta Plateau with constraints of >8°, illumination >35% and communicable >40% [*12]

Location	Total Area with >8° slope (m^2)	Maximum Illumination (%)	Mean Illumination (%)	Maximum Com. (%)	Minimum Com. (%)
Leibnitz Beta Plateau	21760025	76.04	44.90	100.00	86.33

1.4. Mission Requirements

This mission must adhere to the customer constraints specified in the mission task document. As the vehicle is a secondary payload aboard a primary vehicle, there are mass and volume constraints that may not be exceeded by any amount. The vehicle's total mass shall not exceed 85 kg and shall not exceed a stored configuration volume of 1.5m in length, width, and height. Post-deployment, it is allowable for the vehicle to expand to a larger volume. Additionally, the total cost of the mission, including the cost of the system, salaries, travel, outreach, and other expenses, shall not exceed a total cost of $225 million. Since it is a secondary payload, launch and cruise costs are assigned to the primary payload. The vehicle must be ready for launch by September 1st, 2028 at Cape Canaveral, adjacent to the Kennedy Space Center. The customer has also imposed constraints on the science instrumentation of the vehicle. All of the mission's science objectives shall be achievable with no more than two science instruments in total. This includes duplicates and instrument suites with more than one instrument. Furthermore, the vehicle is prohibited from using a Radioisotope Thermoelectric Generator (RTG) and any derivative thereof. The total amount of allowable radioactive material is limited to a cumulative maximum mass of 5 g. If any of the customer constraints stated above are exceeded by any amount, the mission will be subject to cancellation.

The top-level mission requirements are shown below in Table 3. This table outlines the top-level specifications, derived from the customer constraints and scientific traceability matrix (STM), that are necessary for a successful mission. Mission requirements (MR) 1 and 2, were chosen as mission requirements because the launch date and launch location were specified and required by the customer in the Mission Task document due to the fact that this mission's vehicle is a secondary payload launching with a primary payload. MR-3 was chosen based on the customer's stipulation that the vehicle must investigate science sites no more than 10 km from the designated landing site, as indicated in the Mission Task document. Additionally, MR 5 and 6 were included because the mass and volume constraints were outlined by the customer in the Mission Task document. As a secondary payload, there's specific max mass and volume that cannot be exceeded. If these were exceeded by any amount, the mission would be subject to cancellation. MR-7 is the budget specified by the customer. The entire cost of the mission may not exceed the budget specified by the customer in the Mission Task document. The system requirements (SYS) are also included below in Table 3. SYS-1 and SYS-2 describe the science objectives from the STM that are required to be satisfied in order to accomplish the science goals 2a and 6n, as specified in the Mission Task document and the Artemis III Science Definition Team Report. Failure to meet these requirements will result in a failed mission. SYS-3 was chosen because the customer required, in the Mission Task document, the system to not use more than a cumulative mass of 5g of radioactive material. SYS-4, derived from MR-3, is necessary because the vehicle needs to be able to operate in the temperature ranges it will encounter in order to satisfy the mission objectives. All the requirements mentioned above outline the top-level mission requirements necessary for the science goals to be accomplished and for the mission to be a success.

Table 3. *Top Level Mission Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mission Reqs							
MR-1	The vehicle shall be ready for launch by September 1st, 2028.	Since the vehicle is a secondary payload, it must be ready for launch when the primary payload launches.	Customer	N/A	Inspection	All	Met
MR-2	The vehicle shall launch from Cape Canaveral adjacent to the Kennedy Space Center.	Since the vehicle is a secondary payload, it must launch with the primary payload.	Customer	N/A	Demonstration	All	Met
MR-3	The system shall operate within a 10 km radius from the landing location in Leibnitz Beta Plateau.	The site the vehicle is investigating cannot exceed a distance of 10 km from the landing site as specified in the mission task document.	Customer	SYS-4 MEC-1 MEC-7 CDH-3	Test	All	Met
MR-4	The system shall have a mission lifespan of TBD days.	The minimum amount of time to acquire sufficient data to satisfy the science objectives.	Customer	MEC-2 MEC-4 MEC-5 MEC-7 EPS-2 EPS-8 TCS-2 TCS-3	Analysis	All	Met
MR-5	The system shall have a max total mass of 85 kg.	The mass of the system cannot exceed a mass of 85 kg due to being a secondary payload as specified by the customer in the mission task document.	Customer	MEC-3 EPS-6 TCS-4 CDH-4	Inspection	All	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MR-6	The system shall have a max volume of Length 1.5m x Width 1.5m x Height 1.5m for the stored configuration prior to deployment.	The volume of the system cannot exceed the allowed volume due to being a secondary payload as specified by the customer in the mission task document.	Customer	MEC-6	Inspection	All	Met
MR-7	The mission shall have a max cost of $225M.	The mission may not exceed the allowed budget specified by the customer in the mission task document.	Customer	MEC-8 EPS-9 TCS-5 CDH-2	Inspection	All	Met
MR-8	The system shall support instrumentation to collect data to achieve science goal 2a.	The system must be capable of satisfying the science objective in order to accomplish the science goal 2a as specified in the mission task document.	Science Goal 2a	MEC-6 EPS-7 TCS-2 CDH-1	Test	All	Met
MR-9	The system shall support instrumentation to collect data to achieve science goal 6n.	The system must be able to satisfy the science objectives in order to accomplish the science goal 6n as specified in the mission task document and the Artemis III Science Definition Team Report.	Science Goal 6n	MEC-6 EPS-7 TCS-2 CDH-1	Analysis	All	Met
System Reqs							
SYS-1	Any radioactive material used by the system shall have a max cumulative mass of 5g.	The system cannot use more than 5g of radioactive material in total as specified by the customer in the mission task document.	Customer	N/A	Inspection	Power Payload	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
SYS-2	The system shall operate in the temperature ranges encountered in Leibnitz Beta Plateau.	The system needs to be capable of operating in extreme temperatures in order to satisfy the mission objectives.	MR-3 MR-4	MEC-7 EPS-5 TCS-1	Test	Mechanical Thermal Payload	Met

1.5. System Definition

1.5.1. Spacecraft Overview

In order to satisfy the science objectives chosen for the mission, the spacecraft chosen is a rover. This rover will be designed to traverse the lunar surface, more specifically, the terrain within the Leibnitz Beta Plateau. Inside the designated area, the rover will traverse to a PSR in order to collect scientific data on the ice deposits outlined in the STM. It will then transmit the scientific data to the primary mission orbiter. The rover will have five different subsystems (mechanical, power, CDH, thermal, and the payload). The top-level subsystem requirements are shown below in table 4.

The mechanical subsystem provides the structure, suspension, locomotion, GNC, a drill for sample collection, and the mechanical components necessary for deployment of the science instrumentation and solar panels. The structure is the base of the vehicle and will support all of the other components and subsystems. The suspension is responsible for ensuring stability and protection of the vehicle from shocks and vibrations. The locomotion subassembly enables the rover's mobility and maneuverability through the use of wheels, motors, and gearboxes. The guidance, navigation, and control (GNC) subassembly is in charge of sensing the terrain and movement of the rover (such as tipping and acceleration), as well as, object avoidance to ensure the rover doesn't accidentally damage itself. [1] In addition to these four subassemblies, the mechanical subsystem will also include mechanisms for instrument and solar panel deployment in order to have a storage configuration during transportation within the volume constraint. Finally, the subsystem will also include a drill that will be used to collect samples of the ice deposits in order for them to be analyzed by the science instrumentation.

The power subsystem provides power generation, power storage, and power distribution. The rover will include solar panels in order to generate power for the system. Since PSRs do not have adequate sunlight to produce energy, the rover shall leave the PSR in order to charge when it gets to a certain power percentage. Additionally, the power subsystem will include a battery to store the energy generated from the solar panels. This way, the rover can still use power when in the PSRs. Lastly, the power subsystem will reliably supply power to all other subsystems in order to accomplish the mission goals.

The command and data handling (CDH) subsystem manages the rover's communications, data storage, commands, and recovery processes. Its main purpose is to receive the scientific data from the instruments in the payload and send the information to the primary mission orbiter. Additionally, the CDH subsystem will keep data on the other subsystems to ensure all components and subassemblies are working efficiently. The subsystem will also relay commands to the other subsystems, and thermal management instructions to the thermal subsystem when a subassembly is overheating for example, in order to ensure mission success.

The thermal subsystem is in charge of regulating the temperatures of all of the other subsystems in order to ensure they are all operating at the required temperatures. It consists of heaters, thermal insulation, and temperature sensors. It is essential that components and instrumentation remain at their operating temperatures in order to maintain the rover's functionality throughout the entire mission.

The payload subsystem hosts the two science instruments that will be used to collect scientific data in order to satisfy the science objectives. The instruments chosen to include on the rover are the Strata Ground Penetrating Radar (GPR) and the Near Infrared Volatile Spectrometer System (NIRVSS). These instruments are designed to detect/analyze the ice found in the regolith. This subsystem is essential for mission success.

Table 4. *Top Level Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mechanical Reqs							
MEC-1	The system shall be capable of traversing the terrain within 10 km of the landing location in the Leibnitz Beta Plateau.	The system needs to be able to traverse the terrain in order to satisfy the mission objectives.	MR-3		Test	Mechanical	Met
MEC-2	The mechanical subsystem shall draw power less than TBD watts.	The total system has a limited amount of power available and will need to be able to run throughout the mission in order to satisfy the mission objectives.	MR-4		Analysis	Mechanical	Met
MEC-3	The mechanical subsystem shall have a max mass of TBD kg.	The system has a specific amount of money allocated to the mechanical subsystem in order to remain within the budget.	MR-5		Inspection	Mechanical	Met
MEC-4	The mechanical subsystem shall be able to withstand a maximum vibration level of TBD hz.	The system needs to be able to handle vibrations caused by takeoff and landing in order to not get damaged which could jeopardize the mission.	MR-4		Test	Mechanical	Met
MEC-5	The mechanical subsystem shall be capable of withstanding TBD Newtons.	The system needs to be capable of withstanding expected loads and stresses during operation and transportation.	MR-4		Test	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MEC-6	The system shall be capable of deploying mechanisms for power consumption and scientific data collection.	The system has a predetermined volume and power from the constraints of being in the primary launch vehicle, so it will need to deploy solar panels for power generation, and deploy the instruments in order to satisfy the mission objectives..	MR-6 MR-8 MR-9		Demonstration	Mechanical	Met
MEC-7	The mechanical system shall be able to withstand a temperature range of TBD degrees celsius.	The components and subassemblies in the mechanical subsystem need to be able to expand and contract safely with the temperature fluctuations on the moon's surface.	MR-3 MR-4 SYS-2		Test	Mechanical	Met
MEC-8	The mechanical system shall cost less than $TBD.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-7		Inspection	Mechanical	Met
Electrical Power System Reqs							
EPS-1	The system shall not have a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof.	The customer requested that the system shall not include a RTG or any derivative thereof in the mission task document.	Customer	N/A	Inspection	Power	Met
EPS-2	The system shall have sufficient power in its operation for the duration of the mission lifetime of TBD.	The system needs to have sufficient power throughout the entire mission in order to satisfy the mission objectives.	MR-3	EPS-3	Analysis	Power	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
EPS-3	The power subsystem shall have a minimum power generation capacity of 200 watts.	The system needs to be able to generate power. 200 watts was derived from subsystem analysis and power budget.	EPS-2		Test	Power	Met
EPS-4	The power subsystem shall include a battery with a minimum storage capacity of 500 watt-hours.	The system needs to be capable of storing power in order to have power in the PSRs.	EPS-2		Test	Power	Met
EPS-5	The power subsystem shall be able to operate on temperatures ranging from -250°C to +120°C.	The system needs to be able to withstand and function in the range of temperatures of the moon's surface in order to remain functional throughout the mission.	SYS-2		Test	Power	Met
EPS-6	The power subsystem shall have a max mass of 50 kg.	The system cannot exceed a mass allowance of 50 kg which is derived from the overall rover mass budget outlined in the Mission Task document. If the mass exceeds this amount, the mission could be subject to cancellation.	MR-5		Inspection	Power	Met
EPS-7	The power subsystem shall be designed to meet all electromagnetic compatibility (EMC) requirements.	It is important for the electrical subsystem to have no interference with the other subsystems.	MR-8 MR-9		Test	Power	Met
EPS-8	The power subsystem shall be capable of withstanding transportation, including shocks and vibrations.	The subsystem needs to be able to withstand vibrations and shocks of the launch and landing in order to be operable	MR-4		Test	Power	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		throughout the mission.					
EPS-9	The power system shall cost less than $TBD.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-7		Inspection	Power	Met
Thermal Control System Reqs (TCS)							
TCS-1	The system shall operate in temperatures ranging from -233°C to 123°C.	The lunar environment presents extreme temperature variations, from the cold of permanently shadowed regions to the heat of lunar daytime and the system needs to be able to operate throughout the entire mission and be able to handle vast fluctuations.	SYS-2		Test	Thermal	Met
TCS-2	The thermal control system shall keep the other subsystems and instruments within the required operating range of TBD-TBD°C.	The temperature sensitive instruments and components in all of the subsystems need to be protected thermally to ensure they remain withing operating temperature throughout the entire mission.	MR-4 MR-8 MR-9		Test	Thermal	Met
TCS-3	The thermal control system shall use less than TBD watts of power.	The thermal subsystem cannot use more than the allotted power due to having a limited amount of power for the entire rover.	MR-4		Test	Thermal	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
TCS-4	The thermal control system shall have a mass less than TBD kg.	The system cannot exceed the mass allowance which is derived from the overall rover mass budget outlined in the Mission Task document. If the mass exceeds this amount, the mission could be subject to cancellation.	MR-5		Inspection	Thermal	Met
TCS-5	The thermal control system shall cost less than $TBD.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-7		Inspection	Thermal	Met
Command & Data Handling Reqs (CDH)							
CDH-1	The subsystem shall communicate with the primary mission orbiter for the duration of the mission lifetime of TBD.	The system needs to be able to communicate with the orbiter throughout the mission in order to communicate the information collected to accomplish the science objectives.	MR-8 MR-9		Demonstration	CDH	Met
CDH-2	The subsystem shall cost a max amount of $TBD	The system needs to stay within the mission's assigned budget.	MR-7		Inspection	CDH	Met
CDH-3	The subsystem shall be able to operate in the lunar environment.	The system needs to remain operational throughout the mission in order to accomplish the mission objectives.	MR-3		Test	CDH	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH-4	The subsystem shall have a max mass of TBD kg.	The system cannot exceed the mass allowance which is derived from the overall rover mass budget outlined in the Mission Task document. If the mass exceeds this amount, the mission could be subject to cancellation.	MR-5		Inspection	CDH	Met

1.5.2. Mechanical Subsystem

1.5.2.1. Mechanical Subsystem Requirements

The table below is the mechanical subsystem requirements table which baselines the criteria subassemblies that can provide the best support to the rover. Many of the requirements are derived from the system and mechanical requirements from the MCR and the descendants of such determine the characteristics of subassemblies.

Table 5. *Mechanical Subsystem Requirements*

Mechanical Reqs							
Req #	**Requirement**	**Rationale**	**Parent Req**	**Child Req**	**Verification method**	**Relevant Subsystem**	**Req met?**
MEC-1	The structure of the rover shall be capable of withstanding TBD Newtons.	The structure needs to be capable of withstanding expected loads and stresses during operation and transportation.	SYS-1	TBD	Test	Mechanical	Blank
MEC-2	The mechanical subsystem shall not draw more power than TBD watts.	The system has a limited amount of power available.	SYS-8	CDHR 1	Test	Mechanical	Blank
MEC-3	The mechanical subsystem shall not exceed a mass of TBD kg.	In order to comply with the mass constraints from the system requirements, the mechanical subsystem must not exceed a specific value.	SYS-1	TBD	Inspection	Mechanical	Blank
MEC-4	The mechanical subsystem shall not cost more than $TBD.	The system has a specific amount of money allocated to the mechanical subsystem in order to remain within the budget.	SYS-3	TBD	Inspection	Mechanical	Blank
MEC-5	The system shall be capable of moving TBD m/s.	The rover must move at a certain speed in order for the selected science instrumentation to gather data.	SYS-9	TBD	Test	Mechanical	Blank
MEC-6	The subsystem shall withstand a maximum vibration level of TBD Hz.	The suspension allows contact between the surface of the moon and the rover's wheels.	MR-8 MR-9	TBD	Test	Mechanical	Blank

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MEC-7	The rover shall be capable of traversing a maximum slope of 15 degrees.	Provided by Mission Document.	SYS-10	TBD	Test	Mechanical	Blank
MEC-8	The system shall not traverse further than 10 km from the landing zone.	Provided by Mission Document.	SYS-9 SYS-10	TBD	Demonstration	Mechanical	Blank
MEC-9	The system shall be capable of deploying mechanisms for power consumption and scientific data collection.	The system has a predetermined volume and power from the constraints of being in the primary launch vehicle so it will need to deploy solar panels for power storage, and deploy the instruments.	SYS-2	TBD	Test	Mechanical	Blank
MEC-10	The system shall be able to detect environmental hazards and avoid them.	The rover must not get stuck or damaged by environmental hazards in order to successfully accomplish the science goals.	SYS-10	TBD	Test	Mechanical	Blank
MEC-11	The structure of the rover shall maintain structural integrity within the temperature range of TBD-TBD degrees celsius.	The rover's structure can expand and contract with the temperature fluctuations of the moon's surface temperature.	SYS-9 TCS-2	TBD	Analysis	Mechanical	Blank

1.5.2.2. Mechanical Subsystem

This section of the SRR will outline the mechanical conceptual sketch of the lunar rover. The rover is engineered to optimize for the challenging lunar environment while also maintaining the working functions of a moving vehicle.

The primary mechanical sub-assemblies include:

1. Chassis and Frame: The structural backbone of the rover, strong enough to withstand the load of all the other components of the rover and the lunar surface.
2. Body: Envelops the rover's internal components so there is no exposure to radiation, dust, or temperature fluctuations.
3. Suspension: Encompasses the in-wheel motors, springs, dampers, control arms, and linkages to ensure contact with the ground is maintained while other mechanisms can be deployed successfully.
4. Locomotion: Highlights specialized wheels that are designed to navigate the Moon's regolith.
5. Motor and Gearbox: Generates rotational motion in addition to speed and modifies power as well as input, respectively, to provide the seamless power to the rover.
6. Guidance, Navigation, and Control (GNC): Utilizes acceleration and terrain sensing technologies to navigate and traverse the landscape.
7. Payload: Equipped with a drilling and collection device to sample and investigate the lunar ground, with a main focus on gears and motors to deploy such.

The chassis of the rover is an undercarriage that supports the entire structure. This usually is a metal skeleton that must endure the terrain load and load of the components of the rover itself. The chassis material was chosen under the criteria of high yield strength, fracture toughness, stress corrosion cracking resistance, and the mass impact it would have on the overall weight constraints. All of these principles are based upon material properties and have been the benchmark to select the most compatible material for the Moon. With a high yield strength, the chassis will not be as influenced to deformation nor will it be with a high fracture toughness as well, which is the ability of a material to withstand load until cracking or fatigue. The purpose of including stress corrosion cracking resistance came after the fact that “scientists were recently surprised to find evidence that our airless Moon has rust on it”. This accompanied the hypothesis of water under the Moon’s surface so in the event of data sampling, water or ice that can cause rust should be taken preventative measures toward the structural integrity of the chassis. After an extensive trade study, it was determined that the 7050 Aluminum Alloy would be the right candidate for the structural support of the rover.The frame is the same concept for support and will be made of the material.

The body is designed to protect the rover’s vital components from the temperature ranging from -233°C to 123°C while going to and fro the PSR. This element works alongside the thermal subsystem as thermal systems will allow the cooling and heating regulation, which in turn is accompanied by electrical thermal management. Additionally a source of concern comes from the regolith’s influence to damage the instrumentation on board the rover. This would call for the material of the body to be resistant toward such abrasive effects. The average particle size of lunar dust is 72 μm and it is inevitable. Later in this section, the influence of design based on lunar dust is further explored through the selection of wheels as well. Historically, multi-layer insulation (MLI) has been efficient in terms of low thermal emission and durability, however the traditional materials are mostly loose fibers. Through the progression of technology, multi-layer aerogel composites have been emerging as a promising alternative. This material has a stronger cross-link than just MLI and with silica aerogel being very moldable, this combination allows for a denser layer that can combat the regolith and thermal insulation.

The suspension of the mechanical system is designed to absorb shocks and maintain traction on the ground despite the challenging obstacles on the Moon. Various components that will be included in the suspension are in-wheel motors, springs, dampers, control arms, and linkages which all together will optimize the rover’s performance. Each wheel on the rover will be accompanied by in-wheel motors to assist in the range of the rover’s journey to and from the PSR. This design improves torque distribution and will give the rover the ability to steer difficult terrain. Springs and dampers will absorb the shocks and impacts from rocks and regolith so that the scientific instrumentation on board is not damaged from the jolts. And, finally, control arms and linkages provide controlled movement from the wheels to the main body of the rover.

For mobility and range purposes, a wheel is far more compatible with the mission concept for the rover than other locomotives such as tracks. As mentioned earlier, dust is an obstacle that cannot be ignored and should be taken into high consideration when determining which type of wheel should be on the rover. Previous designs such as the Lunar Roving Vehicle’s shape memory alloy tires were considered since it has been proven and tested, however they are susceptible to single point failures and have an elastic limit. For this mission, Venturi’s hyper-deformable wheel is a plausible option to consider. It can tackle the issue of lunar temperatures at approximately -150° and is highly durable as it is puncture proof and radiation resistant.

The motor and gearbox assembly is extremely critical to the lunar rover as it provides the necessary power and speed to navigate the terrain. A motor will be selected for the design parameters compatible with the rover in next steps which will optimize power output, efficiency, and thermal stability. It will operate within the power constraints to maximize performance. The gearbox is paired with the motor to modify and operate at desired torque to smooth power transmission. This will of course be in conjunction with the Power subsystem as it relates to the rover’s operational life. A prospect that was looked into is NASA’s Bulk Metallic Glass Gear (BMGG) project which is promising in terms of “greater wear and corrosion resistance”.

There will be GNC included in the mechanical subassembly of this subsystem for acceleration sensing and terrain sensing. Further research will be conducted as well as a trade study to determine which accelerometer can have the greatest contribution to the mission as parts can vary depending on purpose. Examples include vibration monitoring to motion detection. Terrain sensing most likely be determined depending on which aspect is more desirable, optical or data-based. Examples of these include camera systems and the Terrain Relative Navigation (TRN).

As more information is researched and modeling gets started, the following table will populate with values that can be of assistance to the other subsystems as well as the overall mission.

Table 6. *Mechanical Subsystem Sub Assembly Breakdown*

Mechanical Subsystem Sub Assembly Breakdown				
Subassembly	**TRL**	**Mass (kg)**	**Volume (m^3)**	**Max Power Draw (W)**
Chassis	8	TBD	TBD	0
Body	7	TBD	TBD	0
Suspension	8	TBD	TBD	TBD
Locomotion	4	TBD	TBD	TBD
Motor	4	TBD	TBD	TBD
GNC	9	TBD	TBD	TBD

1.5.2.3. Mechanical Subsystem Trade Studies

The following section is composed of tables that demonstrate the trade studies that led to component selections.

Table 7. *Rover Chassis Metal Trade Study*

Rover Chassis Metal Trade Study						
Criteria	**Explanation**	**Grade**	**Weight**	**2219 Aluminum Alloy**	**2014 Aluminum Alloy**	**7050 Aluminum Alloy**
Yield Strength	Ability of the material to withstand load until deformation, MPa	10 = high, 5 = medium, 1 = low, 0 = Fail	20%	3	5	6
Fracture Toughness	Ability of the material to withstand load until cracking or fatigue, MPa - m ½	10 = high, 5 = medium, 1 = low, 0 = Fail	25%	5	3	5
Stress Corrosion Cracking Resistance	Resistance to cracking that occurs under the combination of stress and corrosive environment	10 = high, 5 = medium, 1 = low, 0 = Fail	25%	4	3	6
Mass	Compactness of the material to later determine its impact on the overall weight	10 = low impact on mass 5 = medium 1 = high impact on mass 0 = Fail	30%	5	5	4
		TOTAL:	**100%**	43.50%	40%	51.5%

Table 8. *Rover Body Trade Study*

Rover Body Trade Study							
Criteria	**Explanation**	**Grade**	**Weight**	**Carbon Fiber**	**Silica Aerogel**	**Multi-layer insulation (MLI)**	**Multi-layer Aerogel Composite**
Durability	The body must be able to withstand all wear, tear, and damage from the lunar surface	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	5	5	7
Thermal Protection	The body must be able to protect against extreme temperatures	10 = high, 5 = medium 1 = low 0 = Fail	25%	3	6	5	9
Cost	Material cost of the body, dollars/ pound	10 = low cost 5 = medium cost 1 = high cost 0 = Fail	25%	5	4	5	3
Radiation	The body must ensure radiation damage does not occur internally	10 = high, 5 = medium 1 = low 0 = Fail	25%	5	9	8	10
		TOTAL:	**100%**	52.50%	60.00%	57.50%	72.50%

1.5.3. Power Subsystem

1.5.3.1. Power Subsystem Requirements

Table 9. *Power System Requirements Table*

Power Subsystem Requirements (PSR)	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
PSR-01	The power subsystem shall provide continuous power to all rover subsystems throughout the mission.	Derived from mission requirement MR-01.	MR-01	PSR-01.1, PSR-01.2	Test	Power Subsystem	Blank
PSR-01.1	The power subsystem shall include a primary power source (solar panels) and a secondary power source (regenerative fuel cells).	Ensures power availability during eclipse periods and other conditions.	PSR-01		Test	Power Subsystem	Blank
PSR-01.2	The power subsystem shall be capable of switching seamlessly between power sources.	Ensures continuous power supply.	PSR-01		Test	Power Subsystem	Blank
PSR-02	The power subsystem shall have a minimum power generation capacity of 200 watts.	Derived from subsystem analysis and power budget.	MR-01	PSR-02.1, PSR-02.2, PSR-02.3	Test	Power Subsystem	Blank
PSR-02.1	The solar panels shall generate a peak power	Based on solar panel	PSR-02		Test	Power Subsystem	Blank

	of 150 watts under standard test conditions (STC).	efficiency and surface area.					
PSR-02.2	The solar panels shall be capable of operating at a minimum efficiency of 25% at end-of-life (EOL).	Ensures long-term power generation capability.	PSR-02		Test	Power Subsystem	Blank
PSR-02.3	The regenerative fuel cells shall provide 50 watts of power during periods of low solar energy availability.	Ensures backup power generation capability.	PSR-02		Test	Power Subsystem	Blank
PSR-03	The power subsystem shall include a battery with a minimum storage capacity of 500 watt-hours.	Based on mission duration and power consumption calculations.	MR-01	PSR-03.1, PSR-03.2	Test	Power Subsystem	Blank
PSR-03.1	The battery shall have a cycle life of at least 2000 cycles under the specified load conditions.	Ensures longevity and reliability.	PSR-03		Test	Power Subsystem	Blank
PSR-03.2	The battery shall maintain at least 80% of its initial capacity after 2000 cycles.	Ensures adequate performance over the mission lifetime.	PSR-03		Test	Power Subsystem	Blank
PSR-04	The power subsystem shall be able to operate in temperatures ranging from -250°C to +120°C.	Ensures functionality in varying thermal	MR-02	PSR-04.1, PSR-04.2, PSR-04.3	Test	Power Subsystem	Blank

		environments.					
PSR-04.1	The solar panels shall be coated with a material that minimizes degradation in extreme temperatures.	Enhances durability and performance.	PSR-04		Test	Power Subsystem	Blank
PSR-04.2	The battery shall include thermal management to maintain operational temperature.	Ensures battery efficiency and safety.	PSR-04		Test	Power Subsystem	Blank
PSR-04.3	The regenerative fuel cells shall be designed to operate efficiently in the specified temperature range.	Ensures backup power system reliability.	PSR-04		Test	Power Subsystem	Blank
PSR-05	The power subsystem shall have a redundancy level of 100%, ensuring mission-critical operations in case of failure.	Based on risk analysis and redundancy planning.	MR-03	PSR-05.1, PSR-05.2	Test	Power Subsystem	Blank
PSR-05.1	Critical components shall have at least one redundant counterpart.	Ensures continued operation in case of component failure.	PSR-05		Analysis	Power Subsystem	Blank
PSR-05.2	The power distribution unit (PDU) shall have failover capabilities.	Ensures uninterrupted power supply.	PSR-05		Test	Power Subsystem	Blank

PSR-06	The power subsystem shall include solar panels with an efficiency of at least 25%.	Ensures optimal energy generation from available solar energy.	MR-04	PSR-06.1, PSR-06.2	Test	Power Subsystem	Blank
PSR-06.1	The solar panels shall be tested for efficiency under both laboratory and simulated space conditions.	Ensures accuracy of efficiency claims.	PSR-06		Test	Power Subsystem	Blank
PSR-06.2	The solar panels shall incorporate anti-reflective coating to enhance efficiency.	Maximizes energy absorption.	PSR-06		Test	Power Subsystem	Blank
PSR-07	The power subsystem shall have a mass not exceeding 50 kg.	Derived from overall spacecraft mass budget.	MR-05	PSR-07.1, PSR-07.2, PSR-07.3	Demonstration	Power Subsystem	Blank
PSR-07.1	The solar panels shall be made of lightweight materials to minimize mass.	Optimizes spacecraft mass budget.	PSR-07		Analysis	Power Subsystem	Blank
PSR-07.2	The battery shall be designed with high energy density to minimize mass.	Balances energy capacity and mass.	PSR-07		Analysis	Power Subsystem	Blank
PSR-07.3	The regenerative fuel cells shall be designed to optimize power density and minimize mass.	Ensures efficient backup power without excessive	PSR-07		Analysis	Power Subsystem	Blank

		weight.					
PSR-08	The power subsystem shall include a power distribution unit (PDU) capable of managing power to all subsystems.	Ensures efficient power distribution and management across the spacecraft.	MR-06	PSR-08.1, PSR-08.2	Test	Power Subsystem	Blank
PSR-08.1	The PDU shall include overcurrent protection for each output channel.	Prevents damage to subsystems from power surges.	PSR-08		Analysis	Power Subsystem	Blank
PSR-08.2	The PDU shall be capable of monitoring and reporting the power usage of each subsystem.	Enables power management and diagnostics.	PSR-08		Test	Power Subsystem	Blank
PSR-09	The power subsystem shall be designed to meet all electromagnetic compatibility (EMC) requirements.	Ensures no interference with other spacecraft systems.	MR-07	PSR-09.1, PSR-09.2	Test	Power Subsystem	Blank
PSR-09.1	The power subsystem shall include shielding and grounding to mitigate electromagnetic interference (EMI).	Ensures EMC compliance.	PSR-09		Analysis	Power Subsystem	Blank
PSR-09.2	The power subsystem shall be tested for EMC compliance in both lab	Verifies EMC performance.	PSR-09		Test	Power Subsystem	Blank

	and field conditions.						
PSR-10	The power subsystem shall be capable of withstanding the launch environment, including vibrations and shocks.	Ensures durability and integrity during launch.	MR-08	PSR-10.1, PSR-10.2	Test	Power Subsystem	Blank
PSR-10.1	The power system shall be able to withstand a vibration of TBD.	Validates design robustness.	PSR-10		Test	Power Subsystem	Blank
PSR-10.2	The power subsystem shall be designed to prevent any loose components or connections.	Ensures mechanical integrity.	PSR-10		Inspection	Power Subsystem	Blank
PSR-11	The power subsystem shall include health monitoring capabilities to detect and report anomalies.	Enables early detection and troubleshooting of issues.	MR-09	PSR-11.1, PSR-11.2	Test	Power Subsystem	Blank
PSR-11.1	The health monitoring system shall include sensors to monitor voltage, current, and temperature of key components.	Provides real-time status of the power subsystem.	PSR-11		Test	Power Subsystem	Blank
PSR-11.2	The health monitoring system shall be capable of logging data for post-mission analysis.	Facilitates performance assessment and troubleshooting.	PSR-11		Test	Power Subsystem	Blank
PSR-12	The power subsystem shall be capable of safe shutdown and restart	Ensures controlled recovery	MR-10	PSR-12.1, PSR-12.2	Test	Power Subsystem	Blank

	procedures.	from anomalies or maintenance activities.					
PSR-12.1	The power subsystem shall include a manual override for shutdown procedures.	Provides fail-safe operation in case of automated system failure.	PSR-12		Test	Power Subsystem	Blank
PSR-12.2	The power subsystem shall ensure that all critical data is saved prior to shutdown.	Prevents data loss during power-down events.	PSR-12		Test	Power Subsystem	Blank
PSR-13	The power subsystem shall be compatible with the spacecraft's overall thermal management system.	Ensures coordinated operation and thermal stability.	MR-11	PSR-13.1, PSR-13.2	Analysis	Power Subsystem	Blank
PSR-13.1	The power subsystem shall include thermal insulation for heat-sensitive components.	Protects components from extreme temperatures.	PSR-13		Test	Power Subsystem	Blank
PSR-13.2	The power subsystem shall be designed to dissipate excess heat generated during operation.	Prevents overheating and ensures optimal performance.	PSR-13		Test	Power Subsystem	Blank
PSR-14	The power subsystem shall be designed for ease of integration and	Facilitates assembly, testing, and	MR-12	PSR-14.1, PSR-14.2	Inspection	Power Subsystem	Blank

	maintenance.	repairs.					
PSR-14.1	The power subsystem components shall be modular to allow for easy replacement.	Simplifies maintenance and upgrades.	PSR-14		Analysis	Power Subsystem	Blank
PSR-14.2	The power subsystem design shall include standardized connectors and interfaces.	Ensures compatibility and ease of integration.	PSR-14		Inspection	Power Subsystem	Blank
PSR-15	The power subsystem shall include regenerative fuel cells capable of storing excess energy produced by solar panels.	Enhances energy storage and availability.	MR-01	PSR-15.1, PSR-15.2, PSR-15.3	Test	Power Subsystem	Blank
PSR-15.1	The regenerative fuel cells shall be capable of efficiently converting stored energy back into electrical power.	Ensures effective use of stored energy.	PSR-15		Test	Power Subsystem	Blank
PSR-15.2	The regenerative fuel cells shall be designed for rapid charging and discharging cycles.	Ensures responsiveness to changing power demands.	PSR-15		Test	Power Subsystem	Blank
PSR-15.3	The regenerative fuel cells shall include safety mechanisms to prevent overcharging and discharging.	Ensures system safety and longevity.	PSR-15		Test	Power Subsystem	Blank

1.5.3.2. Power Subsystem Overview

The power subsystem for the lunar rover mission is designed to provide reliable and continuous power to all rover subsystems throughout the mission. This design includes both primary and secondary power sources, energy storage, and distribution components to ensure a successful operation under the extreme environment of the Lunar South Pole. The following sections consist of each subassembly and their sub-components with Technology Readiness Level (TRL):

1. Primary Power Source: Solar Panels - The primary source of power for the rover is a set of high-efficiency solar panels. These panels are designed to capture solar energy and convert it into electrical power.
   Sub-components:
   - Solar Cells: High-efficiency photovoltaic cells with an efficiency of 25% at end-of-life (EOL).
   - Anti-Reflective Coating: Applied to the surface of the solar cells to enhance light absorption.
   - Panel Structure: Lightweight materials to minimize the mass of the panels.
   - Deployable Mechanism: A system to deploy and orient the panels towards the sun.

   Technology Readiness Level (TRL): 7 (System prototype demonstration in an operational environment)
2. Secondary Power Source: Regenerative Fuel Cells - The secondary power source is regenerative fuel cells that store excess energy generated by the solar panels and provide power during periods of low solar availability.
   Sub-components:
   - Electrolyzer: Converts water into hydrogen and oxygen using surplus electrical power.
   - Fuel Cell Stack: Converts stored hydrogen and oxygen back into electrical power when needed.
   - Storage Tanks: Stores hydrogen and oxygen gas safely.

- Control Electronics: Manages the operation of the electrolyzer and fuel cell stack.

Technology Readiness Level (TRL): 6 (System/subsystem model or prototype demonstration in a relevant environment)

3. Energy Storage: Battery System - The energy storage system consists of high-density batteries designed to store electrical power for use during periods when neither the solar panels nor the fuel cells can provide sufficient power.
   Sub-components:
   - Battery Cells: High energy density cells with a minimum capacity of 500 watt-hours.
   - Battery Management System (BMS): Monitors and manages the state of the battery cells to ensure optimal performance and safety.
   - Thermal Management: System to maintain the operational temperature range of the battery.

   Technology Readiness Level (TRL): 8 (Actual system completed and qualified through test and demonstration)

4. Power Distribution Unit (PDU) - The PDU is responsible for distributing electrical power from the power sources and storage to the various rover subsystems
   Sub-components:
   - Power Bus: Main distribution lines that carry power to different subsystems.
   - Overcurrent Protection: Circuitry to prevent damage from current spikes.
   - Monitoring and Control: Sensors and controllers to manage power distribution and report usage.

   Technology Readiness Level (TRL): 7 (System prototype demonstration in an operational environment)
5. Thermal Management System - The thermal management system ensures that all power subsystem components operate within their specified temperature ranges.
   Sub-Components:
   - Insulation Materials: High-performance materials to protect components from extreme temperatures.
   - Heat Dissipation Mechanisms: Systems to dissipate excess heat generated during operation.

- Thermal Sensors: Monitor the temperature of critical components.

Technology Readiness Level (TRL): 6 (System/subsystem model or prototype demonstration in a relevant environment)

6. Health Monitoring System - This system includes sensors and electronics to monitor the health and performance of the power subsystem components, ensuring early detection and reporting of anomalies.
   Sub-components:
   - Voltage, Current, and Temperature Sensors: Embedded in critical locations to monitor the operational parameters.
   - Data Logging: Records operational data for post-mission analysis.
   - Anomaly Detection Software: Analyzes sensor data to detect and report any anomalies.

The overall TRL of the power subsystem is determined by the lowest TRL among the subassemblies. In this case, the lowest TRL is 6, which applies to the regenerative fuel cells and thermal management system. Therefore, the overall TRL of the power subsystem is 6.

The following table summarizes the mass, volume, and maximum power draw for each subassembly of the power subsystem:

Table 10. *Power Subassemblies Table*

Subassembly	Mass (kg)	Volume (m^3)	Max Power Draw (W)
Solar Panels	**15**	**0.08**	**150**
Regenerative Fuel Cells	**12**	**0.05**	**50**
Battery System	**10**	**0.04**	**100**
Power Distribution Unit	**5**	**0.02**	**10**
Thermal Management System	**6**	**0.03**	**5**

Health Monitoring System	**2**	**0.01**	**5**
Total	**50**	**0.23**	**320**

1.5.3.3. Power Subsystem Trade Studies

Trade studies are critical in evaluating various design alternatives and making informed decisions to optimize the performance, reliability, and cost-effectiveness of the power subsystem. The following sections outline the trade studies conducted for each subassembly of the power subsystem: Solar Panels, Regenerative Fuel Cells, Battery Systems, Power Distribution Unit (PDU), Thermal Management System, and Health Monitoring System.

1. Solar Panels

Objective: To select the most efficient and durable solar panel technology suitable for the Lunar South Pole environment.

Alternatives Considered:

1. Silicon-based Solar Panels:
    - Efficiency: 15-20%
    - Pros: Mature technology, cost-effective.
    - Cons: Lower efficiency, heavier.
2. Gallium Arsenide (GaAs) Solar Panels:
    - Efficiency: 25-30%
    - Pros: High efficiency, excellent performance in low-light conditions.
    - Cons: Expensive, moderate weight.
3. Multijunction Solar Panels:
    - Efficiency: 30-40%
    - Pros: Highest efficiency, excellent performance across various wavelengths.
    - Cons: Very expensive, complex manufacturing process.

Trade-Off Analysis:

- Efficiency: Multijunction panels offer the highest efficiency, critical for maximizing power generation.

- Cost: Silicon-based panels are the most cost-effective, but their lower efficiency makes them less attractive.
- Weight: GaAs panels offer a balance between efficiency and weight, making them a viable option.

Selected Option: Gallium Arsenide (GaAs) Solar Panels due to their high efficiency and relatively lower cost compared to multijunction panels.

2. Regenerative Fuel Cells

Objective: To choose an efficient and reliable regenerative fuel cell system for energy storage and conversion.

Alternatives Considered:

1. Proton Exchange Membrane (PEM) Fuel Cells:
   - Pros: High efficiency, rapid response.
   - Cons: Requires high-purity hydrogen, costly.
2. Solid Oxide Fuel Cells (SOFCs):
   - Pros: High efficiency, fuel flexibility.
   - Cons: High operating temperature, slower start-up.
3. Alkaline Fuel Cells (AFCs):
   - Pros: High efficiency, operates at lower temperatures.
   - Cons: Sensitive to CO_2 contamination, complex electrolyte management.

Trade-Off Analysis:

- Efficiency: All options offer high efficiency, but PEM cells provide the best performance for rapid response needs.
- Operational Temperature: AFCs operate at lower temperatures, simplifying thermal management.
- Contaminant Sensitivity: PEM cells are less sensitive to CO_2 compared to AFCs.

Selected Option: Proton Exchange Membrane (PEM) Fuel Cells for their high efficiency, rapid response, and manageable operational requirements.

3. Battery System

Objective: To determine the most suitable battery technology for energy storage.

Alternatives Considered:

1. Lithium-Ion Batteries:

    - Energy Density: High
    - Pros: High energy density, long cycle life.
    - Cons: Thermal runaway risk, requires complex BMS.
2. Nickel-Metal Hydride (NiMH) Batteries:
    - Energy Density: Moderate
    - Pros: Safer, simpler BMS.
    - Cons: Lower energy density, heavier.
3. Solid-State Batteries:
    - Energy Density: Very high
    - Pros: High energy density, safer than lithium-ion.
    - Cons: Emerging technology, expensive, limited availability.

Trade-Off Analysis:

- Energy Density: Solid-state batteries offer the highest energy density but are not yet fully mature.
- Safety: NiMH batteries are safer but have lower energy density.
- Cycle Life: Lithium-ion batteries provide a good balance between energy density and cycle life.

Selected Option: Lithium-Ion Batteries for their high energy density and well-established technology, with an advanced BMS to mitigate safety risks.

4. Power Distribution Unit (PDU)

Objective: To design an efficient and reliable power distribution system.

Alternatives Considered:

1. Centralized PDU:
    - Pros: Simplified design, easier to control.
    - Cons: Single point of failure, potential for higher losses.
2. Decentralized PDU:
    - Pros: Redundancy, lower losses.
    - Cons: More complex design, higher initial cost.
3. Hybrid PDU:
    - Pros: Combines advantages of centralized and decentralized systems.
    - Cons: Complex to design and integrate.

Trade-Off Analysis:

- Reliability: Decentralized and hybrid systems offer better reliability due to redundancy.

- Complexity: Centralized systems are simpler but have a single point of failure.
- Efficiency: Decentralized systems can reduce losses by shortening power distribution paths.

Selected Option: Hybrid PDU to balance reliability, complexity, and efficiency.

5. Thermal Management System

Objective: To select the most effective thermal management approach for maintaining component temperatures.

Alternatives Considered:

1. Passive Thermal Management:
    - Methods: Insulation, radiative cooling.
    - Pros: No moving parts, low power consumption.
    - Cons: Limited effectiveness in extreme temperatures.
2. Active Thermal Management:
    - Methods: Heaters, heat pipes, pumps.
    - Pros: Highly effective, precise control.
    - Cons: Higher power consumption, complexity.
3. Hybrid Thermal Management:
    - Combination of passive and active methods.
    - Pros: Optimized performance, reduced power consumption compared to fully active systems.
    - Cons: More complex than purely passive systems.

Trade-Off Analysis:

- Effectiveness: Active and hybrid systems provide better temperature control.
- Power Consumption: Passive systems are more power-efficient.
- Complexity: Active and hybrid systems are more complex to design and maintain.

Selected Option: Hybrid Thermal Management System to balance effectiveness and power consumption.

6. Health Monitoring System

Objective: To implement an effective system for monitoring the health and performance of the power subsystem.

Alternatives Considered:

1. Basic Health Monitoring:
    - Pros: Simple, low cost.
    - Cons: Limited data, less accurate.
2. Advanced Health Monitoring:
    - Pros: Detailed data, high accuracy.
    - Cons: Higher cost, more complex.
3. Integrated Health Monitoring:
    - Pros: Comprehensive monitoring, integrates with other systems.
    - Cons: Highest cost, most complex.

Trade-Off Analysis:

- Accuracy: Advanced and integrated systems provide more detailed and accurate monitoring.
- Cost: Basic systems are cheaper but offer limited functionality.
- Integration: Integrated systems offer the best overall health management but at a higher cost and complexity.

Selected Option: Advanced Health Monitoring System for its balance of accuracy and cost.

Mass, Volume, and Max Power Draw Table

The following table summarizes the mass, volume, and maximum power draw for each subassembly based on the selected options:

Table 11. *Power System Subassemblies*

Subassembly	Mass (kg)	Volume (m^3)	Max Power Draw (W)
Solar Panels	15	0.08	150
Regenerative Fuel Cells	12	0.05	50
Battery System	10	0.04	100
Power Distribution Unit	5	0.02	10
Thermal Management System	6	0.03	5
Health Monitoring System	2	0.01	5

Total	**50**	**0.23**	**320**

1.5.4. Command and Data Handling (CDH) Subsystem

1.5.4.1. CDH Subsystem Requirements

Table 12. *Command and Data Handling Requirements*

Command & Data Handling Reqs (CDH)							
CDHR 1	The CDH system will not consume more than TBD watts per second during peak activity.	Limit the power usage of the CDH system	SYS-8, MEC-2, PSR 2.1		Test	CDH Subsystem	Blank
CDHR 2	The CDH System will not cost more than TBD to build and operate over the span of the TBD day mission.	Stay within budget of the mission	SYS-3		Analysis	CDH Subsystem	Blank
CDHR 3	CDH System employs error detection and correction through voting logic to withstand up to 7 single event upsets per second.	Remain operation al while being bombarde d by space radiation	MR-7		Test	CDH Subsystem	Blank
CDHR 4	The CDH system displays a total ionizing radiation dose tolerance of 300 mSv of radiation.	Remain operation al while being bombarde d by space radiation	MR-7		Test	CDH Subsystem	Blank
CDHR 5	CDH operations scheduled around temperatures ranging from -250°C to +120°C.	Remain operation al in extreme temperatu re fluctuation s	MR-7		Analysis	CDH Subsystem	Blank
CDHR 6	CDH employs a real time operating system with	Operating system to	MR-7		Test	CDH Subsystem	Blank

	scheduling and the synchronization of multiple tasks	manage CDH system					
CDHR 7	CDH employs telemetry monitoring system health and real-time capabilities.	Monitor system health and system capability	MR-5		Test	CDH Subsystem	Blank
CDHR 8	CDH downlink scheduling system prioritizes data transmission based on criticality and optimizes use of available bandwidth for data transmission efficiency.	Organize data storage	MR-5		Analysis	CDH Subsystem	Blank
CDHR 9	CDH transmits and stores in a data format standardized by the Consultative Committee for Space Data Systems (CCSDS), which includes deployment of the Space Packet Protocol (SPP) and binary data.	Standardize data transformations and delivery	SYS-7		Analysis	CDH Subsystem	Blank
CDHR 10	The CDH system uses Ultra High Frequency (UHF) for communication between rover and orbiter for a bandwidth of a few kilobits per second and S band and X band for a bandwidth of up to tens of mbps.	Communication with orbiter and mission control	SYS-7		Analysis	CDH Subsystem	Blank

1.5.4.2. CDH Subsystem Overview

The Command and Data Handling (CDH) system is the central nervous system of the rover, integrating various subsystems to coordinate efficient operations. The CDH subsystem manages commands, processes data, and maintains communication with Earth, enabling the rover to perform its mission tasks effectively.CDH system exists to support the function of systems such as:

1. Telemetry

2. Telecommunications
3. On board computers
4. Data storage units
5. On-board software and processing tools

The CDH is divided into subsystems each containing their own components. The applications interface serves as the abstraction layer connecting high-level mission software with the underlying hardware and low-level system software. The interface performs several essential functions that ensure smooth and efficient operation of the rover's tasks.

The execution platform provides the necessary environment for running application software from the application layer and manages hardware interactions.

The processing function includes the central computing tasks from the built-in applications that allow it to execute commands, process data, and perform mission-critical operations. It involves the use of CPUs (Central Processing Units) and FPGAs (Field Programmable Gate Arrays) to handle a variety of computational tasks for the rover.

Sensors and actuators are devices that detect and measure physical properties from the rover's environment and convert them into data for the rover's computer systems so it can be processed and stored. Actuators, furthermore, can execute physical actions based on this incoming data by converting electrical signals into mechanical movement.

Data storage ensures that all collected data, commands, and operational parameters are securely stored, easily accessible, and efficiently managed. Random-Access Memory (RAM) provides temporary storage for data so that the CPU can function to manage rover activity. RAM is volatile, meaning its contents are lost when power is off. For long-term storage, non-volatile memory is deployed.

Instruments are essential for conducting scientific research and achieving the mission's exploration goals.

Application Layer

The health monitoring and telemetry software monitors the rover's various systems and collects telemetry data such as temperature, position in space, motor functions, and other statistics to ensure that the rover operates within safe parameters and provides real-time feedback to mission control on Earth.

The fault management software handles the detection, diagnosis, and response to faults in the rover's hardware or software systems. It includes predictive algorithms to anticipate potential issues before they occur, allowing for an appropriate response.

Data processing software onboard the rover preprocesses and compresses data collected from sensors and instruments to reduce the volume of data transmitted back to Earth, to efficiently use communication channels.

Communication software manages communication between the rover, orbiter, and mission control, utilizing protocols for interplanetary distances. It ensures reliable transmission of commands and data, enabling scientists and engineers on Earth to remotely control and monitor the rover's activities.

Execution Layer

The real time operating system (RTOS) ensures that critical tasks on the rover are executed within precise timing constraints for operations such as controlling motors, responding to sensor inputs, and managing communication protocols. It is designed to handle tasks with deterministic timing requirements, where deadlines must be met consistently.

Middleware acts as a bridge between the application software and the underlying hardware components of the rover. It abstracts the complexities of hardware interactions, providing standardized interfaces and services that applications can use. Middleware facilitates communication between various software modules, such as sensor data acquisition, telemetry processing, and command execution. It ensures that different parts of the rover's software ecosystem can interact seamlessly without needing to understand the specific details of each hardware component. Middleware also enhances the modularity and flexibility of the rover's software architecture, allowing for easier integration of new sensors or instruments during the mission.

Processing Function

The CPU is the brain of the rover, responsible for executing instructions and coordinating all tasks. It handles navigation computations, data processing, communication protocols, and higher-level decision-making processes. The CPU can operate reliably in harsh environments with varying temperatures and radiation levels. It has multiple cores to handle parallel tasks efficiently and may be optimized for low power consumption to maximize the rover's operational lifespan.

Sensors and Actuators

The sensor integrator within the rover's software and hardware architecture manages the integration and coordination of sensor data. It collects data from various sensors and processes it for decision-making algorithms and telemetry.

The actuator integrator coordinates the control and operation of actuators so they respond accurately to commands and maintain operational safety and efficiency.

The high gain antenna is designed to transmit and receive signals with high directionality and gain. It lets the rover establish high-bandwidth communications with Earth from great distances. The HGA lets the rover transmit large volumes of scientific data and operational telemetry efficiently for real-time command updates and data downloads.

The low gain antenna has a wider beam width and lower gain compared to a HGA. It is used for communication when precise pointing towards the Earth or a specific satellite is not required. The LGA is used for initial communication setup, emergency communications, or as backup systems when the rover's orientation limits the use of the HGA.

Data Storage

RAM provides the necessary memory space for the rover's computer to process data from its various sensors, cameras, and scientific instruments in real-time. This is critical for CDH tasks. SSDs provide reliable storage for the large amounts of data collected by the rover's instruments and cameras. This includes high-resolution images, scientific measurements, and telemetry data.

Technology Readiness Level 2
Telemetry - F Prime Flight Software and Embedded Systems Framework
CPU - RAD 750
Operating System - VxWorks
Low Gain Antenna - Dipole antenna X band
High gain Antenna - Parabolic Antenna X band
Non Volatile Storage - Leonardo DRS DDR3/NAND Flash Solid-State Drive
Volatile Storage - Texas Instruments Radiation Hardened SDRAM

1.5.4.3. CDH Subsystem Trade Studies

Table 13. *CPU Trade Study*

CPU						
Criteria	**Explanation**	**Grade**	**Weight**	**RAD 750**	**RAD 6000**	**Intel 80C85**

Instructions per cycle	Higher IPC means the CPU can do more work per clock cycle, which can significantly enhance performance.	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	5	1
Cache Memory	Larger and faster caches (L1, L2, and L3) improve performance by reducing the time the CPU spends waiting for data.	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	7	1
Durability	Radiation hardening to withstand space and ability to function reliably over extended periods of time.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	7	4
Cost	Total cost and feasibility of implementation into final design	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	6	7
		TOTALS:	**100%**	85.00%	62.50%	32.50%

Table 14. *High Gain Antenna Trade Study*

High Gain Antenna					
Criteria	**Explanation**	**Grade**	**Weight**	**Parabolic Antenna**	**High-Gain Antenna Gimbal**
Beam Width	The beam width must be suitable for the mission plans and goals.	10 = high, 5 = medium 1 = low 0 = Fail	25%	4	6

Gain	The antenna must be able to amplify the signal in specific direction to ensure long distance signal strength.	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	8
Data Rate uplink/downlink	CDHR 8	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	8
Cost	Total cost and feasibility of implementation into final design	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	5
		TOTALS:	**100%**	72.50%	67.50%

Table 15. *Data Storage Trade Study*

Data Storage					
Criteria	**Explanation**	**Grade**	**Weight**	**NAND Flash SSD**	**RadiationHardened SDRAM**
Capacity	The system can store enough data to support the success of the mission	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	4
read/write speed	CDHR 8	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	9
Reliability	The storage will operate without failure over a specific period which also ensures data integrity.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	9
Radiation Hardening	The storage must be able to withstand the radiation environment of space.	10 = high, 5 = medium 1 = low 0 = Fail	25%	6	10
		TOTALS:	**100%**	75.00%	80.00%

Table 16. *Data Handling Trade Study*

Data Handling					
Criteria	**Explanation**	**Grade**	**Weight**	**Batch Data Handling**	**Real-Time Data Handling**
Data Reliability	The data	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	8
Response Time	The speed at which data is processed is fast enough for decision-making	10 = high, 5 = medium 1 = low 0 = Fail	25%	3	10
Latency	The system should be able to transmit data fast enough to support mission goals and plans.	10 = high, 5 = medium 1 = low 0 = Fail	25%	3	10
Scalability	The system can handle increased amounts of data rates to account for alterations from mission plans.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	9
		TOTALS:	**100%**	55.00%	92.50%

1.5.5. Thermal Management Subsystem

1.5.5.1. Thermal Management System Requirements

Table 17. *Thermal Control System Requirements*

Thermal Control System Reqs (TCS)							
Req #	**Requirement**	**Rationale**	**Parent Req**	**Child Req**	**Verification method**	**Relevant Subsystem**	**Req met?**
TCS-1	The system shall maintain an internal temperature of TBD ± TBD degrees Celcius for the duration of the mission.	Ensure systems are able to properly function.	SYS-9	TCS-5 TCS-6 TCS-8	Test	All	Blank
TCS-2	The system shall operate in temperatures ranging from -233°C to 123°C.	The lunar environment presents extreme temperature variations, from the cold of permanently shadowed regions to the heat of lunar daytime.	SYS-9	TCS-3	Test	System	Blank
TCS-3	The thermal control system shall keep other subsystems and instruments within the required operating range of TBD-TBD°C.		SYS-9			All	

TCS-4	The thermal control system shall include passive thermal insulation to minimize heat loss and gain.	Ensure temperature stability within the spacecraft and reduce the need for active thermal control, reducing power needs.	SYS-9 TCS-1		Test	Thermal Control System	Blank
TCS-5	The thermal control system shall include active thermal control mechanisms to maintain the desired temperature range.	Due to the extreme temperatures, only thermal insulation will not be sufficient for keeping the internal temperature within operating range and thus active thermal control will be required.	SYS-8 SYS-9 TCS-1		Test	Thermal Control System Power Mechanical	Blank
TCS-6	The thermal control system shall use less than TBD watts of power.		SYS-8 PSR-02		Test	Thermal Control System Power	
TCS-7	The thermal control system shall be capable of withstanding thermal cycles experienced between sunlit and shaded regions as well as day/night cycles, including PSRs.	Thermal cycles can cause significant stress on components; designing for these cycles ensures durability.	SYS-9		Test	Thermal Control System	Blank

TCS-8	The thermal control system shall monitor and report the temperature in real-time.	Real-time data is essential for managing thermal conditions effectively and monitoring critical components.	SYS-8 SYS-9 TCS-1		Analysis	Thermal Control System Power	Blank
TCS-9	The thermal control system shall have a mass less than TBD kg.		SYS-1		Inspection	Thermal Control System	Blank
TCS-10	The thermal control system shall cost less than $TBD.		SYS-3		Analysis	Thermal Control System	Blank

1.5.5.2. Thermal Management Subsystem Overview

The thermal control system (TCS) was designed keeping in mind that it must endure the extremely cold temperatures, which can reach as low as -220°C, of the chosen landing site in Leibnitz Beta Plateau. Thus, it will need good insulation and a heater to sustain the cold temperatures and keep it warm. The outskirts of the PSR will have temperatures around -170°C so the TCS will be optimized for the -170°C. At its warmest, it can get up to 40°C when the sun is out. It will consist of a passive and an active system. The overall TRL is 5 due to the multi-layer aerogel composite having a TRL of 5, but the other subassemblies have higher TRLs.

The passive thermal control will be mainly for insulation. Multi-layer aerogel composite was chosen for the rover body, which consists of multi-layer insulation (MLI) combined with aerogel. The MLI will provide the primary insulation and aerogel will provide enhanced thermal protection along with enhanced durability. Another form of passive thermal control is the use of phase change materials (PCMs) to act as a thermal buffer for critical components. To keep the rover cool when exposed to the sun, low absorptivity white paint will be used to lessen solar radiation. The MLI will also prevent the temperature of the rover from climbing too much as well as the PCMs. In addition, louvers

The MLI will consist of several layers and sub-components: outer cover, interior layers, separators, inner cover, tapes, threads, and attachments. For the outer cover, aluminized Beta cloth was chosen for micrometeoroid protection, even though it is heavier compared to other outer covers. For the interior layers, aluminized mylar was chosen based on a trade study. The other two options in the trade study, aluminized Kapton and goldized Kapton scored high as well, but aluminized mylar had the option of thinner, lower-density blanket which means it can result in a lower overall mass of the interior layers and thus ensuring compliance with the mass constraint of the rover. All the 3 blanket options had almost identical emissivity values and temperature ranges they can withstand meaning they would be equally good in thermal protection. Although not covered in the trade study, the 3 options also had the same absorptivity meaning they would also reduced heating when the rover is exposed to the sun. For the separator layer, either Dacron or Nomex netting can be used and they have similar specifications. For the inner cover, a laminated inner cover was chosen due to increased tear strength compared to a non-laminated inner cover. A trade study was done and a lightweight laminated inner cover that is aluminum coated and perforated was chosen due to it having a lower mass, thus reducing the mass of the rover. The other 2 options, double Nomex laminated and Kevlar/Kapton laminated scored equally well in terms of emissivity and durability but they were heavier. At this point, the exact tapes, threads and adhesives have not been chosen yet, but careful research and potentially trade studies will have to be done to choose these. The multi-layer aerogel composite has TRL 5 because it has been tested in a lab as a component but full prototype testing in an operational space environment has not been done.

Phase Change Materials (PCMs) act as a thermal buffer for critical components, slowing down the heat transfer. It also acts as a sort of redundancy if the active thermal control system malfunctions, it can release stored energy over time, which may allow the rover to have enough time to get back up to the sunlit surface and reduce the likelihood of it getting too cold, thus enhancing mission success. PCMs will be placed on critical components such as the battery, power distribution unit (PDU), command and data handling system (CDH), and the science instruments. The TRL of PCMs for this application is determined to be 7 because PCMs have been used in spacecraft and satellites, which means they have been used in an operation environment, but not specifically for a lunar south pole rover mission.

To keep the rover cool in the sun, low absorptivity white painting will be applied to the sides and the top of the rover. Since the bottom of the rover is facing the surface and not the sun, white paint will not have to be applied there. The TRL of the white paint is 8 because although white paint is commonly used for many missions, it has not been used on a rover going to a PSR in the lunar south pole hence why it does not reach TRL 9.

The active thermal control system will consist of electric heaters along with thermostats and temperature sensors to keep it warm, and to keep it cool thermally actuated louvers will be used. The temperature sensors will alert the thermostats to trigger the electric heater to run when it falls below the desired operating temperature. The louvers will automatically open by thermal actuation whenever the temperature rises and will thus ensure the rover does not overheat in the sun.

Louvers were chosen over other heat dissipating mechanisms such as a radiator due to its ability to dynamically dissipate heat whenever the temperature rises, whereas a radiator would constantly dissipate heat, making it an inefficient choice when the rover will be in the shaded and cold PSR. The louvers would stay closed in the cold PSR, reducing heat waste and keeping the rover warm and they would only open up whenever the temperature of the rover increases when it is exposed to the sun, preventing the rover from overheating. The exact TRL will have to be determined based on further design choices but for now an approximate TRL for thermally actuated louvers is 7 since it has been used in spacecraft but not specifically in a rover mission.

The electric heaters will heat the rover to the desired operating temperature to ensure the rover and its components do not get too cold. But they need thermostats and temperature sensors to function. The thermostat is the device that will trigger an electric heater to start a heating cycle whenever it drops below a certain threshold temperature. The thermostat will need accurate temperature readings which it will get from the temperature sensors placed throughout the rover, particularly near the critical components such as the battery, PDU, CDH, and science instruments. The TRL of the entire active thermal control system including the electric heaters, thermostats, and temperature sensors is 8 because electric heaters, thermostats, and temperature sensors have been used extensively for many space and rover missions, but it they have not been used on a rover going to a PSR in the lunar south pole hence why it does not reach TRL 9.

1.5.5.3. Thermal Management Subsystem Trade Studies

Table 18. *MLI Interior Layers Material Trade Study*

MLI Interior Layers Material Selection						
Criteria	**Explanation**	**Grade**	**Weight**	**Aluminized Kapton**	**Goldized Kapton**	**Aluminized Mylar**
Emissivity ε	A measure of emitted thermal radiation. Lower emittance is good to reduce heat transfer.	10 = Low emissivity, 5 = Medium emissivity 1 = High emissivity	40%	9	10	9
Density	Density of the material in g/cm^2. Lower density will result in lower overall weight of the blanket, which is good to ensure compliance with the mass constraint of the rover.	10 = Low density, 5 = Medium density 1 = High density	20%	7	7	10
Temperature resistance	The temperature range it can be exposed to. Since the PSRs are cold, it is beneficial if it can withstand colder temperatures.	10 = high 5 = medium 1 = low 0 = fails to meet the temperature requirements	20%	10	10	10
		TOTALS:	**80%**	70.00%	74.00%	76.00%

Table 19. *MLI Laminated Inner Cover Material Trade Selection*

MLI Laminated Inner Cover Material Selection						
Criteria	**Explanation**	**Grade**	**Weight**	**Double Nomex Laminate**	**Kevlar/ Kapton Laminate**	**Lightweight Laminate**
Emissivity ε	A measure of emitted thermal radiation. Lower emittance is good to reduce heat transfer.	10 = Low emissivity, 5 = Medium emissivity 1 = High emissivity	40%	10	10	10
Mass	Mass of the material, lower mass is beneficial to ensure compliance with mass constraint.	10 = Low mass, 5 = Medium mass 1 = High mass	30%	6	8	10
Durability	Considers tear resistance and tensile strength which is important to ensure the blanket does not break during the mission.	10 = high, 5 = medium 1 = low 0 = Fail	30%	10	10	10
		TOTALS:	**100%**	88.00%	94.00%	100.00%

1.5.6. Payload Subsystem

1.5.6.1. Payload Subsystem Requirements

The payload consists of the scientific instruments required for the mission. The requirements for this subsystem are based on the science objectives of the team and the instruments must adhere to the minimums set within these requirements. The instruments included in the payload are a Strata Ground Penetration Radar and a Near-Infrared Volatiles Spectrometer System. These two combined are able to make the measurements necessary to accomplish the chosen science objectives. On top of this, the subsystem must adhere to the constraints of weight, cost, and power usage set by other, higher level requirements.

Table 20. *Payload Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mission Reqs							
PAY-1	The payload subsystem shall not exceed a cost of $TBD	The total mission cost must not exceed $225.	MR-7		Inspection	Payload Subsystem	Blank
PAY-2	The payload subsystem shall not exceed a mass of 10 kg	The total mission mass must not exceed 85 Kg	MR-5		Inspection	Payload Subsystem	Met
PAY-3	The payload instruments shall not exceed a maximum power draw of 40 watts	The subsystem must be able to operate on battery power over extended periods	EPS-3		Test	Payload Subsystem	Met
PAY-4	The payload instruments shall be able to measure the water content of the first meter of lunar regolith	Mission must be able to complete science objective 2a	MR-9	PAY-4.1	Test	Payload Subsystem	Blank
PAY-4.1	The Ground Penetration Radar shall be able to measure water-ice presence within at least 1 meter of surface regolith within 5 centimeters	Mission must be able to complete science objective 2a	PAY-4		Test	Payload Subsystem	Blank
PAY-5	The Near-Infrared Volatile Spectrometer System(NIRVSS) shall complete science objective 6n	Mission must be able to complete science objective 6n	MR-8	PAY-5.1 PAY-5.2	Test	Payload Subsystem	Blank
PAY-5.1	The NIRVSS shall be able to measure the physical conditions of hydrogen, oxygen, and water condensation	Mission must be able to complete science objective 6n	PAY-5	PAY-5.1.1 PAY-5.1.2 PAY-5.1.3	Test	Payload Subsystem	Blank
PAY-5.1.1	The NIRVSS shall differentiate between liquid water and gaseous hydrogen, oxygen and water vapor	Instrument must be able to determining physical characteristics of condensation	PAY-5.1		Test	Payload Subsystem	Blank

PAY-5.1.2	The NIRVSS shall be able to measure temperatures of various gasses and liquids	Instrument must be able to measure physical constraints of condensation	PAY-5.1		Test	Payload Subsystem	Blank
PAY-5.1.3	The NIRVSS shall be able to differentiate between gaseous hydrogen and oxygen	Instrument must be able to individually determine hydrogen and oxygen condensation parameters	PAY-5.1		Test	Payload Subsystem	Blank
PAY-5.2	The NIRVSS shall be able to measure the composition of water and suspense regolith during the sedimentation process	Mission must be able to complete science objective 6n	PAY-5	PAY-5.2.1 PAY-5.2.2 PAY-5.2.3	Test	Payload Subsystem	Blank
PAY-5.2.1	The NIRVSS shall be able to differentiate between water and regolith suspended in liquid water using a spectral resolution of at least 50 nm	Instrument must be able to determine sedimentation characteristics under lunar gravity	PAY-5.2		Test	Payload Subsystem	Blank
PAY-5.2.2	The NIRVSS shall be able to determine the temperature of a given sample around the liquefaction temperature of water	Instrument must be able to determine sedimentation characteristics under lunar gravity	PAY-5.2		Test	Payload Subsystem	Blank
PAY-5.2.3	The NIRVSS shall be able to determine the location of suspended particles in liquid water within TBD cm	Instrument must be able to determine sedimentation characteristics under lunar gravity	PAY-5.2		Test	Payload Subsystem	Blank

1.5.6.2. Payload Subsystem Overview

The CHILLY mission rover will consist of two main science instruments, a Strata Ground Penetrating Radar (GPR) and a Near Infrared Volatile Spectrometer System (NIRVSS). The GPR is a significant and necessary tool for this mission as it is the primary instrument that will fulfill the customer given criteria (2a) of measuring the water ice abundance in the top 1 meter of the lunar regolith with an accuracy of at least +/- 5%. The GPR measures water ice abundance by measuring permittivity, an electromagnetic property that indicates the presence of water ice as well as other structures in the lunar regolith [2]. Electromagnetic waves are a crucial indicator of composition of the lunar regolith as waves reflect or refract when coming into contact with different materials. Analyzing the behavior of the electromagnetic waves provides data about the composition of the lunar surface and subsurface. Frequency of the permittivity bands in particular will give insight into not only the presence of water ice, but its abundance far below the lunar surface as well [5]. When specifically looking at high frequencies, the GPR is capable of mapping accurate water ice structures 10 meters below the surface, demonstrating that the goal of identifying water ice in the top 1 meter of the regolith will be easily fulfilled [6]. As previously stated, the electromagnetic capabilities of the GPR extend to the other materials present in the regolith. This will help to fulfill science objective 6n which includes analyzing the sedimentation of the lunar regolith. Specifically, the GPR has been shown to find the chemical and mineral composition of the lunar surface which will help when discerning different sediment particles that have settled under the lunar surface.

The primary physical characteristics that were researched in conjunction with functionality included the mass, volume, and maximum power draw of the GPR. It was found that the mass of the GPR models tends to be around 4 kg while the volume is only .01 m^3 (see Table 21). This compact size was a significant consideration which is outlined in the Payload Trade Studies. Additionally, the maximum power draw of the GPR can vary from 7 to 10 W depending on the modifications and time it is used (see Table 21). The functionality of the GPR, its physical qualities, and test runs are vital factors when determining its Technology Readiness Level (TRL) which indicates how mature the technology is. The GPR has not only been developed and used here on Earth but also has been successfully used on lunar rovers on both the Chang'E-3 mission and the Chang'E-4 mission [2] [5]. Since the technology has been tested on the moon aboard a rover, the GPR is considered to be TRL-9, which is the highest level of readiness [8]. Having a high TRL is beneficial as it reduces the risk of using the GPR as one of two science instruments aboard the rover for this mission.

The NIRVSS instrumentation will be used to identify lunar surface composition, morphology, and thermophysical properties [4]. The primary scientific objectives to be fulfilled by this instrument will include the identification of hydrogen and oxygen concentrations (6n). This instrument has two main components: a bracket assembly and a spectrometer box. The spectrometer box contains two spectrometers with distinctive capabilities to account for ice and mineral and organic compounds [11]. The bracket assembly includes a CMOS sensor that distinguishes wavelengths between 340-940 nm, a long wave calibration sensor for monitoring surface temperatures, thermopile sensors, and an infrared lamp for illumination [7]. This optimal wavelength range provides higher sensitivity to detecting atmospheric gasses, surface minerals and volatiles. The identification of elemental compositions on the moon surface is crucial for determining lunar water distribution while high resolution imaging capabilities will help capture lunar surface morphology. Additionally, the NIRVSS will further help measure the lunar surface's thermophysical responses to characterize surface materials and their behavior under microgravity. Observations obtained from the NIRVSS will ultimately provide insight into lunar surface composition, variation in volatiles including water, hydrogen, and oxygen.

NIRVSS has a TRL-9 with flight-proven technology attributed to previous and ongoing missions, including the soon to launch moon rover mission by Astrobotic's Griffin lander [3]. Some of the metrics pertaining the NIRVSS instrumentation include a mass of 3.6 kg, a volume of 0.0025 m^3, and a maximum power draw of 30 W (Table 21). Lower metrics are desirable and are met by the two chosen instruments. A max power draw of 30 W is appropriate given it is a multi-system-based instrument— and one that will overlap the criteria of two science objectives.

Table 21. *Physical Characteristics of Science Instrumentation*

Instrument	Mass (kg)	Volume (m^3)	Max Power Draw (W)
GPR	~4	.01	7 to 10
NIRVSS	3.6	.0025	30

1.5.6.3. Payload Subsystem Trade Studies

Payload subsystem trade studies were performed for determining the science instrumentation (Table 22). Three main instruments were identified as candidates for meeting the criteria highlighted in the scientific objectives of this mission: Strate Ground-Penetrating Radar (GPR), Mars Environmental Dynamics Analyzer (MEDA), and Near Infrared Volatile Spectrometer System (NIRVSS). A higher weight percentage was given to TRL and power draw as these are integral to ensuring technology readiness and successful maintenance with low energy expenditure. Ultimately, GPR and NIRVSS instruments were chosen as they fall within budget limits, demonstrate low risk, and have excellent TRLs.

To determine the rating for each instrument, quantifiable acceptable ranges were used for each criteria. The overall weight of the entire rover, as per the customer constraint, cannot exceed 85 kg. This weight limit includes the science instrumentation as well. Since the previously stated mission requirements have allocated around 50-65 kg to the various subsystems, each of the two science instruments cannot exceed a weight of 8 kg in order to stay under the total weight limit while accounting for changes that may be made to the remaining subsystems. Volume was evaluated in a similar manner by considering that the entire spacecraft cannot exceed a volume of length 1.5m x width 1.5m x height 1.5m. The volume for each instrument was found and rated by giving it a 10 rating if it was as small as can be and decreasing the number as the volume increased. Since the volume of all the instruments was relatively small, the ratings were made in comparison to each other, indicating that the smaller the volume the better. This was decided in order to allow space for the many other subsystems within the spacecraft which have higher volume as seen in previous sections. Additionally, the cost of each instrument is also significant as the given constraint states that the cost of this mission after landing cannot exceed $225 M. Considering the cost of the mission as a whole excluding the science instruments, it was found that the science instrumentation cannot exceed a total cost of $22 M. These calculations can be found in the 1.7.2 Cost Estimate section. To allow for some extra funds in case of any subsystem modifications, the cost limit was set to $11 M for each instrument. Splitting the total budget for instrumentation equally for each instrument was reasonable as each of the three instruments researched have relatively similar costs. Risk, reliability, and TRL of each instrument were also criteria that heavily affected the ratings in the trade study. The higher the TRL and reliability (therefore lower risk), the higher the rating came to be. This was evaluated by analyzing how advanced the technology is, what environments it has been tested in, and the missions these instruments have been used in. Lastly, power draw is also important as the rover has a set capacity of the power it can exert before recharging again. Considering that the previously stated subsystems each have power draws, the instrumentation was rated based on the amount of power it uses with low power usage being the highest rating.

The most important criteria that was evaluated in the trade study if the science instrumentation actually fulfilled one or more of the science requirements for the three objectives outlined in the Science Traceability Matrix (see Table #). This criteria is a pass/fail criteria as the science instrumentation has no purpose if it cannot fulfill the requirements needed to complete the goals for this mission. The exact reason for how the chosen instrumentation fulfills every requirement is explained in section 1.5.6.2 Payload Subsystem Overview.

Although MEDA was not chosen as one of the science instruments, it did fulfill the mission requirements as it can record both temperature and pressure of the water ice and the gasses/particles trapped within it during phase change [10]. MEDA received a low rating of 75% on the STR mainly based on cost, volume, and risk. It weighs 5.5 kg with an average total volume of 466 cubic inches [10]. MEDA is a multi-sensor system that has been used successfully on Martian surface; however, it has not yet been involved in lunar rover missions and would need to be recalibrated for this mission. For this reason, lower scores were given to risks and TRL as the same results cannot be promised on lunar missions. MEDA has a power draw up to 17 W, depending on scheduled measurements, granting it a higher value on the scale [10].

Both GPR and NIRVSS have received higher total percentage ratings on the STR, mainly determined by acceptable weight ranges, cost, low risks, high TRLs, and lower power draws. GPR has a weight of 4 kg and a low-volume of ~10,000 cc .[14] NIRVSS has a weight of 3.56 kg and a volume of about 2,500 cc.[14] Given these measurements, both instruments fall significantly below the allotted weight limit of 85 kg. Given extensive literature on previous lunar missions successfully implementing both instruments, low risks and high TRLs are linked to both the GPR and the NIRVSS .[14] Low power draw values were also obtained for each instrument. GPR has a maximum power draw between 7 to 10 W, which is well under the maximum acceptable range. On the other hand, NIRVSS has a maximum power draw of up to 30 W. Nevertheless, it is important to note that it is a multi-system instrument and one that also has an average power draw of 12 W .[9] NIRVSS is considered to be one instrument composed of multiple parts that work together to achieve a common objective: to characterize lunar surface composition, morphology, and thermophysical properties. All components are coordinated simultaneously to ensure proper integrated functionality for measuring and analyzing volatile compounds on the lunar surface. This integrated design allows for precise data collection, providing a comprehensive view of the lunar environment. By operating as a unified system, NIRVSS facilitates data interpretation and ensures more accurate results.

Table 22: Science Instrumentation Payload Subsystem Trade Studies

Payload Subsystem Trade Studies: Science Instrumentation						
Criteria	**Explanation**	**Grade**	**Weight**	**Strata Ground-Penetrating Radar (GPR)**	**Mars Environmental Dynamics Analyzer (MEDA)**	**Near Infrared Volatile Spectrometer System (NIRVSS)**
Weight	Portability, operational efficiency, structural integrity	10 = falls on the lower end of desired weight range (0-8kg) 5 = middle of weight range 1 = higher end of weight range 0 = Fail	15%	8	8	9
Cost	Within budget estimates (relate to cost estimate breakdown)	10 = much lower than max budget ($10 mil) 5 = middle of budget 1 = reaches max budget 0 = Fail = surpasses max budget	15%	9	8	8
Risks/Reliability	Potential hazards, hardware malfunction, mitigation strategies available	10 = very low risks to none 5 = medium 1 = low 0 = Fail (high risk)	15%	8	5	9
Volume	Portability, operational efficiency, spatial constraints	10 = less than supported upper limit 5 = medium 1 = low 0 = Fail =	15%	7	6	8

		supasses upper limit				
TRL	reliability, minimizing malfunction	10 = high 5 = medium 1 = low 0 = Fail	20%	10	9	10
Power Draw	minimize costs	10 = much lower than max power draw 5 = medium expected power draw 1 = reaches max power draw (50 W) 0 = Fail = supasses max power draw	20%	10	9	9
Science Requirement Fulfilled	Must fulfill requirements for the science objectives	Pass: fulfills one or more requirements Fail: does not fulfill any requirements	Cannot be an instrument if Fail	Pass	Pass	Pass
		TOTALS:	**100%**	86.50%	75.00%	89.00%

1.5.7. Recovery and Redundancy

Power Subsystem:

Primary Power Source: Solar Panels

Redundancy: The solar panels are a critical component of the power subsystem, providing the primary source of electrical power. Due to their large size and high cost, duplicating the entire solar panel array is not feasible. Instead, redundancy is achieved through the use of multiple smaller panels configured in parallel. This design ensures that if one panel or a section of panels fails, the remaining panels can continue to generate power, at a cost reduced in capacity. Additionally, the deployment and orientation mechanisms are designed with multiple actuators to ensure reliability in case of a single actuator failure.

Recovery: Software controls are in place to manage the deployment and orientation of the solar panels. In the event of a partial panel failure, the system can adjust the orientation of the remaining panels to maximize power generation. The health monitoring system continuously checks the performance of each panel and can isolate and bypass failed sections to maintain overall system functionality.

Secondary Power Source: Regenerative Fuel Cells

Redundancy: Regenerative fuel cells are important for storing excess energy and providing power during periods of low solar availability. While duplicating the entire fuel cell system is not practical due to size and cost, redundancy is incorporated at the component level. Multiple fuel cell stacks are used, each capable of independent operation. This ensures that if one stack fails, the others can continue to function, providing a backup for energy conversion.

Recovery: The control electronics include software algorithms that manage the operation of the fuel cells. In the event of a fuel cell stack failure, the system can switch operations to the remaining stacks, ensuring continuous power supply. The software also manages the charging and discharging cycles to optimize the health and longevity of the fuel cells.

Energy Storage: Battery System

Redundancy: The battery system, essential for energy storage, incorporates redundancy through multiple battery packs. Each pack operates independently, allowing the system to continue functioning even if one or more packs fail. The battery management system (BMS) monitors the health of each pack and can isolate failed units to prevent them from affecting the overall system.

Recovery: The BMS software plays a crucial role in recovery, actively managing the charge and discharge cycles of the batteries. In case of a battery pack failure, the BMS can redistribute the load among the remaining packs, ensuring uninterrupted power supply. The system also includes algorithms for thermal management to prevent overheating and ensure safe operation.

Power Distribution Unit (PDU)

Redundancy: The PDU is designed with multiple redundant pathways for power distribution. This means that if one pathway or circuit fails, alternative routes can be used to maintain power flow to critical subsystems. Overcurrent protection and multiple power line ensures the reliability of the distribution network.

Recovery: The PDU software continuously monitors the status of all power distribution pathways. In the event of a failure, the system can automatically switch to alternative routes, ensuring that power is consistently delivered to all subsystems. Diagnostic software helps identify and isolate faults quickly, minimizing downtime.

Thermal Management System

Redundancy: The thermal management system uses a hybrid approach combining passive and active elements. Redundancy is achieved by using multiple heat pipes and heaters, ensuring that if one component fails, others can take over its function. This layered approach ensures effective temperature regulation across all power subsystem components.

Recovery: Software controls manage the activation and deactivation of heaters and the flow through heat pipes. If a thermal sensor detects a failure or abnormal temperature, the system can adjust the thermal management strategy in real-time, activating backup heaters or rerouting heat dissipation mechanisms to maintain optimal operating temperatures.

Health Monitoring System

Redundancy: The health monitoring system includes multiple sensors distributed throughout the power subsystem. Redundant sensors ensure that if one sensor fails, others can still provide the necessary data to monitor system health. This redundancy is critical for maintaining accurate and reliable monitoring.

Recovery: The health monitoring software aggregates data from all sensors and can detect discrepancies that indicate sensor failures. In such cases, the system can rely on redundant sensors to continue monitoring without interruption. Additionally, if the health monitoring system itself fails, the rover is equipped with a communication protocol to transmit its data to the control team on Earth. This manual backup option allows mission control to manually check on the rover's status, analyze the data, and make informed decisions to address any issues, ensuring continued operation and safety. Furthermore, handling manual control to expertise could be an option.

Conclusion

Each subassembly of the power subsystem has been carefully designed with both hardware redundancy and software recovery mechanisms. While some components, such as solar panels and regenerative fuel cells, cannot be entirely duplicated due to size and cost constraints, strategic redundancy at the component level ensures reliability. Software recovery plays a crucial role in managing failures and maintaining uninterrupted power supply. The additional capability for manual monitoring by the control team on Earth provides an extra layer of safety, ensuring the power subsystem's robustness and reliability throughout the lunar rover mission.

Thermal Subsystem:

The passive thermal control, the multi-layer aerogel composite with multiple insulating layers, acts as a form of redundancy if the active thermal control system or power generation malfunctions. This would only be sufficient for a limited period of time until the rover eventually gets cold. One strategy to deal with this is for the rover to drive up from the PSR to the sunlit surface to warm up again, but this would be cumbersome since the rover would have to continually drive back and forth between the sunlit surface and the PSR, affecting mission operations and efficiency.

Another form of passive redundancy is the use of PCMs to protect critical components such as the battery. If the active thermal control system malfunctions, the PCM would act as a thermal buffer and reduce heat transfer and thus slow down the rate of cooling/heating for the sensitive components, meaning they have a higher chance of surviving and thus the rover itself has a higher chance of surviving. The strategy described above where the rover would intermittently drive between the PSR and the sunlit surface would further increase the likelihood of the rover surviving should there be a malfunction of the heating system because the rover could store heat energy in the PCMs.

Redundancy in the active thermal control systems will be employed, instead of just one electric heater and thermostat, at least 2 will be used so if one malfunctions, the backup component will be utilized. Multiple temperature sensors will be used in different locations of the rover for the critical components, but for redundancy, at least 2 temperature sensors will be placed in each location in case one malfunctions. A trade space analysis between mass, volume, cost and complexity (potentially other factors too) will have to be done to determine the appropriate level of redundancy of the active thermal control system.

1.5.8. Interface Control

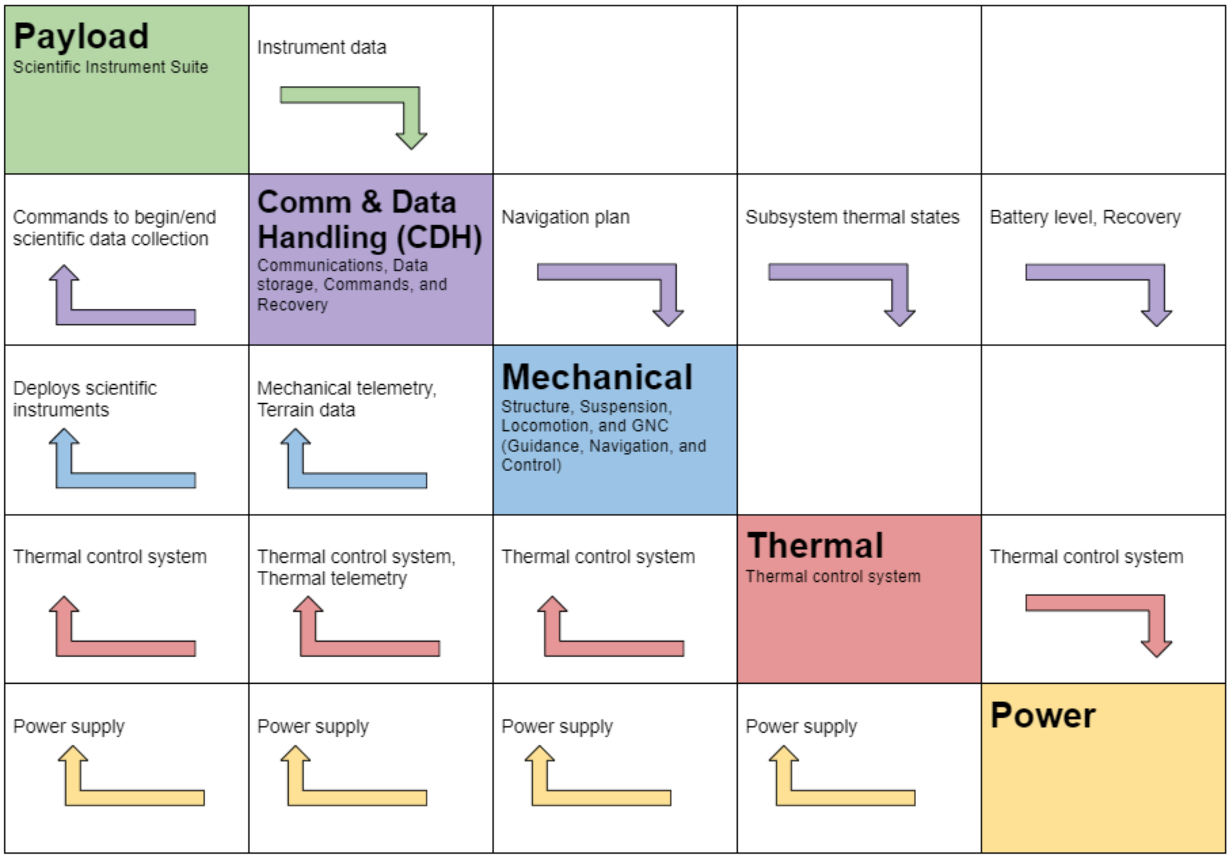

Figure 6. *N^2 Diagram*

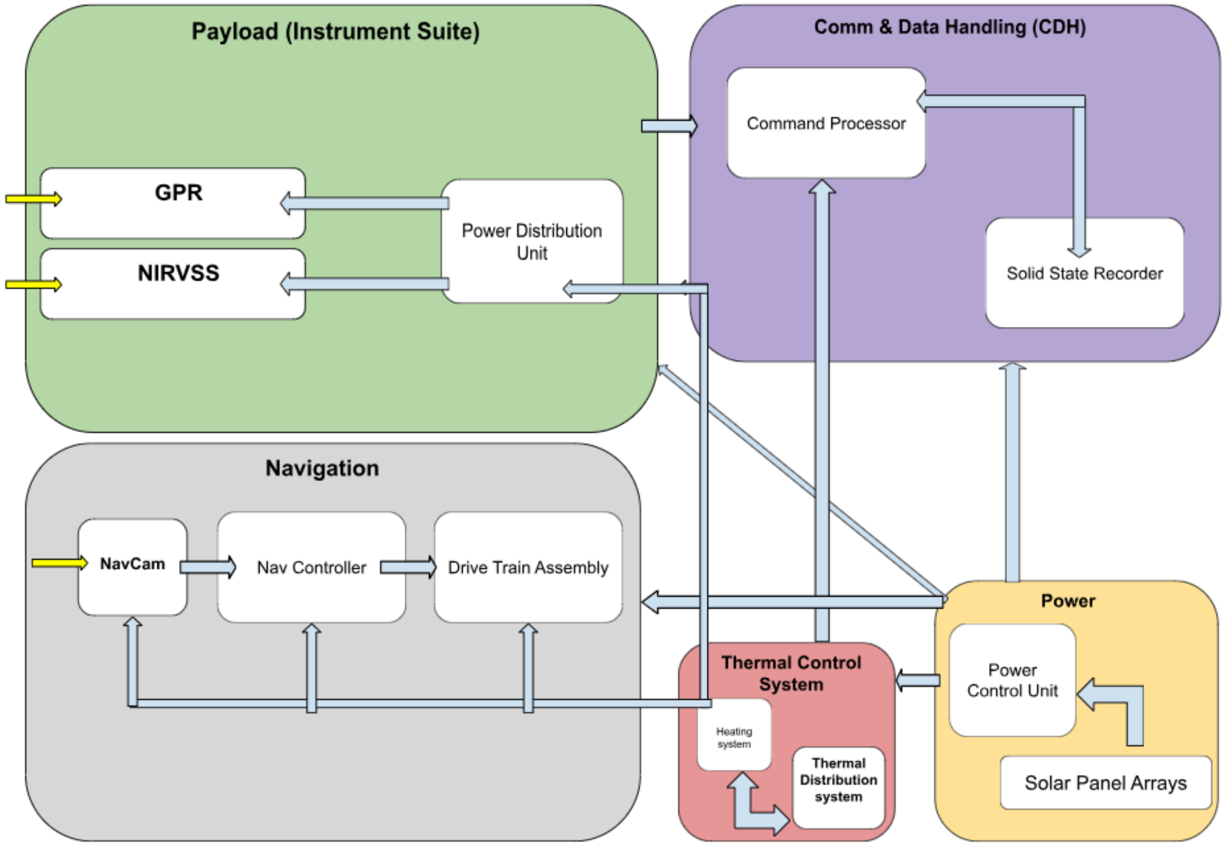

Figure 7. *Block Diagram*

1.6. Risk Analysis

1.7. Programmatics

1.7.1. Team Organization

Workload Delegation and Team Structure - Team 9's workload will be distributed based on the sub-team each member belongs to, focusing on their specific area of work. The team consists of 14 people divided into three sub-teams: Programmatics, Science, and Engineering. The delegation of work between teams and members of each team will be determined as a group led by the project manager. Within the subteams, the sub-team leaders, chief scientist, deputy project manager, and lead systems engineer, will discuss with the sub-team to delegate workload. To distribute the workload to each upper-level team, team Chilly will meet and discuss what team would be best for each section. With input from everyone, the project manager will have final say on the distribution of work. To prevent a work overload on any given team, communication will be held to ensure that each upper-level team will be able to complete their assigned sections on time.

Programmatics: This is the main management team responsible for overseeing the schedule, cost, and outreach of the mission. They will handle tasks related to the mission's timeline and budget. Additionally, they will communicate with the Project Manager and the other sub-teams.

Science: Led by the Chief Scientist, this team handles research and analysis tasks. Responsibilities include researching mission requirements, selecting necessary instruments, and analyzing related data. Tasks should be evenly distributed among team members.

Engineering: This team is in charge of mission design, problem-solving, and documenting the design process. Their tasks include conducting first-order analysis to meet technical requirements, developing solution plans based on research, designing prototypes for science instruments, creating CAD models, and tracking budgets and milestones. They will report to the Lead Systems Engineer.

Team Preparedness and Support - If a team member feels unprepared for an assigned task, they are encouraged to ask for assistance. Each member should contribute as much time as possible to their tasks. If someone cannot complete their task, other team members should be ready to help. Keeping an eye on the discord for any messages pertaining to this will be required and expected of each team member. Otherwise, doing research in order to complete the task may be necessary. In the case of a lack of proper communication, the team will have frequent meetings between each sub-team as well as the overall team throughout the time allotment for the assignment. During these meetings, each team member or sub-team will be able to explain any shortcomings they expect. This will include a full-team meeting on the day of the due date where everything will be finalized for the submission.

Handling Differences in Opinion - When differences in opinion or ideas arise, the team will handle them through open discussion, ensuring that all viewpoints are heard and considered. Ultimately, it will come to either a team vote, a decision made by the sub-team leader, or a decision made by the project manager, depending on the scope of the issue/disagreement.

Time Commitment - Each role will require different time requirements, however, an amount of time is required to complete all -work assigned to each person as well as roughly 3 hours a week for team meetings is required. However, some roles will require extra time. These are mainly the leadership roles of chief scientists, deputy project manager of resources, lead systems engineer, and project manager. As these are management roles, extra time is necessary to complete the assigned task as well as the other tasks required from these leadership roles. The work distribution will be done to make sure everyone has roughly the same time commitment for any given assignment. If someone must go over, they will either contact the other members of the sub-team or one of the leaders of the sub-teams/project manager.

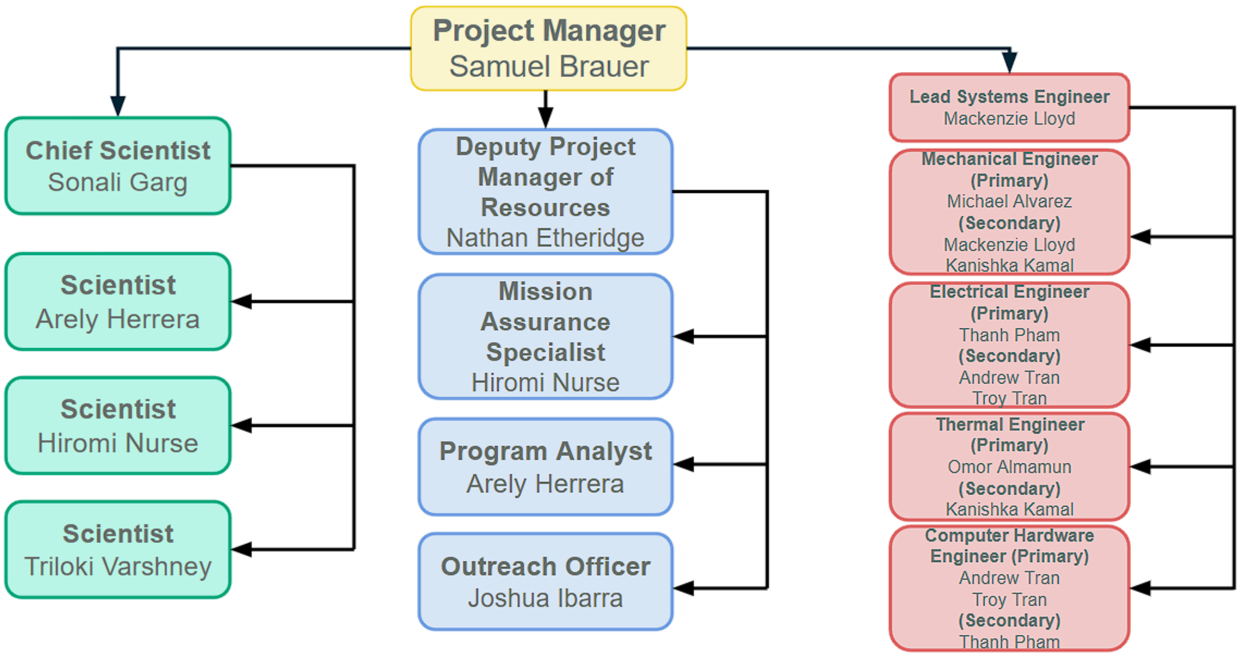

Figure 8. Hierarchy of Project Team

1.7.2. Cost Estimate

Using the proposed designs for each of the subsystems and the current plan of the overall mission, the mission budget of the Lunar Rover post-PDR along with the additional required expenses can be summarized into a mission budget chart as seen in Table 23.

The description of each major field of expense is listed below:

1. Personnel Costs: This field of expenses assumes a team of roughly 29 to 31 members throughout the duration of the project. The theorized team includes 7 Science Personnel, 10 Engineering Personnel, 7-10 Technicians, 4 Administration Personnel, and 1-2 Management Personnel. All costs associated with team personnel are based on the recommended salaries given by the Mission Task Document.
2. Travel Costs: This field of expenses encompasses the total travel costs of the entire team assuming a size of 29 members for both launch testing in

Cape Canaveral and the final launch from Cape Canaveral on September 1, 2028. These costs utilize the US General Service Admissions FY 2023 Per Diem Rates for Cape Canaveral and include food, housing, and transportation costs for a 5-day trip for each member.[15] This field also includes the travel of team leads in Phase C-D to present data to NASA headquarters in Cape Canaveral or other miscellaneous tasks that require travel costs.

3. Outreach Costs: This field of expenses involves the promotion of the mission to the general public through informational materials such as brochures and posters along with promotional events held in local venues such as community centers and schools. The costs for this category are restricted to Phases D and E-F of the mission as outreach will be performed in the period leading up to the launch of the mission and the duration of the vehicle's mission on the moon.
4. Direct Costs: This field of expenses encompasses all of the major subsystems and instrumentation associated with the vehicle. The direct costs category begins with the manufacturing and testing of the subsystems/instrumentation in Phase C of the mission to the final maintenance and management of the vehicle after its return from the mission in Phase F. How each subsystem's cost was calculated is explained briefly below:
    a. Mechanical Subsystem: The cost for the mechanical subsystem was calculated using the Mechanical/Structures Subsystem Model CER found in NCIM Version 9c. [#] This total cost was then broken into its components relevant to each phase with manufacturing costs being placed in Phase C, testing and systems engineering costs being placed in Phase C-D and Phase D, product assurance and management costs being placed in Phase E, and final management/maintenance costs being placed in Phase F of the mission.
    b. Power Subsystem: The cost for the Power subsystem was calculated using the Electronics Subsystem Model CER found in NCIM Version 9c. [#] This total cost was then broken into its components relevant to each phase with manufacturing costs being placed in Phase C, testing and systems engineering costs being placed in Phase C-D and Phase D, product assurance and management costs being placed in Phase E, and final management/maintenance costs being placed in Phase F of the mission. The power subsystem comprised the largest portion of the

direct costs field given its need for component redundancy to ensure the long-term operation of the vehicle.

c. Thermal Control Subsystem: The cost for the Thermal Control subsystem was calculated using the Thermal/Fluids Subsystem Model CER found in NCIM Version 9c. [16] This total cost was then broken into its components relevant to each phase with manufacturing costs being placed in Phase C, testing and systems engineering costs being placed in Phase C-D and Phase D, product assurance and management costs being placed in Phase E, and final management/maintenance costs being placed in Phase F of the mission.
d. Comms & Data Handling Subsystem: The cost for the Comms & Data Handling subsystem was calculated using both the Electronics and Software Subsystem Models CER found in NCIM Version 9c. [1]6 This total cost was then broken into its components relevant to each phase with manufacturing costs being placed in Phase C, testing and systems engineering costs being placed in Phase C-D and Phase D, product assurance and management costs being placed in Phase E, and final management/maintenance costs being placed in Phase F of the mission.
e. Guidance, Nav, & Control Subsystem: The cost for the Guidance, Nav, & Handling subsystem was calculated using the Software Subsystem Model CER found in NCIM Version 9c. [16] This total cost was then broken into its components relevant to each phase with manufacturing costs being placed in Phase C, testing and systems engineering costs being placed in Phase C-D and Phase D, product assurance and management costs being placed in Phase E, and final management/maintenance costs being placed in Phase F of the mission.
f. Science Instrumentation: Given Team 9's selection of a GPR and a temperature/pressure-sensing device, the costs for the instrumentation were calculated using the Body Mounted In-Situ Instrument System Model CER for the temperature/pressure-sensing device and the Active Microwave Instrument System Model CER for the GPR which were both found in NCIM Version 9c.[16] This total cost was then broken into its components relevant to each phase with manufacturing costs being placed in Phase C, testing and systems engineering costs being placed in Phase C-D and Phase D, product assurance and management costs being placed in Phase E, and final

management/maintenance costs being placed in Phase F of the mission.

Using this budget estimation, the mission's total falls within the required limit of $225 Million considering all aspects of work on the mission. This estimation also considers that the aforementioned schedule is followed and the mission is completed efficiently and within the required time frame for launch in 2028.

Table 23. *Mission Budget*

NASA L'SPACE Mission Concept Academy Budget - *C.H.I.L.L.Y.*						
Mission Phase	**Phase C**	**Phase C-D**	**Phase D**	**Phase E-F**	**Phase F**	
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 4**	**Cumulative Total**
PERSONNEL						
Science Personnel	$ 560,000	$ 589,120	$ 603,680	$ 618,240	$ 632,800	$ 3,003,840
Engineering Personnel	$ 800,000	$ 841,600	$ 862,400	$ 883,200	$ 904,000	$ 4,291,200
Technicians	$ 600,000	$ 631,200	$ 452,760	$ 463,680	$ 474,600	$ 2,622,240
Administration Personnel	$ 240,000	$ 252,480	$ 258,720	$ 264,960	$ 271,200	$ 1,287,360
Project Management	$ 240,000	$ 252,480	$ 258,720	$ 264,960	$ 271,200	$ 1,287,360
Total Salaries	$ 2,440,000	$ 2,566,880	$ 2,436,280	$ 2,495,040	$ 2,553,800	**$ 12,492,000**
Total ERE	$ 681,004	$ 716,416	$ 679,966	$ 696,366	$ 712,766	**$ 3,486,517**
Personnel Margin	$ 204,301	$ 214,925	$ 203,990	$ 208,910	$ 213,830	**$ 1,045,955**
TOTAL PERSONNEL	$ -	$ 181,907	$ 258,978	$ 353,633	$ 452,451	**$ 17,024,472**
TRAVEL						
Total Flights Cost	$ -	$ 34,200	$ 171,000	$ 171,000	$ 171,000	**$ 547,200**
Total Hotel Cost	$ -	$ 29,100	$ 145,500	$ 145,500	$ 145,500	**$ 465,600**
Total Transportation Cost	$ -	$ 19,500	$ 97,500	$ 97,500	$ 97,500	**$ 312,000**
Total Per Diem Cost	$ -	$ 6,540	$ 32,700	$ 32,700	$ 32,700	**$ 104,640**
Travel Margin	$ -	$ 14,098	$ 72,231	$ 73,974	$ 75,716	**$ 236,018**

Total Travel Costs	$ -	$ 93,986	$ 481,543	$ 493,157	$ 504,771	**$ 1,573,456**
OUTREACH						
Total Outreach Materials	$ -	$ -	$ 300,000	$ 300,000	$ -	**$ 600,000**
Total Outreach Venue Costs	$ -	$ -	$ 150,000	$ 150,000	$ -	**$ 300,000**
Total Outreach Travel Costs	$ -	$ -	$ 250,000	$ 250,000	$ -	**$ 500,000**
Total Outreach Services Costs	$ -	$ -	$ 75,000	$ 75,000	$ -	**$ 150,000**
Total Outreach Personnel Costs	$ -	$ -	$ 500,000	$ 500,000	$ -	**$ 1,000,000**
Outreach Margin	$ -	$ -	$ 150,000	$ 150,000	$ -	**$ 300,000**
Total Outreach Costs	$ -	$ -	$ 1,536,150	$ 1,573,200	$ -	**$ 3,109,350**
DIRECT COSTS						
Mechanical Subsystem	$ 8,500,000	$ 1,390,000	$ 1,390,000	$ 620,000	$ 330,000	**$ 12,230,000**
Power Subsystem	$ 30,666,000	$ 4,390,000	$ 1,280,000	$ 2,070,000	$ 1,670,000	**$ 40,076,000**
Thermal Control Subsystem	$ 1,900,000	$ 200,000	$ 200,000	$ 260,000	$ 80,000	**$ 2,640,000**
Comms & Data Handling Subsystem	$ 7,700,000	$ 2,300,000	$ 2,300,000	$ 1,060,000	$ 290,000	**$ 13,650,000**
Guidance, Nav, & Control Subsystem	$ 4,200,000	$ 1,300,000	$ 1,300,000	$ 500,000	$ 170,000	**$ 7,470,000**
Science Instrumentation	$ 15,400,000	$ 2,840,000	$ 2,840,000	$ 800,000	$ 740,000	**$ 22,620,000**
Spacecraft Cost Margin	$ 34,183,000	$ 6,210,000	$ 4,655,000	$ 2,655,000	$ 1,640,000	**$ 49,343,000**
Total Spacecraft Direct Costs	$ 102,549,000	$ 19,598,760	$ 15,054,270	$ 8,793,360	$ 5,559,600	**$ 151,554,990**
Manufacturing Facility Cost	$ 14,816,000	$ 4,444,800	$ 888,960	$ -	$ -	**$ 20,149,760**
Test Facility Cost	$ 584,000	$ 8,322,000	$ 1,664,400	$ -	$ -	**$ 10,570,400**
Facility Cost Margin	$ 7,700,000	$	$ 1,276,680	$ -	$ -	**$ 15,360,080**

		6,383,400				
Total Facilities Costs	$ 23,100,000	$ 20,146,010	$ 4,128,783	$ -	$ -	**$ 47,374,794**
Total Direct Costs	$ 125,649,000	$ 39,744,770	$ 19,183,053	$ 8,793,360	$ 5,559,600	**$ 198,929,784**
Total MTDC	$ 102,549,000	$ 19,598,760	$ 15,054,270	$ 8,793,360	$ 5,559,600	**$ 151,554,990**
FINAL COST CALCULATIONS						
Total F&A	$ 6,836,600	$ 1,338,876	$ 1,039,927	$ 613,836	$ 391,960	**$ 10,221,199**
Total Projected Cost	$ 132,485,600	$ 41,359,540	$ 22,499,651	$ 11,827,186	$ 6,908,782	**$ 215,080,759**
Total Cost Margin	$42,087,301	$ $ 12,822,423	$ 6,357,901	$ 3,087,883	$ 1,929,545	**$ 66,285,054**
	31.8%	31.0%	28.3%	26.1%	27.9%	
Total Project Cost	$ 132,485,600	$ 41,359,540	$ 22,499,651	$ 11,827,186	$ 6,908,782	**$ 215,080,759**

1.7.3. Schedule Estimate

Following the completion of Phases A-B, Team 9’s focus will shift to the completion of the mission vehicle for its scheduled launch on September 1st, 2028 from Cape Canaveral adjacent to the Kennedy Space Center. To meet this requirement and have the vehicle fully tested and prepared by the desired time, the schedule estimate in Table 24 consists of concrete phases and subtasks based on historical mission data that need to be ideally completed in the given period for the entire mission to go as smoothly as possible.[17]

The description of each of these tasks is provided below and listed in order of ID #:

1. Initial Construction and Software Development: Aligns with Phase C of the NASA Mission Life Cycle Timeline. This phase begins after the presentation of the team's PDR on the date of August 25, 2024. This task is divided into subtasks pertaining to the completion of each subsystem and concludes with the finalization of construction/software development and the writing of the CDR.

2. Endurance/Environmental Testing: Aligns with Phase C-D of the NASA Mission Life Cycle Timeline. This phase is designed to test the mission vehicle against the simulated harsh conditions of the lunar landing sight to ensure stability and implement any needed improvements to the vehicle.

3. Test Launch and Validation: Aligns with Phase D of the NASA Mission Life Cycle Timeline. This phase is designed to test a simulated launch day experiment to analyze how the mission vehicle handles the launch and weather conditions of Cape Canaveral and validate its upcoming final launch.

4. Launch Preparation and Travel: Aligns with Phase D of the NASA Mission Life Cycle Timeline. This phase prepares the mission vehicle for launch in Cape Canaveral and includes the transport of important materials and personnel to the landing sight for validation and later launch viewing.
5. Launch: Aligns with Phase D of the NASA Mission Life Cycle Timeline. This phase includes the final launch of the vehicle from Cape Canaveral on September 1, 2028, and the analysis of the mission as it departs to the Moon after launch. The mission vehicle is expected to land in the Leibnitz Beta Plateau approximately 4-5 days after launch by September 6, 2028.

6. Lunar Exploration and Travel: Aligns with Phase E-F of the NASA Mission Life Cycle Timeline. This phase monitors the mission vehicle while it is performing its mission task on the surface of the moon while also ensuring proper operation and sustainment of the vehicle for the duration of the mission period. The vehicle is expected to conclude its research by Janary 24, 2029, completing the desired 20-week period by the team.

7. Return and Analysis: Aligns with Phase F of the NASA Mission Life Cycle Timeline. This phase includes the return and retrieval of data from the

mission for the team to analyze and draw conclusions from. The mission is expected to be completed 40 weeks after return and will conclude with the final mission report.

Table 24. *Schedule Estimate*

ID#	PHASE	ASSIGNED TO	START	END	DAYS
1	**Initial Construction & Software Development**		8/25/24	7/26/26	701
1.1	Finalize Vehicle Design and obtain approval	Admin/Engineering	8/25/24	9/29/24	36
1.2	Construction of Mechanical Subsystem	Mechanical/Engineering	11/4/24	1/13/25	71
1.3	Construction of Power Subsystem	Electrical/Engineering	1/14/25	3/24/25	70
1.4	Construction of Thermal Control Subsystem	Science/Engineering	3/25/25	6/2/25	70
1.5	Construction of Comms & Nav Subsystems	Software/Engineering	6/2/25	8/10/25	70
1.6	Construction of Science Instrumentation	Science	8/10/25	10/18/25	70
1.7	Construction of Science Instrumentation	Science	8/10/25	10/18/25	70

1.8	Complete Hardware + Software Verification of Subsystems	All Teams	10/19/25	2/1/26	106
1.9	Schedule Margin		2/2/26	2/9/26	8
1.10	Conduct and Present CDR	All Teams	2/9/26	5/25/26	106
1.11	Finalize Construction and Software Development	All Teams	5/25/26	7/26/26	63
2	**Endurance/Environmental Testing**		7/27/26	6/22/27	331
2.1	Develop Testing Protocols	Admin	7/26/26	8/26/26	32
2.2	Prepare Testing Environment	Science/Mechanical	8/27/26	10/14/26	49
2.3	Conduct Environmental Testing	All Teams	10/15/26	3/4/27	141
2.4	Schedule Margin		3/4/27	3/11/27	8
2.5	Analyze Test Results	All Teams	3/12/27	4/11/27	31
2.6	Implement Improvements	All Teams	4/12/27	6/22/27	72
3	**Test Launch and Validation**		4/12/27	8/20/28	497
3.1	Coordinate Logistics	Admin	4/12/27	4/19/27	8
3.2	Final Vehicle Verification	All Teams	4/20/27	6/9/27	51
3.3	Schedule Margin		6/9/27	6/16/27	8
3.4	Transport to Launch Site	All Teams	6/17/27	7/1/27	15
3.5	Initial Test Launch	All Teams	7/1/27	7/15/27	15

3.6	Perform Final Modifications	All Teams	7/15/27	8/20/28	403
4	**Launch Preparation and Travel**		8/21/28	9/1/28	12
4.1	Travel to Cape Canaveral	Science, Engineering	8/21/28	8/28/28	8
4.2	Launch Day	Science, Engineering	8/28/28	9/1/28	5
5	**Launch**		9/1/28	9/6/28	6
5.1	Initial Launch	All Teams	9/1/28	9/1/28	1
5.2	Monitor Flight Path	All Teams	9/1/28	9/4/28	4
5.3	Estimated Landing on Selected Site	All Teams	9/5/28	9/6/28	2
6	**Lunar Exploration and Travel**		9/6/28	1/24/29	141
6.1	Monitor Landing and Vehicle Stability	Mechanical, Software	9/6/28	9/13/28	8
6.2	Conduct Lunar Surface Explorations	Science, Engineering	9/13/28	1/20/29	130
6.3	Monitor Vehicle Health	Mechanical, Software	9/13/28	1/20/29	130
6.4	Conduct water-ice experiments on Lunar Surface	Science, Engineering, Software	9/13/28	1/20/29	130
6.5	Schedule Margin		1/20/29	1/24/29	5
7	**Return and Analysis**		1/25/29	11/1/29	281
7.1	Prepare Vehicle for return journey	All Teams	1/25/29	2/8/29	15
7.2	Monitor Return to Earth	All Teams	2/8/29	2/18/29	11
7.3	Ensure Safe Re-entry	All Teams	2/18/29	2/19/29	2
7.4	Schedule Margin		2/19/29	2/25/29	7

7.5	Retrieve Data from Mission Vehicle	All Teams	2/25/29	4/8/29	43
7.6	Analyze Mission Data	All Teams	4/9/29	8/27/29	141
7.7	Prepare and Present detailed mission report	All Teams	8/28/29	11/1/29	66

1.7.4. Change Control

Team 9's process for change control follows a hierarchical system that ensures that all changes are properly requested, reviewed, approved, and implemented at the discretion of the entire team beginning with the team members and ending with the project manager. Team 9's system can be split into three main processes which will all be utilized depending on the action that needs to be taken:

1. Requesting Changes: Given that changes in any of the three sub-teams likely impact the entirety of the mission, when a team member needs to request a change that requires the use of a CRF, the team member will draft a CRF that highlights the nature of the requested change and provides specifics on what exactly the change entails for the mission as a whole. After drafting this CRF, the team member will send this CRF to their sub-team leader who will analyze the change request and, if approved, send the CRF to the project manager to formally submit. If the change requires a CCB, the team member who requested the change and the team lead will attend the CCB to argue the case for the change. If the requested change falls into the extreme change category, however, the project manager will also be suggested to attend the CCB to assist in the justification of the change and be up to date on what this change entails for the rest of the mission. In the case that changes are minor enough not to entail a CRF at the current stage of the project, changes requested by team members simply need to be communicated to the sub-team leader who will choose to approve or deny the change.
2. Implementing Changes: For the implementation of changes requested by RFAs or ADVs in document feedback, the team will collaborate during the weekly meeting to understand the demands of the change requests and

delegate the implementation of the changes to the proper sub-team. This process allows for the entire team to communicate and decide on how to handle the given change requests and come to a consensus on the best possible implementation for the success of the mission. In the case that the requested change is urgent or extremely minor, the change will be handled by the team leads and project manager and communicated to the team in the weekly meeting. If the team does not agree with the implemented change, the process for requesting a change will be followed to handle implementing the desired change.

3. Tracking and Communication: Regardless of what type of change was implemented or approved, all changes made within the team will be tracked within a centralized change log which includes details such as the change request ID (if necessary), description, the status of the change, and the responsible sub-team/team members. Team 9 utilizes this straightforward process for tracking and communicating changes as it ensures that all changes are made transparent to the team and that all team members have the ability to independently track the status of their requested changes.

1.8. Conclusion

To summarize, Team 9's mission rover was meticulously designed with its landing site, the Leibnitz Beta Plateau, at the forefront of the design process in order to ensure optimal data collection and operation throughout the duration of its mission. In order to accomplish this task, each subsystem of the mission vehicle was designed considering the specific conditions of the landing sight and the constraints of the mission requirements. The mechanical system focused on the structure, suspension, and movement of the mission vehicle while also possessing a drill for sample collection. The power subsystem utilized weather resistant solar panels and regenerative fuel cells to ensure 24/7 vehicle runtime even when sunlight was not available in the PSRs. The command and data handling subsystem utilized FPGAs as well as industry level CPU and RAM setups to maintain constant communication. The thermal management subsystem utilized aerogel composite to ensure the vehicle stays in optimal operating conditions. The payload system utilized science instrumentation of the Strata GPR and NIRVSS to ensure the best possible data collection to fulfill the science objectives for the operating area of the vehicle. This design process ensures that the mission vehicle meets the constraints of the mission and also possesses technology optimized for data collection in the Leibnitz Beta Plateau.

Looking ahead, Team 9 plans to focus on the finalization of the specifics of the vehicle system, risk mitigation strategies, and the drafting of a clear and definitive cost and schedule estimate that aligns with the specifics of the mission. While some important tasks such as the risks and redundancies were not up to standard given the time constraints of this document, as we prepare for the MDR, Team 9 aims to accomplish many of the aforementioned goals and present a mission with a clearly defined plan of action.

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> Statement: During the preparation of this work, the team used Chat-GPT4 in order to perform research, find TRLs, and in the creation of our team name. After using this tool, the team reviewed and edited the content as needed and takes full responsibility for the content of the deliverable.