

**L'PACE (Lunar Pit and Cave Explorer)
System Requirements Review**

Mentor: Josh Nelson

Team 18 - The Orchestra

Lorena Britton	Isbah Kurury
Paul Chazhur	Sudipto Mazumder
Edwin Chen	Reem Naeim
Roy Chen	Nick Richie
Carter Delavan-Hoover	Jonathan Sar-Shalom
Dan Huckleby II	Jasmyn Tirado
Riya Kapadia	Avanthika Vuppala

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Acronyms

ATLAS - Advanced Topographic Laser Altimeter System

CFD - Computational Fluid Dynamics

CSFD - Crater Size Frequency Distribution

EEE - Electrical, Electronic, and Electromechanical

EEPROM - Erasable Electronic Programmable Read-Only Memory

FIT - Failures in Time

GCR - Galactic Cosmic Ray

GNC - Guidance, Navigation, and Control

GPR - Ground-Penetrating Radar

GRAIL - Gravity Recovery and Interior Laboratory

HGA - High-Gain Antenna

KeV - Kiloelectron Volt

LGA - Low-Gain Antenna

LHP- Loop Heat Pipe

LO - Lunar Orbiter

LOLA - Lunar Orbiter Laser Altimeter

LPR - Lunar Penetrating Radar

LRS- Lunar Radar Sounder

MeV - Megaelectron Volt

MLI - Multiple Layer Insulation

nm - Nanometers

RAD - Radiation Assessment Detector

SEE - Single Event Effects

SR - Surface Rover

SSR - Sub-Surface Rover

TCS - Thermal Control System

TID - Total Ionizing Dose

TRL - Technology Readiness Level

UHF - Ultra High Frequency

w/w - weight/weight

1. System Requirements Review

1.1 Mission Statement

The goal of this mission is to organize a thorough preliminary investigation of the Marius Hills pit location and delve deep into the exploration, characterization, safety, and science of this lunar region. Assembling the foundational knowledge of the geological frameworks of Marius Hills will allow for the greater advancement of future missions to the lunar surface, in pursuit of potential human habitation and continued scientific research. The data gathered within the contents of this mission shall align with the priorities surrounding the stability and safety of the pit. This includes radiation measurements on the intensity of alpha, beta, and gamma particles through a geiger counter, with a science focus on the potency of radiation shielding. Additionally, analysis of the structural integrity of a possible lunar cave will be achieved by a ground-penetrating radar (GPR) system. Mapping in itself will be an important aspect of this mission, which will broaden the capacity for defining the variations in depth, height, terrain, ease of access and general examination of Marius Hills' constraints on stability. Similarly, temperature readings will be crucial in addressing the outlined priorities, specifically with the documentation of average temperature range within and surrounding the pit at various checkpoints.

Additional science objectives include the search of volatiles through instrumentation like infrared, mass, and neutron spectrometers, thermal imaging cameras for overlap in redundancy and science data, as well as hall sensors for possible electromagnetic field measurements. The architecture of the mission depends on the functionality of two working rovers: lunar surface and subsurface explorers. Their design is contingent on the environment they will interact with, meaning that certain instrumentation will be included within both explorers', such as the temperature measurement tools, whereas other instruments may be included in only one of the rovers. The lunar explorers will direct communication through a relay system to the primary mission Lunar Orbiter (LO), which will follow a circular polar orbit at a distance of 100 km. The data gathered and science conducted will bolster analytical understanding and build the foundation for future lunar and interplanetary exploration, assisting in the preparation of further exploration of the solar system and beyond.

Conducting this science and collecting the data will greatly benefit human exploration and habitation of the Moon. Characterizing the environment in and around the lunar pits will help to inform the viability of habitation in pits and caves, as well as potential risks to human health, assets, and infrastructure placed on the Moon in the future. In addition, the precursor science done by the mission will help lay the groundwork for future human scientific endeavors in the lunar environment.

1.2 Science Traceability Matrix

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements			Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables						
<p>“Develop precursor lunar robotic missions and define those scientific activities that astronauts will conduct on the Moon” - Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032</p>	<p>Characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves to determine the viability of human habitation.</p>	<p>Identify the types of potentially harmful radiation in and around the Marius Hills pit</p>	<p>Detect the amount of Gamma rays and Galactic Cosmic Rays (GCR) for an energy range from .001 to 10000 mega electron volts in and around the lunar pit</p>	Energy range:	.001 - 10000 MeV	.15 - 500 MeV	<p>Radiation Assessment Detector (RAD)</p>	<p>The system shall transmit at TBD bps.</p>	
				Energy resolution:	<9%	3 - 10%			
				Integration time:	Passive	900 seconds			
				Sensitivity:	300 KeV - 9 MeV	.2 - 1 MeV			
	<p>Determine the concentration and characteristics of water ice and other volatiles within lunar pits and the surrounding area</p>	<p>Identify concentration of H2O (water), -OH (hydroxyl), CO (carbon monoxide), and CO2 (carbon dioxide) in and around the Marius Hills pit</p>	<p>Detect absorbance spectra of H2O and -OH in the 2700-3200nm range and CO and CO2 in the 1300-4000nm range within the lunar regolith and rocks in and around the lunar pit</p>	Wavelength range:	1300-4000 nm	1600 - 3400 nm	<p>Near Infrared Volatile Spectrometer System (NIRVSS)</p>	<p>The system shall land within a 100 m diameter zone <5 kilometers from the Marius Hills pit</p>	
				Spectral resolution:	10-50 nm	<15 nm			
				Integration time:	1 seconds	.001-1 seconds			
				Sensitivity:	0.1% (w/w)	.5% (w/w)			
								<p>The system shall use no more than 5 g of radioactive material, if at all.</p>	

Life Support & Habitat: mLSH1 - "Provide safe and enduring habitation systems to protect individuals, equipment, and associated infrastructure" (Lunar Exploration Analysis Group (LEAG) Habitation: HAB-SAT Report, Priority Objectives)	Characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves to determine the viability of human habitation.	Collect topographical data such as elevation, slope, and surface roughness in and around the Marius Hills Pit.	Determine the slope of the surface, possible landing locations, and an accurate topographic map of the area.	Wavelength range:	1064.4 nm	1064 nm(near infrared)	REIGL VUX-1LR Light Detection and Ranging (LiDAR) System	
				Pulse repetition rate:	>28 Hz	up to 820000 Hz		
				Timing resolution:	>0.5 ns	5,000,000 - 100,000,000 ns		
	Characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves to determine the viability of human habitation.	Measure temperatures over a set time period at set time intervals at various locations inside the pit/cave	Record temperatures throughout a whole lunar day at 1) a point under an overhang and 2) deeper inside if there is a cave.	Temperature Range:	230 K - 350 K	233.15K - 343.15K		Leonardo Diagnostic/Retrieval Systems (DRS) Tenum 640
				Resolution:	<=0.05 K	0.02 K		
The system shall have a stowed configuration that fits within 2 m x 1.25 m x 1.25 m.								

	Characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves to determine the viability of human habitation.	Determine the roof thickness and width of the lunar cave.	Measure roof thickness by measuring the vertical distance from the surface outside the cave/pit to the roof of the lunar cave and the width of the lunar cave by measuring distance from one cave wall to the opposite wall.	Depth range:	>60 m	>100 m	Lunar Penetrating Radar (LPR)	The system shall communicate directly with the primary mission orbiter in a circular polar orbit at 100 km.
				Vertical resolution	<2 m	1 m		
	Characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves to determine the viability of human habitation.	Identify the types of potentially harmful radiation in and around the Marius Hills pit	Detect the amount of Gamma rays and Galactic Cosmic Rays (GCR) for an energy range from .15 to 200 mega electron volts in and around the lunar pit	Energy range:	.001-10000 MeV	.15 - 500 MeV	Radiation Assessment Detector (RAD)	The system shall be powered without the use of a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof.
				Energy resolution:	<9%	3 - 10%		
				Integration time:	Passive	900 seconds		
				Sensitivity:	300 KeV - 9 MeV	.2 - 1 MeV		

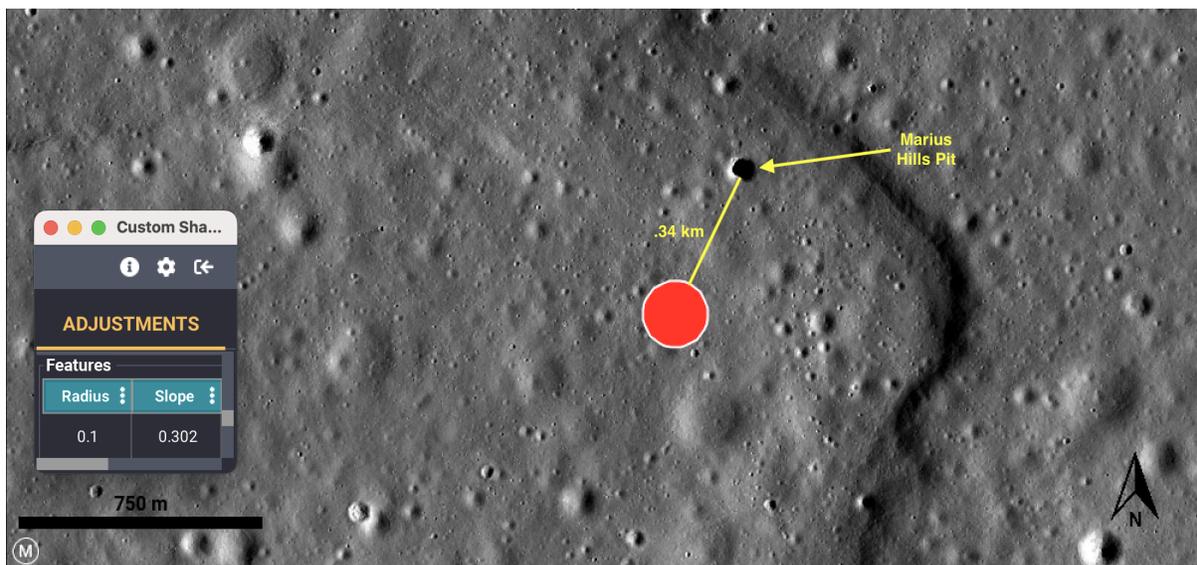
	Determine the concentration and characteristics of water ice and other volatiles within lunar pits and the surrounding area	Identify concentration of H ₂ O (water), -OH (hydroxyl), CO (carbon monoxide), and CO ₂ (carbon dioxide) in and around the Marius Hills pit	Detect absorbance spectra of H ₂ O and -OH in the 2700-3200nm range and CO and CO ₂ in the 1300-4000nm range within the lunar regolith and rocks in and around the lunar pit	Wavelength range:	1300-4000 nm	1600 - 3400 nm	Near Infrared Volatile Spectrometer System(NIRVSS)	The system will traverse across lunar regolith/terrain.
				Spectral resolution:	10-50 nm	<15 nm		
				Integration time:	1 s	.001 - 1 seconds		
				Sensitivity:	0.1% (w/w)	.5% (w/w)		

Table 1. Science Traceability Matrix

1.3 Summary of Mission Location

The mission will be collecting data from the Marius Hills Pit, focusing on the surface and subsurface. The Marius Hills Pit was selected due to its geological significance. The Lunar Radar Sounder (LRS) data from the SELENE mission revealed that the Marius Hills Pit might have a network of lava tubes. Marius Hills is an ideal exploration site, as shown by the mass deficit results from the GRAIL spacecraft and the data of a 50 km subsurface gap that suggests lava tube formations. Another interesting feature of the Marius Hills pit is its location is located directly in a lunar rille, further suggesting its lunar tube possibility. There will be two rovers: one for the subsurface and one for surface exploration. The circular landing area has a 100m diameter and an average slope of .30 degrees. The landing area is located .34 km from the Marius Hills pit. Distance to the pit was specifically chosen to provide as little displacement for the rovers as possible to lower mechanical and power systems risk, while also maximizing distance from the pit to protect from possible contamination due to lunar regolith ejecta due to lander engine exhaust. Lander engine exhaust can eject regolith away from the landing site from tens of meters up to hundreds of meters away.⁴

In order to determine whether a place is suitable for human habitation, the subsurface rover will study the geological composition, look for volatiles (such as water ice), and evaluate the structural and temperature stability. The surface rover will analyze the temperature and radiation differences between the surface and subsurface. Key instruments include the RIEGL VUX-1LR LiDAR for topographic mapping outside the cave to locate ideal landing sites, the Lunar Penetrating Radar (LPR) for probing the depth of the cave, the Radiation Assessment Detector (RAD) for radiation monitoring inside and around the cave, and the Tenum 640 IR Camera to monitor the temperature variations. These results will help NASA evaluate lunar lava tubes as possible future mission homes.



1.4 Mission Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mission Reqs							
MR-1	The system shall have a total cost of \$425M or less.	Provided by Mission Document	Customer		Analysis	All	Met
MR-2	The system shall be ready for launch by March 1, 2030.	Provided by Mission Document	Customer	MR-14	Analysis	All	Met
MR-3	The system shall determine the depth of the lunar pit/cave.	Provided by Mission Document	Customer	PAY-1, MR-14	Demonstration	Payload	Met
MR-4	The system shall determine the height within the lunar pit/cave.	Provided by Mission Document	Customer	PAY-1, MR-14	Demonstration	Payload	Met
MR-5	The system shall characterize the terrain variation of the lunar pit/cave.	Provided by Mission Document	Customer	PAY-1, MR-14	Demonstration	Payload	Met
MR-6	The system shall characterize the ease of access of the lunar pit/cave.	Provided by Mission Document	Customer	PAY-1, MR-14	Demonstration	Payload	Met
MR-7	The system shall determine the structural integrity of lunar pits/caves to determine the viability of human habitation.	Provided by Mission Document	Customer	PAY-1, MR-14	Demonstration	Payload	Met

MR-8	The system shall determine the temperature within the lunar pit/cave.	Provided by Mission Document	Customer	PAY-1, MR-14	Demonstration	Payload	Met
MR-9	The system shall determine the radiation levels within the lunar pit/cave.	Provided by Mission Document	Customer	PAY-1, MR-14	Demonstration	Payload	Met
MR-10	The system shall land within a 100 m diameter zone.	Provided by Mission Document	Customer	MR-11, MR-14	Demonstration	All	Met
MR-11	The system will travel less than 5 km from the landing zone.	Provided by Mission Document	MR-10	MR-12	Demonstration	All	Met
MR-12	The system will traverse across lunar regolith/terrain.	If the system needs to travel from the landing zone to the pit/cave, it must be able to handle the terrain.	MR-11	MR-14, MEC-4	Demonstration	All	Met
MR-13	The system shall use no more than 5 g of radioactive material, if at all.	Provided by Mission Document	Customer	EPS-1	Demonstration	All	Met
MR-14	The system shall have a mission lifespan of 30 days.	The mission necessitates this minimum amount of time to satisfy the mission objectives.	MR-2, MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9, MR-10, MR-12	MEC-3	Demonstration	System	Met

Table 2. Mission Requirements

1.5 System Definition

1.5.1 Spacecraft Overview

Mechanical Reqs	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MEC-1	The system shall have a total mass of no more than 350 kg.	Provided by Mission Document	Customer		Inspection	All	Met
MEC-2	The system shall have a stowed configuration that fits within 2 m x 1.25 m x 1.25 m.	Provided by Mission Document	Customer		Inspection	All	Met
MEC-3	The system shall maintain structural integrity within the temperature range of -150-140°C.	The temperature on the moon fluctuates within this range, with a 10-15°C margin of error built in.	MR-14		Analysis	All	Met
MEC-4	The system shall maintain structural integrity as it traverses the lunar landscape.	The system must be able to stay intact and carry out its tasks effectively no matter the terrain.	MR-12		Test	All	Met
Electrical Power System (EPS) Reqs							
EPS-1	The system shall be powered without the use of a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof.	Provided by Mission Document	Customer, MR-13	EPS-1.1	Inspection	Power, Payload	Met

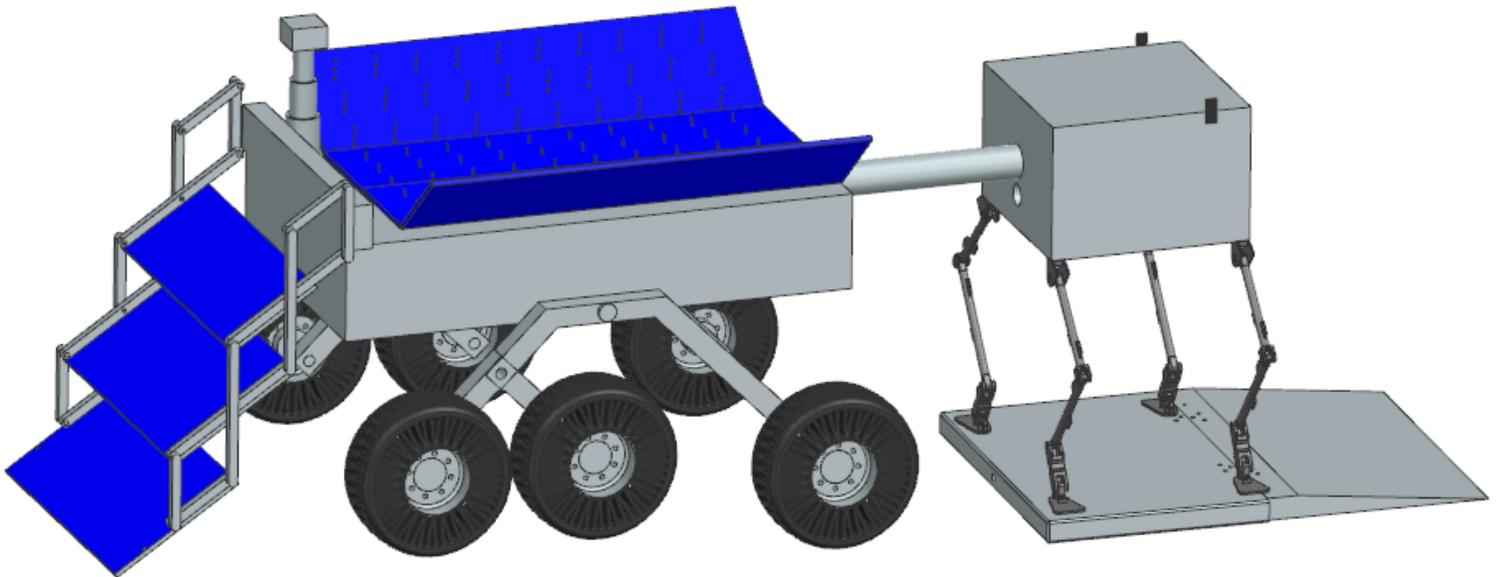
EPS-1.1	The system shall provide sufficient power to maintain operating conditions for the duration of the mission.	The System requires power in order to properly operate for the duration of the mission.	EPS-1	EPS-1.3, EPS-1.4, EPS-1.5, EPS-1.7	Analysis	All	Not Met
Payload Reqs							
PAY-1	The system shall integrate scientific instruments.	Integration of the scientific instruments will guarantee the necessary data is collected.	MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9	PAY-1.1, PAY 1-1.2, CDH-4, INS-1, INS-3	Demonstration	Payload	Met
PAY-1.1	The system shall protect scientific instruments from radiation.	The system and instruments will be prone to radiation on the moon.	PAY-1		Analysis	Payload	Met
PAY-1.2	The system shall keep scientific instruments within their operating temp. ranges.	The system will experience temperature fluctuations on the moon.	PAY-1	CDH-5 INS-2	Analysis	Payload	Met
Command & Data Handling Reqs (CDH)							
CDH-1	The system shall communicate directly with the primary mission orbiter in a circular polar orbit at 100 km.	Provided by Mission Document	Customer	CDH-4, CDH-1.1	Analysis	Command & Data Handling	Met
CDH-1.1	The surface rover shall communicate directly with the primary mission orbiter at range up to 2 Mbps.	Allows for spacecraft to send critical data per communication window within a short period of time.	CDH-1	CDH-1.1.1, CDH-1.1.2, CDH-1.1.3	Analysis	Command & Data Handling	Met

Thermal Control System Reqs (TCS)							
TCS-1	The system shall be maintained within allowable operating temperatures for all environmental conditions experienced on the lunar surface.	Ensures that all rover systems function optimally in extreme lunar conditions.	TCS-1	TCS-1.1, TCS-1.2	Analysis	Thermal Control System	Met
TCS-2	The systems shall maintain sensitive instrumentation and components within their operating temperature ranges.	Protects sensitive instruments from temperature based errors or damage.	MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9	TCS-2.1, TCS-2.2, TCS-2.3, TCS-2.4	Analysis	Thermal Control System, Payload, Power, Mechanical	Met
TCS-3	The systems shall protect sensitive instrumentation and components from damage caused by radiation.	Prevents degradation of instrumentation due to solar, cosmic, or lunar surface radiation exposure.	MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9	TCS-3.1	Demonstration	Thermal Control System	Met
TCS-4	The system shall include redundant thermal components to ensure continued operation in the event of a failure.	Enhances mission success probability by preventing singular points of failure.	MR-14	TCS-4.1	Inspection	Thermal Control System	Met
TCS-5	The system shall optimize energy consumption to maximize the rover's operational lifespan.	Ensures efficient use of limited power resources to ensure maximum lifetime during the mission duration.	MR-14	TCS-5.1	Demonstration	Thermal Control System, CDH, Power	Met
TCS-6	The total mass of both thermal control systems shall not exceed 45.1 kg.	Ensures the system is optimized to be as lightweight as possible to traverse the lunar surface more efficiently.	Customer	TCS-6.1	Inspection	Thermal Control System, Mechanical	Met

Table 3. Spacecraft Overview

In order to explore the Marius Hills lunar pit, this mission will utilize a modular design. It includes three parts: the Surface Rover (SR), the SubSurface Rover (SSR), and a solar pantograph power station. The SR is similar to a traditional rover design, with a rocker bogie drive system. The SSR is a smaller robot that uses four articulating legs to navigate the cave floor. When the spacecraft lands on the lunar surface, it will deploy itself from its stowed position. It is essentially folded into a smaller shape in order to fit within the rocket payload. The system, now in its full form without any modular systems deployed, drives to the mouth of the pit using the drive system of the SR. Once at the mouth of the pit, the SR will deploy its anchoring system and begin the process of lowering the SSR. With the SSR attached to the SR by a cable winch, the SR will begin by pushing the SSR with a telescoping rod while simultaneously turning the winch to keep tension on the tether. Once the SSR is within the mouth of the pit, the winch will slowly turn in order to lower the SSR. Once the SSR reaches the floor of the pit, it will detach from its mount on the cable. Transitioning back to the SR, the SR will deploy the solar pantograph power station with the cable that lowered the SSR attached to it, acting as a power transfer cable. Once the pantograph is deployed and detached from the SR, the SR will navigate around the pit and use its Ground Penetrating Radar (GPR) to measure the depth of possible caves. Transitioning back to the SSR, the SSR will detach from the platform it was lowered down on. This platform will be revisited as a charging station. The tether that the SSR was lowered down with will double as a power transfer method, drawing power from the solar pantograph on the surface. Following detachment, the SSR will navigate the inside of the pit, looking for evidence of a cave.

The CDH subsystem serves as the control hub for the mission's two primary systems: Surface and Subsurface Rovers. It is tasked with managing and processing data from the rovers' instruments, ensuring efficient communication between subsystems, and directing commands to execute mission tasks through its appropriate subassemblies. The subassemblies within the rover systems include telecommunication equipment, data interfacing, onboarding computer (OBC) processing, and storage devices.



Additional system CAD drawings are in Appendix A.

1.5.2 Mechanical Subsystem

1.5.2.1 Mechanical Subsystem Requirements

The lower level requirements for the mechanical subsystem are summarized in Table 4.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MEC-1	The system shall have a total mass of no more than 350 kg.	Provided by Mission Document	Customer	MEC-6, MEC-7	Analysis	Mechanical	Met
MEC-2	The system shall have a stowed configuration that fits within 2 m x 1.25 m x 1.25 m.	Provided by Mission Document	Customer	MEC-2.1	Inspection	Mechanical	Met
MEC-2.1	The system shall deploy from its stowed configuration autonomously.	The system has to deploy from its stowed configuration for full functionality and must do so with minimal human intervention.	MR-14, MEC-2	-	Demonstration	Mechanical	Met
MEC-3	The system shall traverse the lunar landscape and maintain structural integrity.	The system must be able to stay intact and carry out its tasks effectively no matter the terrain.	MR-12	MEC-3.1, MEC-3.2, MEC-3.3, MEC-3.4	Test	Mechanical	Met
MEC-3.1	The system shall maintain structural integrity within the temperature range of -150-140°C.	The temperature on the moon fluctuates within this range, with a 10-15°C margin of error built in.	MEC-3	-	Analysis	Mechanical, Thermal	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MEC-3.2	The system shall maintain structural integrity under low gravity (1.62 m/s ²).	The system and its subcomponents must function effectively under the moon's low gravity.	MEC-3	-	Test	Mechanical	Met
MEC-3.3	The system shall be capable of driving on uneven lunar terrain with inclines up to 15 degrees.	The system will need to access sloped terrain around the lunar pit.	MEC-3	-	Test	Mechanical	Met
MEC-3.4	The system shall have an autonomous guidance and navigation system capable of sensing the rovers' environment.	The GNC system will help the rovers sense their surroundings (separate from the science instruments) and navigate.	MEC-3	-	Demonstration	Mechanical	Met
MEC-4	The surface rover shall carry and deploy a solar panel pantograph capable of automatic extension within 10 minutes and providing continuous power.	The system needs to deploy the solar panels in a timely manner for power generation after landing before using up power from the batteries, and continuous power is essential for the success of the mission.	CDH-1	-	Demonstration	Mechanical, Power	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MEC-5	The subsurface rover shall safely descend the lunar pit.	The subsurface rover needs to safely descend into the pit to reach scientific targets while avoiding damage to sensitive instruments.	MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9	MEC-5.1, MEC-5.2	Test	Mechanical	Met
MEC-5.1	The surface rover shall deploy anchoring systems to secure itself to the ground while the subsurface rover descends and ascends the pit.	The surface rover needs to be stable while it is tethered to the subsurface rover and should not shift or tip.	MEC-9	-	Demonstration	Mechanical	Met
MEC-5.2	The tether connecting the subsurface rover to the surface rover shall deploy to a minimum length of 50 m.	The tether should be designed to cover 2.5 times the pit's depth.	MEC-9	-	Inspection	Mechanical	Met
MEC-6	The surface rover shall accommodate and securely mount up to 9.379 kg of scientific instruments.	The surface rover needs to carry scientific instruments and protect them during deployment using shock isolation.	MR-5, MR-6, MR-7, MR-8, MR-9, MEC-1	-	Analysis	Mechanical, Science Instrumentation	Met

Table 4. Mechanical Subsystem Lower Level Requirements

Verification and Validation

MEC-1

Verification will consist of performing a mass budget analysis on each subcomponent and subassembly. Confirm component weights align with CAD model calculations and weigh each part as it arrives. Sum all verified weights to ensure total system mass does not exceed 350 kg.

For validation after full assembly, weigh the entire system to confirm it meets the total mass requirement of 350 kg or less.

MEC-2

Verification method is inspection. Measure all stowed components in CAD and confirm dimensions using physical measurements with calipers and rulers once parts are assembled. Check against stowed volume requirements in CAD software and during physical inspection.

Validation: after full integration, perform a final inspection of the rover in its stowed state to ensure it fits within the required dimensions. Take measurements from multiple angles to confirm compliance.

MEC-2.1

Verification: demonstration. Set up deployment testing with a controlled stowed configuration. Execute automated deployment sequence and observe system's ability to unfold and reach full operational mode without human intervention.

Validation: conduct multiple autonomous deployment tests with the fully assembled rover. Assess the reliability of the deployment process over repeated cycles and under different conditions to simulate the lunar environment.

MEC-3

Verification: test. Conduct tests to simulate lunar terrain and inclines. Perform integrity tests at various lunar-like slopes (up to 15 degrees) while monitoring for any structural weaknesses.

Validation: perform a full terrain traversal test with the integrated rover over a realistic mock lunar environment. Validate that all mechanical components operate normally over a variety of slopes and rugged surfaces.

MEC-3.1

Verification: analysis. Conduct a thermal analysis (FEA in CAD) to verify materials and components can withstand extreme temperatures. Reference lunar thermal cycling profiles to ensure consistency.

Validation: place the rover in a thermal chamber and cycle through lunar thermal profiles, monitoring for material or structural deformation, component failure, or changes in mobility performance.

MEC-3.2

Verification: test. Conduct reduced gravity simulations. Test for structural resilience, functionality, and load-bearing capabilities.

Validate with the fully assembled system in a gravity offload environment, observing the entire system's behavior under 1.62 m/s^2 .

MEC-3.3

Verification: test. Set up a controlled test environment with mock lunar regolith and varying inclines. Test rover mobility, structural responses, and center of gravity on inclines up to 15 degrees.

Validation: perform system-wide incline testing with the integrated rover on a simulated lunar surface, ensuring all components function normally and remain stable on uneven and sloped terrain.

MEC-3.4

Verification: demonstration. Run system navigation tests on simulated lunar terrain to verify the GNC system's ability to detect, map, and avoid obstacles. Evaluate path-planning functionality.

Validation: test the fully assembled rover's navigation system in a simulated lunar environment, assessing autonomous obstacle avoidance, route planning, and navigation under variable conditions.

MEC-4

Verification: demonstration. Test the pantograph deployment mechanism in a controlled lab setting. Time the full deployment sequence to ensure it completes within the requirement.

Validation: perform repeated deployments with the fully assembled rover under various conditions, such as different temperatures and simulated lunar regolith.

MEC-5

Verification: test. Conduct tests simulating the lunar pit descent using a test structure that replicates the lunar pit. Monitor the subsurface rover's descent performance and tether integrity.

Validation: perform a fully integrated descent test where the subsurface rover descends into a mock lunar pit setup. Monitor for stability and safe descent to validate the system's effectiveness.

MEC-5.1

Verification: demonstration. Test the anchoring system's stability on various simulated lunar surfaces to confirm it secures the rover during tethered operations. Check both soft and hard terrain scenarios.

Validation: conduct fully integrated tests with the surface rover deploying and securing the anchoring system. Verify stability while the subsurface rover descends and ascends the tether.

MEC-5.2

Verification: inspection. Measure the tether's length to confirm it reaches 100 m. Inspect the tether's deployment mechanism to ensure it reliably extends to the required length.

Validation: with the fully assembled system, extend the tether to its full length multiple times to validate that it reaches the minimum length of 100 m and retracts safely.

MEC-6

Verification: analysis. Perform structural analysis of mounting points using CAD models and simulations to ensure they can handle the weight of the science instruments with shock isolation.

Validation: test the system's mounting points with simulated scientific equipment attached, ensuring that they remain secure during operations and under vibration tests for simulated lunar launch conditions.

1.5.2.2 Mechanical Subsystem Overview

The mechanical subsystem of the lunar mission comprises two primary components: the Surface Rover (SR) and the Subsurface Rover (SSR). Together, these rovers are designed to achieve the mission's scientific objectives by exploring the Marius Hills pit and the surrounding volcanic region on the Moon. The SR serves as a mobile base, navigating the lunar surface while providing essential support for the SSR. Through a tethering system, the SR ensures continuous power and communication for the SSR, which specializes in subsurface exploration, gathering critical data on structural stability, radiation levels, and temperature consistency. These are key factors in evaluating potential human habitation sites. When reaching an exploration site, the SR stabilizes itself using an anchoring system, allowing it to safely lower the SSR for detailed subsurface investigation. This coordinated design enables the SR to act as a stable platform while the SSR explores tight spaces, maximizing the scientific impact of their complementary designs.

Surface Rover Design

The SR is designed with a focus on mobility and stability. Its robust chassis, durable suspension, high-traction wheels, anchoring system, and instrument mounts work together to meet the demands of lunar terrain. It is built with aluminum 6061, a lightweight yet durable material, in a rectangular shape to optimize its structural integrity and the integration of necessary components. Certain areas, especially those that support the anchoring and tethering systems, are reinforced with titanium. The chassis also has mounting points for scientific instruments like LiDAR, lunar penetrating radar (LPR), and an infrared (IR) camera, as well as space for a pantograph solar panel system, a thermal radiator, and channels for routing cables to reduce the risk of tangling and wear from lunar dust.

The SR's drivetrain uses high-torque, lightweight gears paired with a six-wheeled suspension system to handle the rough, uneven terrain around the Marius Hills pit. Each wheel is powered by a separate brushless DC motor, giving the rover precise control and backup in case of motor failure. These motors are designed for low energy consumption but still provide the torque needed to navigate lunar obstacles. The SR also employs a differential drive with axle-based steering, which helps reduce the turning radius and improve maneuverability in tight spaces.

For its wheels, the SR uses non-pneumatic metallic mesh designs that are built for durability and superior traction on lunar regolith. The wheels are structured with a high-resilience mesh and steel treads to absorb shocks and resist wear from the harsh lunar environment, which helps ensure the rover's longevity and minimizes maintenance needs.

The scientific instrument suite on the SR includes the GPR for subsurface analysis, a LiDAR unit for mapping the terrain, and an IR camera for thermal imaging. Together, these instruments are vital for gathering important geological and environmental data. The SR's guidance, navigation, and control (GNC) system consists of front and rear cameras, LiDAR, a gyroscope, accelerometer, tachometer, and a tension sensor to help maintain precision and stability during the deployment and retrieval of the SSR.

Solar Pantograph Arrays

The Solar Pantograph Array on the SR serves as the rover's main energy source, specially designed to capture as much solar energy as possible when meeting the unique challenges of the lunar landscape in this mission. Placed at the front of the rover, these pantographs are built to reliably extend and retract as needed, helping the SR maintain its power supply while it navigates the rugged terrain. The front positioning is ideal since the rear of the SR is used for the SSR's tether and hitch, and the sides are needed for the rover's suspension. This arrangement keeps the front area open for the solar array deployment.

The pantograph is attached to the front side of the chassis with a slightly elevated fixed joint and two pin joints that allow it to move smoothly as it extends and retracts. This elevated position helps keep the array away from lunar dust and ensures that it deploys fully. The pantograph array relies on a winch system, which connects to a horizontal bar that runs parallel to the panels. This winch operates through a scissor-like mechanical starting behind the lowest panel, which is shorter than the others so that the winch's cable can directly connect to the horizontal bar. As the winch pulls, it gradually raises the pantograph until it locks into place, held steady by two pins at the top and bottom of the fixed joint.

Once the array is fully extended, the winch starts to lower the locked pantograph by pivoting it around the second pin joint. This lets the array tilt downward until it touches the ground, at which point the cable slackens and two automatic latches release, fully detaching the array. The deployment works in coordination with the winch motor that controls the SSR's tether, minimizing the need for additional components and keeping the overall design simple. By combining the deployment with the tether system,

the pantograph design maximizes energy capture while staying efficient and avoiding added mechanical complexity.

Anchoring System

The SR's anchoring system is designed to provide maximum stability on the lunar surface during deployment of the SSR. This system combines four powerful drill anchors and four telescoping stabilizer arms. Together, these elements ensure the rover remains securely in place, even in cases of uneven terrain or ground shifting.

The four drill anchors are positioned at each corner of the rover in a dedicated slot on the chassis. Each is equipped with a diamond-coated, self-tapping auger designed to penetrate both soft lunar regolith and hard rock. The auger's self-tapping design allows the drill to carve a secure pathway into the lunar surface as it rotates, improving grip and stability. Each drill is powered by a brushless electric motor that provides high torque with low energy consumption. The motor operates in conjunction with a linear actuator that presses the drill into the ground for initial contact and assists in burrowing to the required depth of 1 meter. To protect against jams, the drilling system has a torque limiter that adjusts to prevent excessive force if the drill encounters unexpected resistance. Once the drills reach their target depth, automated clamps secure them in place with reinforced brackets that grip the drill shaft firmly, preventing slippage due to vibration or other movement. Each drill anchor is fitted with a dust-seal barrier that prevents lunar regolith from entering the motor or actuator assemblies.

In addition to the four drill anchors, the system includes four titanium stabilizing arms, located on each side of the rover. These arms provide lateral stability and distribute the rover's weight over a larger area. The arms are motorized, allowing them to extend or retract as needed to adapt to varying terrain. There is a wide foot pad at the base of each arm that presses firmly into the lunar surface, which ensures that the stabilizing arms provide a broader contact area. Each stabilizer arm includes a locking feature that activates once the arm reaches the desired extension, holding it securely in position. The arms fold up and into the rover when not in use.

Subsurface Rover Design

The SSR is specifically designed to navigate and explore the narrow environments of lunar pits or lava tubes. Its compact chassis is also made from aluminum 6061 to strike a balance between strength and lightweight. The attachment point for the tether is reinforced with titanium to withstand the stresses involved in descending and retrieving the rover. This sturdy design ensures that the SSR can manage the challenges of subsurface operations while still being compact enough to fit within the stowed volume of the SR.

For its drivetrain, the SSR uses compact, high-torque gears that allow for low-speed yet highly precise movement. These gears provide the power needed to maneuver through the rugged and potentially steep terrains within lunar pits. Unlike the SR, the SSR relies on a four-legged suspension system, which gives it more flexibility to navigate uneven surfaces and enables it to move with precision in confined spaces.

The SSR's four foldable legs can deploy upon descent and feature multi-jointed articulation points that lock in place, giving the rover three degrees of freedom for stability and control. This flexible leg system allows the SSR to tackle challenging terrain, stabilize during operations, and adapt to the varied topography of the subsurface.

For its scientific exploration, the SSR carries specialized instruments like a radiation detector to check environmental conditions, a Near Infrared Volatile Spectrometer System (NIRVSS) for analyzing surface composition, LiDAR for mapping the insides of pits, and an IR camera for thermal imaging. The SSR's GNC suite includes cameras for navigation, a gyroscope for orientation, an accelerometer for movement tracking, and a tension sensor to ensure safe tether management.

The SR and SSR work together to enable a broad exploration mission, with the SR serving as a mobile base station that stabilizes and supports the SSR's unique subsurface operations. This integrated approach allows for thorough exploration of both surface and subsurface lunar environments, providing crucial data that enhances our understanding of lunar geology and potential resources.

Charging Pad

The Charging Pad is a specialized ramp designed for the SSR to recharge wirelessly. This setup uses a type of magnetic resonance technology similar to wireless phone chargers, so it transfers power through electromagnetic fields instead of requiring direct contact. This approach helps keep dust and regolith from interfering with the charging process, which is crucial given how abrasive lunar dust can be on electronics.

The charging pad can fold over the SR's main battery compartment when not in use, protecting the battery from regolith, temperature extremes, and small impacts. When needed, it unfolds into a ramp, allowing the SSR to walk onto it for charging. The SSR's compact design makes it easy to align itself precisely on the pad, which ensures it receives efficient power transfer. On the right side of the pad, a Kevlar-reinforced tether connects to the SSR, providing a durable link that's designed to withstand abrasion from lunar dust. This tether also allows the SSR to connect back to the SR for power if necessary.

To the left side of the pad, there's a slot for a power cable that links directly to the solar pantograph array, letting the pad charge directly from the SR's solar system. The pad also has four small wheels positioned like a car's wheels to make it stable and easy to move around the SR when needed. With this design, the charging provides a reliable, dust-resistant way for the SSR to recharge and supports both rovers in maintaining a steady power flow, even in the lunar environment's unique conditions.

Tethering System

The tethering system on the surface rover (SR) is designed to safely manage the deployment and descent of the subsurface rover (SSR) over tough lunar terrain. The process starts with the SR towing the SSR to the edge of a crater or pit, where it switches to using a detachable telescoping arm to carefully back the SSR down. This arm applies controlled mechanical force to guide the SSR's position as it's lined up for descent. Once it's in place, the arm can be disconnected, allowing the SSR to fully rely on the tether for the rest of the descent, which keeps things simpler and smoother.

At the back of the SR, a motorized spool carefully manages the tether, adjusting the cable length as needed to either release or retract it smoothly. Equipped with a tension sensor, the spool maintains optimal tautness, preventing slack that could lead to snags or jerks, which might destabilize the SSR. This tension control ensures a steady, controlled descent, reducing any sudden jolts that could potentially damage the tether or either rover.

The tether is made up of two main components, designed to provide both support and power to the SSR as it descends. There's a strong Kevlar rope that holds the weight of the SSR, and a separate power cable to supply electricity (Kevlar isn't used here, though). Both parts are wrapped in Kevlar fabric to protect them from lunar dust and prevent tangling. This Kevlar wrap is essential since lunar dust is abrasive and could damage the tether, while the wrap keeps both cables bundled together neatly.

The system also includes shock absorption features to help reduce impacts and vibrations. Spring-loaded dampeners are built in to absorb any sudden stresses, which protects the rovers if there's a sudden change in movement. There are also flexible couplings to reduce vibration transmission between the SR and SSR, helping to prevent damage from minor bumps or shocks and extending the life of the system.

For emergencies, a quick-release mechanism is included that can be activated remotely, allowing the tether to disconnect quickly if needed. This feature is essential for avoiding tether strain or entanglement if something goes wrong. To make the system more resilient to the lunar environment, dust shields are installed around the spooling and attachment points to keep out abrasive lunar dust, and thermal insulation helps the

tether stand up to extreme lunar temperatures. This setup protects against both high heat during lunar days and freezing temperatures at night.

Technology Readiness Level

The Technology Readiness Levels (TRLs) for the different subassemblies of the rover system show how mature and ready each component is, leading to an overall assessment of the entire system. In the Science Instruments subsystem, components like the Radiation Detector, NIRVSS, LiDAR, and IR Camera have relatively high TRLs of 6 to 7 because they have been used in previous space missions. However, the Lunar Penetrating Radar, or LPR, is rated at TRL 8 since it has been fully validated on the lunar surface, but requires testing in lunar pits and caves. The motors also have high TRLs of 6 to 7, while the wheels are rated at TRL 5 due to the need for traction testing on lunar regolith, making TRL 5 the most appropriate rating for this subsystem.

In the Guidance, Navigation, and Control subsystem, advanced components like the cameras and gyroscope have TRLs of 6 to 7, but the tachometer is at TRL 4 and needs more testing, especially regarding its accuracy and reliability on the Moon. This results in a TRL 4 designation for the entire subsystem. For the drilling anchoring system, the drill bit is rated at TRL 7, meaning its design is a self-tapping auger with a corkscrew shape and diamond coating that has been thoroughly tested, though it still requires further validation in lunar conditions. The telescopic feet are assessed at TRL 5 since they are made of lightweight titanium but have not been rigorously tested in lunar-like environments yet. Overall, the combined TRL for the drilling anchoring system is TRL 5.

The Subsurface Rover subsystem has varying levels of readiness. While the chassis and DC motors are well-tested and sit at TRLs of 6 to 7, the new design of the rover legs is only at TRL 4 because they need more validation for mobility and stability on the Moon, bringing the subsystem down to TRL 4. Ultimately, the entire rover system is rated at TRL 4, as several subassemblies with the lowest TRLs, like the tachometer, and subsurface rover legs, dictate this rating. These critical components need further development and testing to improve the system's readiness for lunar deployment. This assessment highlights the importance of prioritizing these components for additional testing in lunar-like environments to enhance the rover's overall reliability and integration potential.

Subassembly	TRL	Explanation
Science Instruments		
Radiation Detector	7	Radiation detection technology is well-established, with numerous precedents in planetary exploration. While slight modifications for lunar environments might be needed, the core technology is mature.
NIRVSS	6	While the underlying technology for infrared spectrometers is advanced, ensuring stable operation in lunar conditions could necessitate additional testing and qualification.
LiDAR w/ cooling fan	5	LiDAR has been used in terrestrial and Martian exploration, but the integration of a cooling fan for lunar use introduces new design and testing requirements.
LPR	8	LPR is in active development and has been successfully tested on the lunar surface, but requires further testing in lunar pits or caves.
IR Camera	7	The IR camera technology is highly robust, with extensive usage in spaceborne and terrestrial applications, making it reliable for the lunar environment.
Overall (lowest-rated)	5	
Surface Rover		
Chassis	6	The chassis design is generally mature, though unique adjustments for lunar gravity and regolith conditions will need testing to confirm structural integrity over time.
Drivetrain		
Traditional Wheels	5	Previous Mars rover wheel designs serve as a basis, but specific lunar adjustments and testing are necessary to ensure performance on the Moon's surface.
Axles	6	The technology is reliable, but additional testing may be conducted to ensure axle durability in lunar conditions.
DC motors	7	DC motor technology is advanced and reliable, with little additional testing required beyond standard integration checks.
Overall	5	
GNC		
Cameras	7	Camera technology is mature, and few modifications are needed for operation in the lunar environment.
LiDAR w/ cooling fan	5	LiDAR technology itself is advanced, but the cooling component must be validated to ensure reliability in extreme lunar temperatures.
Gyroscope	6	The gyroscope technology is mature, with precedents in planetary missions, yet additional lunar analog testing is recommended.
Accelerometer	6	Accelerometer technology is reliable, though it may require configuration adjustments for optimal lunar performance.

Tachometer	4	Tachometer technology is less mature for space use, with tests needed to confirm accuracy and durability on the lunar surface.
Overall	4	
Anchoring		
Drill Bit	7	The design of self-tapping augers is well-established, and similar tools are used in terrestrial applications.
Telescopic Feet	5	Telescopic systems exist in many applications, but their application on the moon, especially with specific materials and designs (e.g., titanium), may still need validation through testing.
Overall	5	
Subsurface Rover		
Chassis	6	The design is reliable but needs additional endurance testing to confirm long-term stability under lunar gravity.
Drivetrain		
Legs	4	The leg design requires extensive testing to verify durability and maneuverability on the lunar surface.
DC motors	7	DC motor functionality is robust, though specific configurations may be required.
Overall	4	
GNC		
Cameras	6	The cameras have been used in Curiosity on Mars.
Gyroscope	6	The gyroscope has been used in Curiosity on Mars.
Accelerometer	6	Accelerometers have been used in space and on Mars.
Overall	6	

Table 5. Mechanical Subsystem TRL

Mass, Dimensions, Max Power Draw

	Quantity	Mass (kg)	Length (mm)	Width (mm)	Height (mm)	Max Power Draw (W)
Surface Rover						
Body and Drivetrain						
Chassis	1	99	1150	650	200	0
Suspension	1	7.4898	809	50	250	0
Tires	6	5	275	125	275	0
DC motors	6	0.31	119	50	50	75
Winch	1	2	200	200	150	15
Tether	1	0.2	10	6	6	0
GNC						
Cameras	2	0.4	100	100	50	1.5
Gyroscope	1	0.1	50	50	30	2
Accelerometer	1	0.1	30	30	20	0.1
Tachometer	6	0.2	50	50	30	0.5
Tension Sensor	1	0.1	60	40	20	0.1
Torque Limiter	4	0.3	80	80	40	0.1
Anchoring						
Drill Attachment	4	4.55625	300	75	75	50
Stabilizing Arms	4	2.3625	350	50	50	10
Total		138.3248	1150	650	337.5	698.6
Subsurface Rover						

Body and Drivetrain						
Chassis and Body	1	40.7114	500	500	300	0
Legs	4	3.196	200	500	450	0
DC Motors	4	0.31	119	50	50	80
Charging Pad	1	70	750	500	50	0
Winch	1	2	200	200	150	5
Tether	1	0.2	10	6	6	0
GNC						
Cameras	2	0.4	100	100	50	1.5
Gyroscope	1	0.1	50	50	30	2
Accelerometer	1	0.1	30	30	20	0.1
Tension Sensor	1	0.1	60	40	20	0.1
Total		115.1308	750	500	800	330.2
GRAND TOTAL		253.4556	1900	1150	1137.5	1028.8

Table 6. Mass, Dimensions, Power Draw

1.5.2.3 Mechanical Subsystem Trade Studies

The Material Trade Study (Appendix B, Table 1) aimed to choose a structural material that combines strength, weight efficiency, and durability to handle the tough lunar environment. The criteria we considered included weight (30%), strength (35%), cost (20%), and repairability (15%). Weight was heavily weighted to prioritize materials that support efficient movement, while strength was the most important factor to ensure the structure could withstand lunar conditions, impacts, and temperature extremes. Cost and repairability were weighted lower to balance our budget with the need for long-term maintenance in harsh settings. After scoring, Aluminum Alloy was picked as the best material. It scored highest because of its low weight, decent strength, and affordability, making it a great choice for long-term use on the moon. While materials like titanium alloy and carbon fiber did well in strength and weight, they weren't as practical due to high costs (titanium) and brittleness (carbon fiber) in extreme lunar conditions. So, Aluminum Alloy was chosen as the best material, meeting both structural and budget needs while supporting the rover's operations on the moon.

The Subsurface Rover Suspension Trade Study (Appendix B Table 2) was all about picking a system that balances obstacle clearance, shock absorption, and weight efficiency to support stable operations on the moon's surface. The criteria we looked at included obstacle clearance capability (18%), shock absorption (18%), payload accommodation (14%), volume compliance (10%), minimized mass (10%), maneuverability (14%), modularity (8%), and design simplicity (8%). We prioritized obstacle clearance and shock absorption to make sure the rover could handle rough terrain while minimizing vibrations to protect its instruments. Payload accommodation and volume compliance were also important since they affect where we can place and store equipment. We gave mass and maneuverability similar weights, since mass impacts how much payload we can carry, and maneuverability is crucial for moving around lunar features. Modularity and design simplicity were weighted lower, but we still wanted to ensure reliability and ease of assembly. Asagumo-like (4 legs) came out as the best suspension system, scoring high in shock absorption, minimized mass, and design that offers great obstacle clearance and stability, which are essential for the moon's environment while keeping the overall structure lightweight and easy to maneuver. Another system, like the rocker bogie, performed well too but didn't score as high because they were more complex and less adaptable to lunar obstacles. So, we went with the Asagumo-like suspension because it struck a good balance between performance, lightweight design, and effective shock absorption.

The Subsurface Mobility Trade Study (Appendix B Table 3) was conducted to find

the best system for moving through the moon's challenging underground areas, like caves and pits. Where stability, climbing ability, and precise control are super important. The criteria included terrain adaptability (17.5%), load-bearing capability (25%), climbing and stability (25%), energy efficiency (10%), modularity (10%), and stability (12.5%). We gave the highest weights to load-bearing capability and climbing/stability since the rover needs to support heavy equipment while safely going up and down steep slopes. Terrain adaptability was also significantly weighed to ensure the rover could navigate uneven underground areas without losing functionality. Energy efficiency and modularity received moderate weights, balancing power conservation with the need for flexibility in repairs. Stability was just below climbing ability in importance to make sure the rover could rely on inclined or unstable surfaces. After scoring, Articulated Legs were identified as the top choice. They scored high in adaptability, load-bearing capacity, and climbing stability, making them perfect for complex subsurface terrains, even though they require more energy. Traditional wheels and tracks did okay in certain categories, but their overall scores didn't match up due to limited adaptability and stability in rough underground areas. So, we decided on Articulated Legs for subsurface mobility because they offer unmatched versatility and reliability for navigating the lunar subsurface environment.

The Surface Mobility Trade Study (Appendix B Table 4) aimed to find a system that could effectively move across the moon's rough and diverse terrain while also being energy-efficient and durable. The main criteria we looked at were terrain adaptability (25%), load-bearing capability (25%), energy efficiency (15%), durability (15%), steering precision (10%), and modularity (10%). We prioritized terrain adaptability and load-bearing capability because the rover needs to handle lunar regolith, rocks, and slopes without losing stability. Energy efficiency and durability were also important, especially since we have limited power sources and the abrasive lunar dust can affect how long the rover lasts. Steering precision and modularity were weighted lower but are still essential for navigating and repairing, particularly in tight or uneven areas. When we scored the options, Traditional Wheels came out on top. Even though they didn't score as high in terrain adaptability as articulated legs, traditional wheels were better in terms of energy efficiency, load-bearing, and durability. This makes them easier to use and maintain. On the other hand, tracks and articulated legs received lower scores due to their higher energy needs and complexity. In the end, we chose Traditional Wheels because they provide the best mix of simplicity, energy efficiency, and strong durability, allowing effective travel across different lunar terrains.

The Drivetrain Trade Study (Appendix B Table 5) was done to find the best system that could provide solid power, durability, and control for moving the lunar rover over difficult terrains like regolith, slopes, and rocks. The main criteria we focused on were torque and power delivery (30%). Weight (25%), control responsiveness (20%),

and durability (25%). We prioritized torque and power delivery so that the rover could handle obstacles and tough terrains. Weight was also really important because a lighter drivetrain would make the rover more efficient by keeping its total mass lower. Control responsiveness and durability were both equally weighted since we wanted the drivetrain to allow precise movement while being able to hold up in harsh lunar conditions. After scoring each option, the Electric Motor came out on top because it performed well in torque and power delivery and offered good control responsiveness. This system provides strong power output and is easy to control, which makes it a great choice for handling different lunar terrains. Although it isn't the most durable option, its overall performance was better than Hydraulic Systems and Mechanical Gearboxes, which didn't score as well in weight and power delivery. So, we went with the Electric Motor as the best drivetrain choice, as it provides the right mix of power, weight efficiency, and control for lunar exploration.

1.5.3 Power Subsystem

1.5.3.1 Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Electrical Reqs							
EPS-1	The system shall be powered without the use of a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof.	Provided by Mission Document	Customer, MR-13	EPS-1.1	Test	Power, Payload	Met
EPS-1.1	The system shall provide sufficient power to maintain operating conditions for the duration of the mission.	The System requires power in order to properly operate for the duration of the mission.	EPS-1	EPS-1.2, EPS-1.3, EPS-2.1, EPS-2.2, EPS-2.3, EPS-2.4, EPS-3.1, EPS-3.2, EPS-3.3, EPS-3.4, EPS-4.1, EPS-4.2, EPS-4.3, EPS-4.4	Test	All	Met

EPS-1.2	The charge controller subassembly shall be redundant.	Ensures that the solar charge controller is able to recover from component failure.	EPS-1		Inspection	Power	Met
EPS-1.3	The power system shall meet the EMI/EMC per MIL-STD-461.	Ensures the power system adheres to guidelines to function reliably in space.	EPS-1		Test	Power	Met

EPS-2.1	The solar panel on the surface rover shall provide a minimum of 1156 Watts of power throughout one lunar day to sustain operations for the surface rover.	Adequate solar energy must be provided to conduct daily operations of the surface rover.	EPS-1.1	EPS-2.3, EPS-2.4	Test	Power	Met
EPS-2.2	The solar panel deployed on the lunar surface shall provide a minimum of 627 Watts of power throughout one lunar day to sustain operations of the subsurface rover.	Adequate solar energy must be provided to conduct daily operations of the subsurface rover.	EPS-1.1	EPS-2.3, EPS-2.4	Test	Power	Met
EPS-2.3	The solar panels shall be designed to achieve a minimum energy conversion efficiency of 20%.	Maximizes energy generation of the power system.	EPS-1.1, EPS-2.1, EPS-2.2	EPS-2.4	Test	Power	Met
EPS-2.4	The solar panels shall adjust their angle of inclination by up to 180° to ensure optimal sunlight exposure.	Allows the solar panel to maximize energy conversion efficiency and power generation.	EPS-1.1, EPS2.1, EPS-2.2, EPS-2.3		Test	Power	Met

EPS-3.1	The lithium-ion battery on the surface rover shall store a minimum of 1156 Watts to sustain operations.	Ensures that the battery provides ample power to allow the surface rover to conduct operations.	EPS-1.1	EPS-3.3, EPS-3.4	Test	Power	Met
EPS-3.2	The lithium-ion battery on the subsurface rover shall store a minimum of 627 Watts to sustain operations.	Allows for the battery to provide enough power for all subsystems to conduct operations on the subsurface rover	EPS-1.1	EPS-3.3, EPS-3.4	Test	Power	Met
EPS-3.3	The lithium-ion battery shall be rechargeable for at least 2000 cycles.	Ensures that the battery is able to recharge to provide the necessary power to the surface and subsurface rover throughout the mission duration.	EPS-1.1, EPS-3.1, EPS-3.2		Analysis	Power	Met
EPS-3.4	The lithium ion battery shall have a specific energy of at least 150 Wh/kg.	Batteries with a high specific energy allow for a greater storage of energy, allowing for more power to be provided.	EPS-1.1, EPS-3.1, EPS-3.2		Test	Power	Met

EPS-4.1	The cable harnesses shall distribute power to the surface and subsurface rover components efficiently.	Allows for adequate power to be distributed across the surface and subsurface rover to ensure adequate power supply for operations.	EPS-1.1	EPS-4.2 EPS-4.3, EPS-4.4	Test	Power	Met
EPS-4.2	The cable harness shall exhibit an organized layout with smooth bends.	An organized layout and smooth bends minimize the risk of failure and prevent damage.	EPS-1.1, EPS-4.1		Inspection	Power	Met
EPS-4.3	The cable harness shall distribute 202 W of power to the thermal system, 151 W of power to the command and data handling subsystem, 699 W to the mechanical subsystem, and 106 W to the payload subsystem on the surface rover.	Ensures each subsystem has adequate levels of power supply to maintain functionality on the surface rover.	EPS-1.1, EPS-4.1		Test	Power	Met

EPS-4.4	The cable harnesses shall distribute 160 W of power to the thermal system, 37 W of power to the command and data handling subsystem, 330.2 W to the mechanical subsystem, and 101 W to the payload subsystem on the surface rover.	Ensures each subsystem has adequate levels of power supply to maintain functionality on the subsurface rover.	EPS-1.1, EPS-4.1		Test	Power	Met
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Table 7. Power Subsystem Requirements

Verification and Validation

EPS-1

Verification: Test. Conduct a comprehensive review by cross-referencing the design documents and the specifications of the power system through the CAD design to ensure that no RTG or similar devices are present.

Validation: Perform a test of power generation under controlled conditions similar to those on the lunar surface to confirm power output meets necessary requirements without the use of RTG. Monitor the stability and duration of the power output to confirm that the system is performing well.

EPS-1.1

Verification: Test. Set up a controlled laboratory test in which the power system runs under the simulated mission load and power input for the duration of the mission. Monitor the voltage and current provided to the surface and subsurface rover to confirm that power supply is reliable and stable throughout.

Validation: Conduct testing under the temperature, radiation, and other mission-related environmental conditions to validate the system's performance with providing power. Conduct this testing over the mission duration with the mission power load and demands.

EPS-1.2

Verification: Inspection. Inspect the design and configuration and review the design documents to verify the redundancy in the charge controller of the power system.

Validation: Conduct testing in lunar conditions by intentionally simulating failure in the charge controller to ensure that the system remains functional and operates without a decrease in power transferability between the solar array and lithium-ion batteries.

EPS-1.3

Verification: Test. Conduct EMI/EMC testing in the laboratory in an EMC chamber while adhering to MIL-STD-461 standards. Measure the emissions and ensure that all EEE components remain in acceptable levels of functionality, and document the results.

Validation: Conduct EMC testing in an environment that simulates the electromagnetic conditions of the lunar surface, and expose the power system to these conditions to confirm operational stability. Confirm that EMI/EMC compliance is present throughout.

EPS-2.1

Verification: Test. Set up solar panels in a laboratory environment with a light intensity similar to a lunar environment. Conduct power output measurements to confirm that the panels on the surface rover meet the power requirement in the operating conditions.

Validation: Deploy the lunar panels in a lunar-simulated environment with the sunlight, and conduct power output measurements to validate that the solar panels on the surface rover meet the power requirement.

EPS-2.2

Verification: Test. Set up solar panels in a laboratory environment with a light intensity similar to a lunar environment. Conduct power output measurements to confirm that the panels located on the lunar surface will meet the power requirement in the operating conditions.

Validation: Deploy the lunar panels in a lunar-simulated environment with the sunlight, and conduct power output measurements to validate that the solar panels on the lunar surface meet the power requirement needed for the subsurface rover.

EPS-2.3

Verification: Test. Measure the input irradiance and output power of each solar panel in the laboratory setting. Calculate the energy conversion efficiency and ensure that it meets or exceeds 20%.

Validation: Place the solar panels in simulated lunar conditions related to the amount of sunlight and measure the efficiency, confirming that they adhere to the 20% conversion efficiency requirement. Validate that this still remains above 20% throughout lunar day and night cycles.

EPS-2.4

Verification: Test. Measure and record the angle adjustment capabilities of the solar panels in a lab environment. Confirm that the panels allow for the necessary angle adjustment.

Validation: Conduct the angle adjustment testing in a lunar simulated environment, and track the power output at various angles to ensure that the solar panels maximize power generation in response to changing the angles of the light.

EPS-3.1

Verification: Test. Charge the battery to full capacity in a lab and discharge it at a constant rate while measuring the power delivered. Confirm that it delivers the necessary Watts of stored energy over time.

Validation: Simulate lunar conditions by operating the battery to ensure that it provides the Watts of power necessary for the surface rover.

EPS-3.2

Verification: Test. Charge the battery to full capacity in a lab and discharge it at a constant rate while measuring the power delivered. Confirm that it delivers the necessary Watts of stored energy over time for the subsurface rover.

Validation: Simulate lunar conditions by operating the battery to ensure that it provides the Watts of power necessary for the subsurface rover.

EPS-3.3

Verification: Analysis. Conduct testing through computer simulations by charging and discharging the battery and any degradation in capacity. Ensure that the battery retains sufficient capacity after 2000 cycles.

Validation: Use the battery in a simulation of the lunar mission conditions. Validate the ability for the battery to recharge and stability in the capacity to confirm it meets the 2000 cycle requirement.

EPS-3.4

Verification: Test. Since the specific energy is the total energy storage divided by the weight, conduct battery cell performance testing to determine the energy storage and divide by mass.

Validation: Test the specific energy under lunar conditions to confirm that it maintains the necessary specific energy and efficiency during the time the rover is conducting operations

EPS-4.1

Verification: Test. Perform continuity testing to confirm proper routing and connections to all of the components that require power.

Validation: Conduct testing in a simulated lunar environment to confirm that each subsystem receives consistent power and confirm that no drops in power distribution occur due to the harness layout.

EPS-4.2

Verification: Inspection. Inspect the physical layout of the cable harness, measuring the radii of the bends to ensure smooth curves and compliance with standards that reduce stress points.

Validation: Expose the cable harness to mechanical stresses similar to those of lunar transport and operation to confirm that the layout prevents cable damage and maintains functionality.

EPS-4.3

Verification: Test. Use power measurement tools to measure the power output and verify that the cable harnesses consistently deliver the necessary power to the necessary subsystems for the surface rover.

Validation: Conduct testing in a simulated lunar environment and confirm that the solar panels and cable harnesses provide the necessary power on the surface rover.

EPS-4.4

Verification: Test. Use power measurement tools to measure the power output and verify that the cable harnesses consistently deliver the necessary power to the necessary subsystems for the subsurface rover.

Validation: Conduct testing in a simulated lunar environment and confirm that the solar panels and cable harnesses provide the necessary power on the subsurface rover.

1.5.3.2 Power Subsystem Overview

Surface Rover

The surface rover contains the primary power generation source, utilizing a solar array to generate energy. This rover powers its own operations with this solar array. The solar cells contained in the solar array are the XTE-SF (Standard Fluence) Space Qualified Triple Junction Solar Cell, which were chosen because they are space qualified, have a high efficiency of 32.2% BOL and are a highly reliable technology (Spectrolab - A Boeing Company n.d.). All of the subsystems in total require a power draw of 1058 Watts for the surface rover. The area of the solar panels for the surface rover is 3.18 square meters. This was determined by calculating the time-phased power draw for each of the components of the subsystems. The Leonardo DRS Tenum 640 IR Camera requires 1.4 Watts of power and is operational for 1 hour of the lunar day to capture images, requiring a time-phased power draw of 1.4 Watt hours. The Lunar Penetrating Radar requires 9.8 Watts of power and will be operational for 5 hours during the lunar day, which requires a time-phased power draw of 49 Watt hours. Additionally, the LiDAR requires a power usage of 65 Watts and is operational for 6 hours in the lunar day, resulting in 390 Watt Hours. Additionally, the CDH X-Band LGA Antenna requires a power draw of 5 W and will be operational throughout the duration of the lunar day, requiring 125 Watt hours of power. The remaining CDH equipment requires a power draw of 162 W and operates for the 12 hours the science instruments will be operating, resulting in a power draw of 1944 Watt hours. The mechanical subsystem requires 699 Watts of power to sustain operations on the surface rover, and remains operational for the time that science is operating. This results in a time-phased power draw of 8384 Watt hours. Additionally, the thermal subsystem will operate for half of the time that the mechanical, CDH, and science subteams will operate. The thermal subsystem will require 202 W of power for 6 hours during the lunar day, requiring a time-phased power draw of 1212 Watt hours. Then, the area was calculated by dividing the total watt hours required by the solar power density and effective sunlight hours on the moon. The mass of the solar array is 4.134 kg, which was determined by multiplying the mass of each solar cell in mg/cm² by the area and converting units. The solar array will also have an adjustable angle by up to 180 degrees, allowing the array to reorient based on the sun's position and maintain power availability.

There will be a lithium-ion battery present on the surface rover that will store the power that will be generated by the solar array. This was chosen for its high energy density of 330 watt-hours per kilogram and longevity. The lithium-ion battery will store up to 1156 Watts of power, allowing it to store the power that is produced by the solar array. The battery will provide 38 Amps of current at a voltage of 28 V. Additionally, the lithium-ion battery will have a cycle life of 2000 cycles, a self-discharge rate of 3% per month, a failure rate of less than one in a million, and a mean time between failures of

2000 years, as demonstrated by the trade studies on the battery. A solar charge controller will be utilized in order to regulate the charge and current that flows between the solar panel and lithium-ion battery in order to prevent overcharging. The charge controller has a mass of 0.79 kg and dimensions of 0.234 m x 0.175 m x 0.065 m as found by comparing charge controllers (Inverter 2024). The battery has a mass of 48.4 kg, since it requires 12.1 KWh of storage, and lithium-ion batteries require 4 kg of material per KWh of storage (Thunder Said Energy, n.d.). The dimensions of this battery are 0.53 m x 0.308 m x 0.231 m, which was found by researching current 10 KWh lithium ion battery dimensions and scaling up for 11 KWh of power (EG Solar 2021).

Power distribution on the surface rover is maintained through cable harnesses, which are designed to be well-insulated. The cable harnesses will be designed to resist the radiation and temperature-related conditions on the lunar surface. Additionally, the cable harness layout is carefully organized to avoid tangling and ensure reliable connections between the electrical power system and the other onboard systems, including the thermal subsystem, CDH subsystem, mechanical subsystem, and payload subsystem. The cable harnesses will distribute 202 W to the thermal subsystem, 151 W to the command and data handling subsystem, 699 W to the mechanical subsystem, and 106 W to the payload subsystem. The mass of the cable harnesses of the surface rover is approximately 2.5% of the total mass of the system, leading to a mass of 9 kg. A diagram of the power distribution system wiring to the different subsystems is shown in Figure 1.

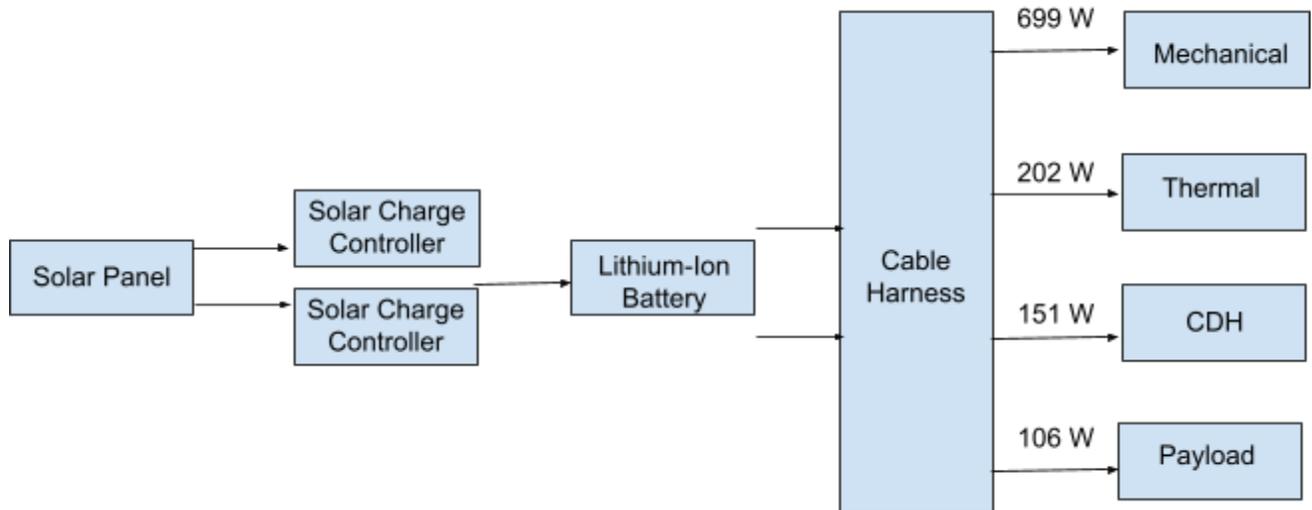


Figure #1 Surface Rover Power Distribution System

Subsurface Rover

The subsurface rover will be powered through the additional solar array that will be deployed onto the lunar surface. The solar array will be in the foldout configuration and will be deployed in an accordion fashion using the pantograph system. Once it is deployed, the solar array will have a total area of 1.6 square meters. This was calculated by determining the time-phased power draw of each of the subsystems for the subsurface rover. On this rover, the science instruments that will be used include the IR Camera, The Radiation Assessment Detector, the NIRVSS spectrometer, and the LiDAR system. The IR camera requires 1.4 Watts of power and will operate for 1 hour on the subsurface rover resulting in a time-phased power draw of 1.4 Watt hours. The Radiation Assessment Detector requires 4.1 Watts of power, will operate for 1.33 hours in the lunar day, and requires 5.453 Watt hours of power. The NIRVSS spectrometer requires 29.6 Watts of power, operates for 3 hours in the lunar day to conduct operations, and requires 88.8 Watt hours of power. The LiDAR requires 65 Watts of power and is operational for 6 hours on the subsurface rover, which requires 390 Watt hours of power. The CDH X-Band LGA Antenna will be operational throughout the lunar day, requiring 5 Watts of power and 125 Watt hours of power. The remaining CDH equipment is operational for the 11.33 hours science is conducting operations. It requires a power usage of 56 Watts and will be operating for 11.33 hours during the lunar day. Thus, the power required for the CDH equipment will be 634.48 Watt hours. The mechanical subsystem is operational for the time that science operates and requires 331 W of power for 11.33 hours. The power for the mechanical subsystem is 3742 Watt hours. The thermal equipment will be operating for 6 hours, as it operates for approximately half of the time that the mechanical, CDH, and science equipment operates. It requires 160 Watts for 6 hours, requiring a time-phased power draw of 960 Watt hours. From this, the area was calculated by dividing the total Watt hours by the effective sunlight hours on the lunar surface and solar power density, resulting in 1.6 square meters. The mass of this solar array is 2.08 kg, which was obtained by multiplying the mass of each solar cell by the area of the solar array.

Additionally, there will be a lithium-ion battery pack that will be placed on the subsurface rover. Similar to the surface rover, the lithium-ion battery on the subsurface rover was chosen for the high energy density and longevity. The lithium-ion battery will store up to 627 Watts of power for the subsurface rover which will be produced by the solar array. The battery will provide 35 Amps of current at a voltage of 28 V. Other factors about the battery are similar to the surface rover, as the lithium-ion battery will have a cycle life of 2000 cycles, a self-discharge rate of 3% per month, a failure rate of less than one in a million, and a mean time between failures of 2000 years, as demonstrated by the trade studies. The battery will receive its power from the solar panel through the use of a solar charge controller. The solar charge controller prevents

the battery from overcharging and provides protection from reverse current (Oehm 2022). The charge controller has a mass of 0.79 kg and dimensions of 0.234 m x 0.175 m x 0.065 m as found by comparing charge controllers (Inverter 2024). The battery has a mass of 24.0 kg, since it requires approximately 6.0 KWh of storage, and lithium-ion batteries require 4 kg of material per KWh of storage (Thunder Said Energy, n.d.). The dimensions of this battery are 0.288 m x 0.168 m x 0.126 m, which was found by researching current 10 KWh lithium ion battery dimensions (EG Solar 2021).

Through the power distribution system with the cable harnesses, 160 W will be distributed to the thermal subsystem, 37 W to the command and data handling subsystem, 330.2 W to the mechanical subsystem, and 101 W to the payload subsystem to power their operations on the subsurface rover. The subsurface rover will be charged through the cable harnesses, which distribute power from the surface rover to the bottom of the lunar pit. The mass of the cable harnesses of the subsurface rover is also approximately 2.5% of the total mass of the system, leading to a mass of 9 kg. When the subsurface rover requires charging, it will plug itself into the charging station that connects to the surface rover using a cable harness. A diagram of the power distribution system for the subsurface rover and the amount of power provided to each subsystem is shown below in Figure 2. The functionality of this is similar to the functionality of a robotic vacuum, where an infrared receiver on the front bumper is able to detect and search for the infrared signal that is emitted by the charging station near the cable harness (Layton 2005). Then, the rover finds this signal, connects itself to the charger, then disconnects when the batteries are fully charged.

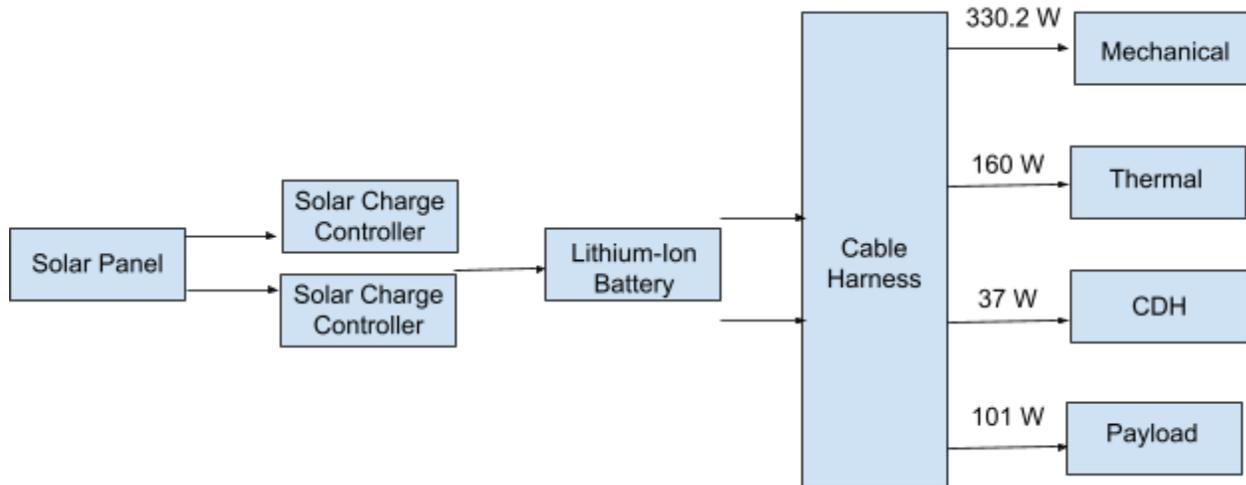


Figure #2 Subsurface Rover Power Distribution System

Technology Readiness Level

Subassembly	TRL	Explanation
Surface Rover		
Solar Panels	7	Solar array technology is highly established and has demonstrated successful performance in a space environment. Solar arrays have been utilized on the Europa Clipper, the Juno Spacecraft, and more. Additionally, the solar cells are listed as space grade materials. However, modifications for the environment on the moon near the lunar pit are required, as this technology has not been utilized in this area.
Lithium-Ion Battery	7	Lithium ion batteries are a highly established technology for space satellites, rovers, and launch vehicles. For instance, they have been utilized in the Eurostar satellites, Lunar Reconnaissance Orbiter, Mars Rovers, Mars Landers, and more (Krause et al. 2021) (European Space Agency 2019). However, it is necessary to account for modifications necessary in the design to account for the conditions near the Marius Hills Pit, as lithium-ion batteries have not been utilized in this area.
Solar Charge Controller	7	A solar charge controller is a proven and tested technology that has demonstrated use in space applications. Satellites such as the Ariel I satellite, Explorer XXVIII spacecraft, Explorers XII and XIV, and additional space technologies have utilized solar charge controllers to prevent the overcharging of the battery (Panlkouich 1967). However, further testing and analysis is required to ensure the solar charge controller will operate on the lunar surface near the Marius Hills Pit due to the unique environmental and radiation-related challenges.
Cable Harnesses	8	Cable harnesses are an established technology for space applications. They have been flown on previous space missions, including the International Space Station, Apollo missions, and more (INSIGHT Staff 2022). However, additional testing is required for their usage on the surface of the moon close to the Marius Hills pit, resulting in a TRL of 8.
Overall	7	

Subsurface Rover		
Solar Array	7	Solar array technology is highly established and has demonstrated successful performance in a space environment. Solar arrays have been utilized on the Europa Clipper, the Juno Spacecraft, and more (NASA Jet Propulsion Laboratory 2024). Additionally, the solar cells are listed as space grade materials. However, modifications for the environment on the moon near the lunar pit are required, as this technology has not been utilized in this area
Solar Charge Controller	7	A solar charge controller is a proven and tested technology that has demonstrated use in space applications. Satellites such as the Ariel I satellite, Explorer XXVIII spacecraft, Explorers XII and XIV, and additional space technologies have utilized solar charge controllers to prevent the overcharging of the battery. However, further testing and analysis is required to ensure the solar charge converter will operate on the lunar surface near the Marius Hills Pit due to the unique environmental and radiation-related challenges.
Lithium-Ion Battery	7	Lithium ion batteries are a highly established technology for space satellites, rovers, and launch vehicles. For instance, they have been utilized in the Eurostar satellites, Lunar Reconnaissance Orbiter, Mars Rovers, Mars Landers, and more (Krause et al. 2021) (European Space Agency 2019). However, it is necessary to account for modifications necessary in the design to account for the conditions near the Marius Hills Pit, as lithium-ion batteries have not been utilized in this area.
Cable Harnesses	8	Cable harnesses are an established technology for space applications. They have been flown on previous space missions, including the International Space Station, Apollo missions, and more (INSIGHT Staff 2022). However, additional testing is required for their usage on the surface of the moon close to the Marius Hills pit, resulting in a TRL of 8.
Overall	7	

Surface Rover Electrical Components			
Component	Mass (kg)	Dimensions (m)	Maximum Power Consumption (W)
Solar Array	4.134 kg	1.59 x 1.59 m	0 W
Cable Harness	9 kg	2 m	0 W
Lithium-Ion Battery	48.4 kg	0.576 m x 0.336 m x 0.252 m	0 W
Solar Charge Controller	0.79 kg	0.234 m x 0.175 m x 0.065 m	0 W

Subsurface Rover Electrical Components			
Component	Mass (kg)	Dimensions (m)	Maximum Power Consumption (W)
Solar Array	2.08 kg	0.8 x 0.8 m	0 W
Cable Harness	9 kg	50 m	0 W
Lithium-Ion Battery	24.0 kg	0.288 m x 0.168 m x 0.126 m	0 W
Solar Charge Controller	0.79 kg	0.234 m x 0.175 m x 0.065 m	0 W

Table #8. Power Subsystem TRL

1.5.3.3 Power Subsystem Trade Studies

The power generation method trade study (Appendix C Table 1) provides a comparison of three different power generation methods to provide power to the lunar rovers. This trade study compares solar arrays, proton exchange membrane fuel cells, and alkaline fuel cells.

The first criteria was the cost of the power generation method which had a weight of 10% due to the importance of adhering to the necessary budget and closing out requirement MR-1. However, other factors such as reliability and amount of power generated are more critical factors in the design, resulting in cost being assigned a lower weight than these factors. The solar array achieved a score of 7, because a typical solar cell that is 4 cm by 8 cm has a total cost of \$400 to \$500 (NASA Technology Transfer Program 2016). One solar cell on average can produce 0.5 watts of power, thus the production of 1622.4 W of power needed for the surface rover requires 3245 cells, needing a cost of \$1,622,500 (Marshall 2023). The cost of proton exchange membrane fuel cells is US \$500 per kW, and the manufacturing and capital investment costs are \$1200 per kW and \$2900 per kW respectively (Kamarudin et al. 2006). So, the cost for generating 1622.4 W of power is \$7464. For alkaline fuel cells, the cost ranges between \$400-600/kW, causing the cost for generating 1622.4 W of power to be approximately \$974 (Ni 2005).

The second criteria was reliability, which had a weight of 20%, because it is important for the technology to be proven to be used in space. Failure in the electric power system can lead to mission critical issues, such as loss of vehicle control and total system failure (Sadey et al. 2021). Solar panels are assigned a score of 8 because they are an abundant, reliable, and renewable source of energy for use on the lunar surface (VR 2023). They have been consistently used in space to power the International Space Station, the Europa Clipper Mission, and more, causing them to be a proven technology for applications in space (Perkins 2023) (Jet Propulsion Laboratory, n.d.). The PEM fuel cells were flown on a spacecraft in 1985 after research and development, however, they experienced reliability concerns due to membrane degradation, decreasing chemical reaction activity, failures in the cooling system and more, resulting in their score of a 6 (Dynamic Reliability Assessment of PEM Fuel Cell Systems citation). Additionally, alkaline fuel cells were assigned a score of 9 due to their excellent mechanical and chemical stability, which causes a high reliability (Ferriday and Middleton 2021).

The radiation tolerance has a weight of 15% because it ensures that the power system can adequately function under the impacts of TID and SEE. However, since there are thermal control measures put into place to control the levels of radiation exposure, this was weighted less heavily. Radiation causes degradation of the solar cells, which can negatively impact the efficiency of the solar array, causing it to achieve a score of 6 (Raya-Armenta et al. 2021). For PEM fuel cells, radiation β -radiation dose of 200 kGy caused minor damage to the membrane, and β -radiation is prevalent on the moon, resulting in its score of a 5. The effects of radiation on alkaline fuel cells were not studied, causing this to achieve a score of a 1.

The temperature was weighted at 15% because it is necessary for the components to operate in the extreme temperature conditions on the moon, however, there are mechanisms in place from the thermal subsystem that ensure the temperature remains regulated. The temperature range for solar panels is -40°C to 95°C . The optimal temperature range for PEM fuel cells is $60\text{--}90^{\circ}\text{C}$ (Tang, Zhang, and Xu 2023), and the temperature range of alkaline fuel cells is $50\text{--}90^{\circ}\text{C}$, resulting in their respective scores.

The efficiency is weighted at 20%, because the more energy output provided from light hitting the cell results in less area required (Enel X 2024). Solar panels have an efficiency of greater than 32% and fuel cell systems have efficiencies of up to 60% resulting in their scores (National Aeronautics and Space Administration, n.d.) (U.S. Department Of Energy 2015).

Safety is weighted at 10% to ensure that risks are minimized and the rover remains safe, however, this a lower priority because humans are not present on the moon, so there are not many detrimental impacts associated with lack of safety. Solar arrays are a safe and reliable method of power production, which reduces technical risk and increases safety (Hickman, Curtis, and Landis 1990). In PEM fuel cells, hydrogen is used as a fuel, which can cause fires when handled incorrectly during the launch (Office of Energy Efficiency & Renewable Energy 2024). Alkaline fuel cells are susceptible to poisoning by carbon dioxide, leading to damage in cell performance and durability, resulting in their score (Office of Energy Efficiency and Renewable Energy 2019).

Size and mass weighted at 10% because it is essential for the components to adhere to the customer requirements, however, factors such as the efficiency and reliability are more crucial. For a 1 kW fuel cell, the mass is 120 kg, so the mass for the power needed for the rover is 192 kg (Kato et al. 2002). The average mass of a solar array is 74.58 kg (National Aeronautics and Space Administration, n.d.), which results in their scores.

Overall, a solar array was chosen as the method of power distribution due to its reliability from being utilized in past space missions, radiation tolerance, and safety.

The three methods compared for the power storage method included batteries, supercapacitors, and flywheels. Details of the decision making process are shown in the Power Storage Method Selection trade study (Appendix C Table 2).

The criteria for cost has an assigned weight of 10% due to the importance of the budget requirements. However, criteria related to the performance of the power storage system have more impact and require a higher weight. The average cost of lithium ion battery packs range between $\$250\text{--}\$1,000$ per kWh for a large system, causing this to achieve a score of 8 (Battery University 2010). The cost of a supercapacitor is approximately $\$10,000$ per kWh, causing this to achieve a score of a 2 (Battery University 2010). Additionally, the cost of flywheels is between $\$190$ and $\$146/\text{MWh}$, which results in a score of 6. Operating temperature range contributes to 15% of the weight because the power storage system must be able to withstand the temperatures of the moon, but there are mechanisms put in place by the thermal subsystem to

regulate power, making it less of a priority compared to lifetime. The operating temperature range of batteries is 20°C to 45°C, the operating temperature of supercapacitors is -40 to 65°C, and the operating temperature of flywheels is -40°C to 70°C, resulting in their scores of 6, 5, and 5 respectively (NJ.gov, n.d.) (Battery University 2010). The specific energy is weighted at 20% because it indicates the ability of a component to store large amounts of energy relative to the weight, which is critical when considering the weight and efficiency of the system. The specific energy of batteries ranges between less than 50 Wh/kg to over 250 Wh/kg, the specific energy of supercapacitors is 5 Wh/kg, and the specific energy of flywheels is 25W-hr/kg, resulting in their scores (“Specific Energy of Batteries Worldwide 2023 | Statista” 2023) (Keim 2024) (Dever, n.d.). The radiation tolerance is weighted at 15% because it is necessary for the power storage system to withstand the high levels of radiation, but mechanisms put into place to prevent the effects of radiation cause this criteria to be weighted less. Radiation in space can alter battery materials and impact performance, resulting in a score of a 5 (Leita and Bozzini 2024). Supercapacitors are able to withstand high levels of radiation because they experienced negligible effects due to TID up to 89 kGy and a maximum dose of 40 kGy, resulting in their score of 8 (Di Buono et al. 2020). Radiation does not pose a very detrimental impact on flywheel technology, resulting in the score of 5 (Huynh, Zheng, and McMullen 2007). The cycle life of batteries is 2000, the cycle life of supercapacitors is usually in the 100's of thousands of cycles, and the cycle life of flywheels is greater than 50,000 resulting in their scores (Abracon 2024) (NJ.gov, n.d.). Lifetime is a key factor to consider because it determines the amount of cycles completed of charging and discharging before a decrease in performance, which negatively impacts operations. Overall, batteries were chosen as the power storage method due to their low cost, minimal mass, and high specific energy.

The three different types of batteries compared for power storage include Nickel-Cadmium, Nickel-metal hydride, and Lithium Ion. The trade study can be found in Appendix C, Table 3. The lifetime was weighted at 15% because of the importance of determining the number of life cycles of a component before performance is negatively impacted for the rover. However, since factors such as mass are key requirements in this mission, factors such as specific energy are weighted higher. Nickel cadmium batteries have a cycle life of 1000, Nickel-metal hydride batteries have a cycle life of 300-500, and Lithium ion batteries have a cycle life of at least 2,000 charging cycles, resulting in their respective scores of 4, 1, and 8 (Battery University 2010a). The energy density is an important factor that is weighted 30% because a higher energy density results in a battery emitting greater charge in relation to the size (Dragonfly Energy 2021). Nickel cadmium batteries have an energy density of 40 Wh/L, nickel metal hydride batteries have an energy density of 170–420 Wh/L, and lithium ion batteries have an energy density of 300 to 700 watt-hours per liter (“The Energy Density of a Lithium-Ion Battery” 2024) (Nayak, Ganguli, and Ajayan 2023) (Koehler 2019). The specific energy is weighted at 25% because of the ability of a component to store large amounts of energy relative to the weight, which is critical when considering the weight and efficiency of the system. The specific energy of nickel-cadmium batteries is 45-80 Wh/kg, the specific energy of nickel-metal hydride batteries was 60-120 Wh/kg, and the specific energy of lithium ion batteries ranges between 90-250 Wh/kg, resulting in their respective scores. The self-discharge rate is a key factor in determining the battery’s

ability to store energy to sustain the operations of the rover, and is weighted at 20% because it closes out requirement EPS-3.3. Nickel cadmium batteries experience a notably high self-discharge rate compared to nickel metal hydride batteries with a 1% daily self-discharge rate and lithium ion batteries with a self-discharge rate per month of 1-2% (Battery University 2010c) (EPEC Engineered Technologies n.d.) (Marketing 2024). The battery cell voltage has a weight of 10% because high voltage batteries are best to employ in aerospace due to their capability of producing high energy density and power output. However, since there are safety concerns associated with higher voltage batteries, this component is weighted less than others. Nickel-cadmium batteries have a battery cell voltage of 1.2 V/cell, nickel metal hydride batteries have a battery cell voltage of 1.2 V, and lithium ion batteries have a battery cell voltage of 3.2-3.7 V, resulting in their respective scores. Overall, lithium ion batteries were chosen from this trade study due to their high lifetime, high energy density, high specific energy, low self-discharge rate, and high battery cell voltage.

The three types of power management and distribution devices compared in the Power Management and Distribution (PMAD) trade study (Appendix C, Table 4) were a cable harness, backplane, and power distribution unit. The criteria of mass and size was weighted at 15% because it is necessary for this to adhere to these requirements, however, it is not as critical as factors such as reliability. Cable harnesses, backplanes, and power distribution units all have a size and mass that adheres to the requirements, as they are relatively lightweight and do not require much space in the rover, so they all received a score of 10.

Reliability has a weight of 30%, because it is essential that that power distribution system is able to reliably distribute power throughout the rovers to sustain its operations. Cable harnesses received a score of 9 because they have very reliable insulation and protection for the conductors on the inside. However, they face challenges in reliability due to the presence of faulty wires, which negatively impact system operations (Cableteque 2024) (EPTAC Staff 2023). Backplanes are highly reliable because they can centralize power distribution and can withstand the harsh weather conditions, however, they do require redundancy and fault-tolerance (Atrenne 2024) (Lenovo 2021). Power distribution units are also reliable, however, they can experience slight challenges such as power surge, inefficiency, low uptime and electromagnetic interference, which reduce their performance and result in a score of 7 (Astrodyne TDI 2024).

Safety was a factor weighted at 30% because it allows for proper operation of the rover and prevents electrical hazards. Cable harnesses are very safe since they are well-insulated to be protected from hazards on the lunar surface and have sheaths and layers for protection, leading to a score of 9 (Consolidated Electronic Wire & Cable 2024). Backplanes are also excellent in terms of safety, as they are developed to withstand extreme environmental conditions safely. However, due to the complexity of the routing of the backplane cables, this can negatively impact the rover systems, leading to a score of 7 (TE Connectivity 2024). Power distribution units have a score of 5 because they must only be used indoors in a dry environment and have hazards of shock, explosions, and arc flash, leading to a score of 5 (Schneider Electric 2024).

Operating temperature range is weighted at 15% because it is critical for components to operate under the conditions on the lunar surface, but the mechanisms put into place to control radiation exposure causes other factors to be a greater priority. Cable harnesses have high performance in temperatures between 65 °C to 250 °C, backplanes operate in temperatures between -55°C to 125°C, and power distribution unit operating temperatures range from 45°C to 60°C, resulting in their respective scores (Consolidated Electronic Wire & Cable 2024) (Amphenol Communications Solutions 2024) (Vertiv 2022).

Cost is 10% of the total weight because factors such as reliability and safety are a higher priority than cost, considering most of these components have a low cost. The cost of cable harnesses is highly dependent on length and material, but typically cost between \$500 - \$1,200 (FQ-Wire Harness 2024). Backplanes are also cost-effective, while power distribution units have a greater cost of up to \$800 which resulted in their scores (CablesPlus USA 2024).

Overall, cable harnesses were chosen as the power management and distribution method because they are reliable, safe, and are able to operate in the temperature ranges on the lunar surface.

1.5.4 Command and Data Handling (CDH) Subsystem

1.5.4.1 CDH Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Validation Method	Relevant Subsystem	Req Met?
CDH-1	The system shall communicate directly with the primary mission orbiter in a circular polar orbit at 100 km.	Provided by Mission Document	Customer	CDH-4, CDH-1.1	Test	Command & Data Handling	Met
CDH-1.1	The surface rover shall communicate directly with the primary mission orbiter at range up to 2 Mbps.	Allows for spacecraft to send critical data per communication window within a short period of time.	CDH-1	CDH-1.1.1, CDH-1.1.2, CDH-1.1.3	Test	Command & Data Handling	Met

CDH-1.1.1	The surface rover system shall utilize a primary antenna capable of up to 2 Mbps transmission and receiving.	This antenna allows for the high data rate transmission to the primary mission orbiter and as a receiver for the subsurface rover data transmission.	CDH-1.1	CDH-1.1.1.1	Test	Command & Data Handling	Met
CDH-1.1.1.1	The subsurface rover system shall utilize a primary antenna capable of 2Mbps transmission and receiving; prioritizing a balance between efficiency and power usage of transmission.	This antenna serves as the transmitter of data to the surface rover high-gain antenna.	CDH-1.1. 1		Test	Command & Data Handling	Met

CDH-1.1.2	The surface rover system shall utilize a secondary antenna.	This antenna serves as redundancy and safety in transmission and receiving.	CDH-1.1		Test	Command & Data Handling	Met
CDH- 1.1.3	The subsurface rover system shall utilize a secondary antenna.	This antenna serves as redundancy and safety in transmission and receiving.	CDH-1.1		Test	Command & Data Handling	Met
CDH-2	The system shall include appropriate storage systems with necessary capacity for the entirety of the mission.	Both rovers should be able to hold data collected from the scientific instruments.	PAY-1	CDH-2.1, CDH-2.2, CDH-2.3	Test	Command & Data Handling	Met
CDH-2.1	The system shall include firmware-allocated storage necessary for mission control and command processing.	This storage device stores firmware and bootloader code, essential for software back-ups for redundancy.	CDH-2		Test	Command & Data Handling	Met

CDH-2.2	The system shall include up to 300MB/s read and 100MB/s write speeds in the form of a flash storage system for data collection from instruments.	This storage device allows for fast read/write capabilities of data and temporarily holds storage when transmission is unavailable.	CDH-2		Test	Command & Data Handling	Met
CDH-2.3	The system shall include a long-term storage system.	This storage device allows for long term storage needs for data that may not be ready or needed for transmission.	CDH-2	CDH-2.3.1, CDH-2.3.2	Test	Command & Data Handling	Met
CDH-2.3.1	The surface rover shall include a 480GB long-term storage system.	The amount of storage is important for the surface rover to hold onto for readiness and processing for transmission of the data.	CDH-2.3		Analysis	Command & Data Handling	Met

CDH-2.3.2	The subsurface rover shall include a 128GB long-term storage system.	The amount of storage should be enough for the subsurface rover to collect and immediately transmit to the surface rover without slowing write performance.	CDH-2.3		Analysis	Command & Data Handling	Met
CDH-3	The system shall include proper data interfacing between instrument, storage, and command systems.	Proper data interfacing allows for smoother working architecture and data handling.	PAY-1	CDH-3.1, CDH-3.2	Analysis	Command & Data Handling	Met
CDH-3.1	The system shall utilize direct interfacing ports connecting to the onboarding computer.	SpaceWire interface harbors the advantages of high-speed data linkage and robustness.	CDH-3		Analysis	Command & Data Handling	Met

CDH-3.2	The system shall utilize a secondary data interfacing system.	MIL-STD-1553 interface allows for redundancy and safety in connection and transport of data.	CDH-3		Analysis	Command & Data Handling	Met
CDH-4	The two rovers shall process all data and communication through their respective onboarding computer (OBC).	The use of an onboarding computer acts as the central hub for the systems.	PAY-1, CDH-1	CDH-4.1, CDH-4.2, CDH-4.3, CDH-4.4	Analysis	Command & Data Handling	Met
CDH-4.1	The surface rover will utilize a single-board OBC that can handle the lunar surface levels of radiation for the entirety of its mission.	This onboarding computer will need to handle large amounts of radiation periodically throughout its mission.	CDH-4		Analysis	Command & Data Handling	Met

CDH-4.2	The surface rover will utilize a single-board OBC with at least a 200MHz clock speed.	This onboarding computer can handle the large constraints of data for transmission with its powerful processing.	CDH-4		Analysis	Command & Data Handling	Met
CDH-4.3	The subsurface rover will utilize a single-board OBC that can handle the lunar pit levels of radiation for the entirety of its mission.	This onboarding computer will need to handle pit radiation levels periodically throughout its mission.	CDH-4		Analysis	Command & Data Handling	Met
CDH-4.4	The subsurface rover will utilize a single-board OBC with at least a 150MHz clock speed.	This onboarding computer is proficient in processing and excels at low power consumption as well as general reliability.	CDH-4		Analysis	Command & Data Handling	Met

CDH-4.5	Both rovers shall utilize a flexible and efficient operating system for their respective onboarding computers.	Flexible and efficient operating systems allow for full control of the system in the most efficient way and stand as a reliable method.	CDH-4		Analysis	Command & Data Handling	Met
CDH-5	The CDH system equipment shall run functionally between the temperature ranges of -55°C to +125°C.	This is the ideal range for many OBC processors which are the most sensitive pieces of equipment within this specific system. Storage temp range is also similar to this range for functionality.	PAY-1.2		Analysis	Command & Data Handling	Met

Table #9. CDH Subsystem Requirements

Verification and Validation

CDH-1

Verification: test. Testing the communication range of transmission and receiving through simulations on Earth with a similar ranged point of contact; i.e. satellite.

Validation: Conduct multiple tests on site of mission between LO and rover systems in order to confirm testing results of communication.

CDH-1.1

Verification: test. Testing the specific range of transmission between the simulated rover and point of contact at up to 2 Mbps.

Validation: Conduct these same tests between the rover systems and LO for this specific range of up to 2Mbps rate to confirm simulated results.

CDH-1.1.1

Verification: test. Work out on testing the designs and development of an antenna capable of outputting transmission of up to 2 Mbps from the SR to the LO.

Validation: Putting the design of the antenna to work and testing a simulation of said design up to the required data rate constraint for the SR to make contact with an orbiter of noted required distance.

CDH-1.1.1.1

Verification: test. Work out on testing the designs and development of an antenna capable of outputting transmission of up to 2 Mbps from the SSR to the LO.

Validation: Putting the design of the antenna to work and testing a simulation of said design up to the required data rate constraint for the SSR to make contact with the SR system from a simulated mission environment.

CDH-1.1.2

Verification: test. Work out on testing the design of a secondary antenna for redundancy purposes that may coexist with the primary antenna system for the SR system.

Validation: Putting the design of the antenna to a test and simulation of transmission in a coexistence scenario to enforce redundancy between the two antenna systems for the SR system.

CDH-1.1.3

Verification: test. Work out on testing the design of a secondary antenna for redundancy purposes that may coexist with the primary antenna system for the SSR system.

Validation: Putting the design of the antenna to a test and simulation of transmission in a coexistence scenario to enforce redundancy between the two antenna systems for the SSR system.

CDH-2

Verification: test. Computational measurements done for data storage taking the expected data quantity of scientific instruments in mind during these simulations.

Validation: Sending expected collected data and filling these storage devices to ensure appropriate storage capacity for the system.

CDH-2.1

Verification: test. Computational measurements taken for the proper allocation of firmware and software boot-up/back-up code necessary for the system.

Validation: Prospective storage device to be filled with anticipated firmware/software code and be tested for the space taken on said storage device.

CDH-2.2

Verification: test. Conduct performance testing to ensure flash storage achieves the specified 300MB/s read speed and 100MB/s write speed for data collection.

Validation: Load flash storage with simulated instrument data and monitor read/write speeds to confirm they consistently meet the 300MB/s read and 100MB/s write speed requirements.

CDH-2.3

Verification: test. Test the design specifications of the long term storage system to confirm it meets the defined requirements for capacity and durability for the accessed data.

Validation: Test the long term storage device by storing various sets of data over a period of time, validating data accessibility when retrieval is necessary.

CDH-2.3.1

Verification: analysis. Analyze the specifications of the 480GB long-term storage system to ensure it meets the capacity requirements for data readiness and processing for the SR system.

Validation: The storage system will be loaded with data and verified that it maintains the 480GB capacity while allowing for efficient data processing and transmission readiness for the SR system.

CDH-2.3.2

Verification: analysis. Analyze the specifications of the 128GB long-term storage system to ensure it meets the capacity requirements for data readiness and processing for the SSR system.

Validation: The storage system will be loaded with data and verified that it maintains the 480GB capacity while allowing for efficient data processing and transmission readiness for the SSR system.

CDH-3

Verification: analysis. Analyze the data interfacing specifications to ensure compatibility and effective communication between the instrument, storage, and command systems.

Validation: Test the integrated system by simulating data transfer scenarios, confirming that data is accurately exchanged and processed between the instrument, storage, and command systems without errors or delays.

CDH-3.1

Verification: analysis. Analyze the specifications of the direct interfacing ports to ensure they conform to Spacewire standards for high speed data transfer and reliability.

Validation: Conduct performance tests on the interfacing ports with the OBC, verifying that data transfer rates meet the high speed requirements.

CDH-3.2

Verification: analysis. Analyze the design and implementation of the secondary data interfacing system to ensure it follows standards for redundancy and safety in data connection and transport.

Validation: Test the secondary data interfacing system by simulating data transporting scenarios, validating that it properly maintains reliability and connection, thereby ensuring data integrity and safety.

CDH-4

Verification: analysis. Analyze the architecture of the rovers to ensure that all data and communication protocols are routed through their respective onboard computers (OBC) as the central hub.

Validation: Conduct tests on both rovers to confirm that all data processing and communication occur smoothly through the OBC, ensuring efficient operation between systems.

CDH-4.1

Verification: analysis. Analyze the specifications of the OBC to ensure it meets radiation tolerance standards suitable for prolonged exposure to lunar surface radiation levels throughout the mission for the SR system.

Validation: Radiation testing is to be performed on the OBC under simulated lunar conditions, confirming that it can properly operate and maintain functionality despite exposure to high levels of radiation throughout its mission duration.

CDH-4.2

Verification: analysis. Analyze the specifications of the single-board OBC to verify that it achieves a minimum clock speed of 200MHz, suitable for handling data transmission constraints for the SR system.

Validation: Conduct performance benchmarking tests on the OBC to ensure it consistently operates at or above the 200MHz clock speed while effectively processing large sets of data for transmission for the SR system.

CDH-4.3

Verification: analysis. Analyze the design specifications of the single-board OBC to ensure it meets radiation tolerance standards for the lunar pit environment, accounting for the specific radiation levels expected throughout the mission for the SSR systems.

Validation: Radiation testing is to be performed on the OBC under a simulated lunar pit environment, confirming its ability to maintain functionality and reliability despite periodic high radiation exposure during the mission.

CDH-4.4

Verification: analysis. Analyze the specifications of the single-board OBC to verify that it achieves a minimum clock speed of 150MHz, suitable for handling data transmission constraints for the SSR system.

Validation: ion: Conduct performance benchmarking tests on the OBC to ensure it consistently operates at or above the 150MHz clock speed while effectively processing large sets of data for transmission for the SSR system.

CDH-4.5

Verification: analysis. Assess the specifications of the operating systems selected to ensure they provide the flexibility and efficiency needed for optimal control of the OBC.

Validation: Conduct functionality tests on the operating systems, evaluating their performance in system resource management, validating that they deliver reliable control and efficiency in operational scenarios.

CDH-5

Verification: analysis. Analyze the specifications of the CDH system equipment to verify it is rated to operate effectively within the temperature range of -55°C to +125°C, particularly for OBC processors and storage components.

Validation: Conduct environmental testing on the CDH system equipment, simulating temperature ranges within the range defined, to validate that all components function reliably and maintain performance throughout the entire temperature spectrum.

1.5.4.2 CDH Subsystem Overview

The CDH subsystem serves as the control hub for the mission's two primary systems: Surface and Subsurface Rovers. It is tasked with managing and processing data from the rovers' instruments, ensuring efficient communication between subsystems, and directing commands to execute mission tasks through its appropriate subassemblies. The subassemblies within the rover systems include telecommunication equipment, data interfacing, onboarding computer (OBC) processing, and storage devices.

Surface Rover

For telecommunications, the SR will communicate and relay information through an X-band-capable transceiver which will transmit and receive commands directly from the Lunar Orbiter (LO) through the rover's antennas. The XLINK-X specializes in X-band frequencies spanning from 8 to 12 GHz and was chosen for its low mass and power constraints. The task of the transmission and receiving of signals for direct communication with the LO is assigned to a High-Gain Antenna (HGA), responding and receiving at rates up to 2Mbps. This range was chosen from analyzing the benefits of faster transference of data and information allowing for more detailed scientific observations and quicker response times for the mission remote operations. It is also the matching range of the Perseverance rover on Mars, giving that specific range more potency due to existing usage in external missions (NASA, n.d.). The HGA has a narrow band signal range and requires directional adjustments when sending and receiving signals to and from the LO. It's because of this directionally-concentrated narrow signal that gives it a higher data rate compared to other types of antennas (Taylor et. al., n.d.). For scenarios that require the transmission of critical data from the SSR to the SR, then the HGA will focus its antenna towards the SSR within the Marius Hills Pit for receiving.

The SR will also carry an additional secondary antenna system; a Low-Gain Antenna (LGA), that is capable of transmitting and receiving at lower data rates for redundancy and safety purposes. The LGA is a prospective choice for redundancy because of its omnidirectional signal range, which allows the antenna to pick-up and send signals without having to move or focus in a specific direction (NASA SPINOFF, 2020). If the HGA is unable to pick up command telemetry from the LO relay point, then the LGA will act as the safety fall-back antenna, in order to keep constant communication flowing throughout the mission. For general or low-priority data transmission, the LGA will be tasked with receiving data transmitted from the SSR.

The SR will be fitted with a RAD5545 single-board computer as the OBC. This computer consists of a radiation-hardened processor that blocks up to a total ionizing dose of 100 krad (BAE, n.d.). This quantitative value was seen as favorable due to the

amount of radiation seen on the lunar surface compared to Mars and Earth. On the moon's surface, the average radiation dose can be around 0.46 rads, with dose rates ranging from 1 to 2 millirads per hour (WOTM, 2008). The OBC also comes equipped with 4 GBytes of DDR3 SDRAM with error correction at 800 MTransfers/second and 1 GBytes of triple modular redundant non-volatile flash memory (BAE, n.d.). The internal access to RAM-type memory is beneficial for quick allocation of processing data within the OBC and allows for the seamless control of data management and communication throughout the SR system. The RAD5545 also exhibits internal SpaceWire ports which shall prove essential with scientific data extraction and handling through the processes of the OBC and into storage or transmission preparations. The software architecture framework present will be the core Flight System (cFS) which includes three key aspects: dynamic run-time environment, layered software, and component based design. The architecture holds a configurable set of requirements and code that simplifies flight software engineering, quality, and allows for the source code to run on different processor/OS platforms (cFS-NASA, n.d.). The primary operating system (OS) that will be going along with the software architecture of the mission will be VxWorks, due to its real-time nature and priority-based scheduling of mission critical tasks (WNDRVR. n.d.).

The interfacing of data shall be done through SpaceWire and MIL-STD-1553 interfacing systems. SpaceWire is already integrated through the OBC whereas MIL-STD-1553 will need to be integrated using a PCI card. This will grant the SR system with both SpaceWire and MIL-STD-1553 interfacing capabilities between scientific instruments, communication, and storage system processes. The purposes of utilizing SpaceWire stems from the overall industry adaptability, which was evaluated during trade study review. SpaceWire provides flexibility to an environment that is not considered to be flexible at all; it is stated to have low error-rates, low power consumption, and high performance metrics for data handling (ESA, n.d.). The purpose of MIL-STD-1553 is primarily to introduce redundancy within the data handling of the system. It is considered a reliable interface due to its robust design and maintaining of constant communication in harsh environments (MAE, 2004). Like SpaceWire, it is also adopted widely within the space industry. By incorporating reliable safety's along with high-speed interface technology, we are able to balance out the most effective and efficient prospective results of this mission for the SR system.

Storage devices for the SR include EEPROM, NAND Flash, and SSD. The EEPROM provides allocated storage to the OBC, storing firmware and bootloader code, essential for software back-ups for redundancy, which shall be allocated to 4 MB of space, following in suite of similar martian rover setups. The EEPROM storage device will only be interfaced with the OBC system. The need for NAND Flash as opposed to the sole usage of the SSD is due to the benefit of partitioning data between the SR

system, for either long-term storage or immediate transference of data. Scientific measurements shall flow through and into the NAND Flash device and utilize its fast read/write speeds of 300/100 Mbps, respectively (Mellor, 2023). The NAND shall contain 4 GB of allocated space, to accommodate for the processing of readied data for transmission. From there, it will either flow into the SSD for long-term storage needs, or be sent directly through the transceiver as a signal to the LO. Previously stored data in the SSD shall also flow back through the NAND when required for transmission. Because of the potential case for long-periods of wait time for transmission, the SSD device will be designed for 480 GB of storage space. This should satisfy the data generated by the scientific instruments for the entirety of the mission in cases of long-wait-time and mass-data ratios. The Perseverance rover on Mars has already incorporated a similar system for long-term storage handling (Mellor, 2023).

Subsurface Rover

The SSR shall use the same LGA as the SR system for the same reasoning; redundancy and constant flow of communication. The SSR will encounter obstacles during data and command transmission and receiving, hence the omni-directional advantage of the LGA being beneficial for the mission. The primary antenna however will be a Ultra-High Frequency Medium-Gain antenna (UHF), which also holds similar properties of omni-directional signal range. The UHF antenna is able to keep higher data rate connections than the LGA and so will only be used for mission critical needs requiring speedy transmission or receiving. The LGA will handle general or low-critical priority communication. The LGA will also be in linkage with its own XLINK-X transceiver, similar to the configuration in the SR. As for the UHF antenna, it will be linked through the TRX-U, which is a UHF-capable transceiver. This specific transceiver only consumes a max of 2 W of power and fits well within the CDH compartment of the SSR, matching dimensional and power constraints (SatSearch, n.d.).

For this rover system, the use of a RAD750 single-board computer will be sufficient as the SSR's OBC. This is because of the expected minimal radiation dosage within the pit environment. This OBC consumes 30% less power than its successor variant, the RAD5545, and blocks a lower radiation dosage of 50 krad (BAE, n.d.). Although the radiation blockage dose is lower than the SR's OBC, it will still handle its job within its own environment. The same software architecture framework and OS will be used as with the SR system; cFS and VxWorks.

The interfacing of the SSR shall remain the same as with the SR. No specific changes necessary. The OBC, similarly to the RAD5545, also includes SpaceWire interfacing, while the MIL-STD-1553 interfacing will require the same PCI card.

Storage devices shall match those of the SR; 4 MB EEPROM and 4 GB NAND Flash, however the SSD storage device shall instead hold 128 GB of storage space, which is in contrast to the 480 GB SSD in the SR system. The SSR will be a much smaller rover that will consistently transfer scientific data to the SR above, where the surface system will be the primary system to hold and transmit data to the LO. Therefore the SSR will not require the larger allocation of data storage space.

Technology Readiness Level

Subassembly	TRL	Explanation
Telecommunications		
High-Gain Antenna	7	High-gain antennas are well-developed, with a good history in space communications for distant missions, like the moon. Although minor tuning may be required to match the lunar mission needs, the core technology has proven to effectively handle long-range data transmission.
Low-Gain Antenna	8	Low-gain antenna technology is highly mature, with a long history of use in space missions for reliable and short-range communication. The technology has been thoroughly validated in actual mission environments, promising consistent performance and reliability.
UHF Antenna (Medium-Gain)	8	UHF medium-gain antennas have been widely used in space missions for robust communication at medium ranges. This technology has been tested and proven in actual mission environments, such as the lunar surface, confirming its ability to maintain reliable data transmission.
XLINK-X (Transceiver)	7	The XLINK-X transceiver technology has been utilized in various space applications for reliable data communication through X-Band frequencies. It has excelled primarily in satellite relay communications with LEO-type ranges. It has not had applications of interplanetary usage, however proves as a promising technology for use of this mission.
TRX-U (UHF Transceiver)	7	The TRX-U transceiver technology has been successfully deployed in multiple space missions for effective communication over UHF frequencies. It has demonstrated reliable performance in satellite communications. While it has not been used in interplanetary missions, it shows potential for adaptation and application in lunar communications.
Overall	7	
Onboarding Computers (OBCs)		
RAD5545 Single-Board Computer	6	The RAD5545 single-board computer technology has been utilized in some space applications, like satellites. However, it may require additional testing and qualification to ensure stable performance in the specific conditions of the lunar environment.

RAD750 Single-Board Computer	8	The RAD750 single-board computer has been successfully employed in various space missions, including martian-rover surface applications. Its performance has been thoroughly tested in operational environments, demonstrating reliable functionality under harsh conditions.
Overall	6	
Data Interfacing		
SpaceWire	8	SpaceWire technology has been successfully implemented in numerous space missions for high-speed data communication. It has undergone extensive testing in operational environments, demonstrating robust performance and reliability in transmitting data between systems.
MIL-STD-1553	8	MIL-STD-1553 technology has been extensively utilized in military and space applications for reliable data communication. It has been rigorously tested in various operational environments, such as martian rover systems.
Overall	8	
Storage System Devices		
EEPROM	7	EEPROM technology has been utilized in several space missions, including those involving the Moon, for storing critical data and firmware. While it is a mature technology, some adjustments may be needed to optimize its performance for the unique conditions of the lunar surface environment.
NAND Flash	8	NAND Flash technology has been successfully used in various space missions, including lunar surface applications, for data storage due to its high density, reliability, and read/write speeds. It has undergone extensive testing in operational environments.
SSD	8	SSD technology has been utilized in a range of space missions, including lunar surface exploration. Extensive testing in operational environments has confirmed its reliability and performance in long-term storage under harsh conditions.
Overall	7	
Software		
Core Flight System	8	This software framework has been extensively used in various space missions, demonstrating its reliability and adaptability for flight operations. The CFS has undergone rigorous testing in operational environments, confirming its effectiveness in managing spacecraft systems and proves promising for the lunar surface environment.
VxWorks (Operating System)	8	This real-time operating system is widely used in critical space missions and aerospace applications, demonstrating proven reliability and performance under various operational conditions.
Overall	8	

Table #10 CDH Subsystem TRL

CDH Equipment Specifications

Surface Rover CDH Equipment			
	Mass (g)	Dimensions (mm)	Max Power Consumption (W)
X-Band HGA Antenna	15000	1000 height 500 radius	100
X-Band LGA Antenna	200	50 height 75 radius	5
XLINK-X (Transceiver)	200	90 x 65 x 25.3	16
RAD5545 - includes SpaceWire Interface	2500	233.35 x 160 x 20.32	35
MIL-STD-1553 Interface Card	100	74 x 149	10
EEPROM SOIC (4MB)	3	8 x 6 x 1.5	~0.003
NAND Flash (4GB)	10	14 x 18 x 1.0	~0.033
SSD M.2 (480 GB)	50	22 x 80 x 3.5	~0.165

Table #11 Surface Rover CDH Equipment

Subsurface Rover CDH Equipment			
	Mass (g)	Dimensions (mm)	Max Power Consumption (W)
UHF MGA Antenna	500	750 height 200 radius	10
X-Band LGA Antenna	200	50 height 75 radius	5
XLINK-X (Transceiver)	200	90 x 65 x 25.3	16

TRX-U (UHF Transceiver)	140	83 x 57 x 16	8
RAD750 - includes SpaceWire Interface	549	100 x 160	10.8
MIL-STD-1553 Interface Card	100	74 x 149	10
EEPROM SOIC (4MB)	3	8 x 6 x 1.5	~0.003
NAND Flash (4GB)	10	14 x 18 x 1.0	~0.033
SSD M.2 (128 GB)	50	22 x 80 x 3.5	~0.165

Table #12 Subsurface Rover CDH Equipment

Software Architecture Flowchart

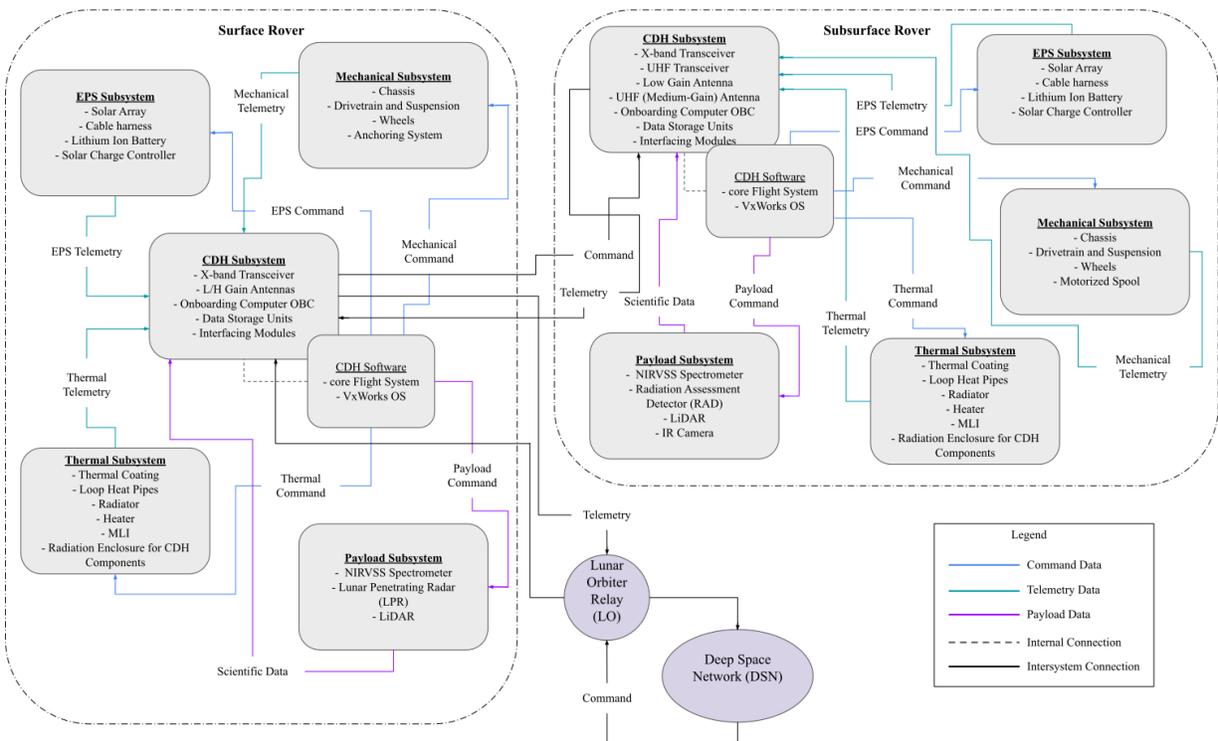


Figure #3 Software Architecture Flowchart

1.5.4.3 CDH Subsystem Trade Studies

This initial trade study (Appendix D, Table 1) compares antenna types for communication between the SR, SSR, and LO systems, assessing High-Gain, Low-Gain, UHF, and X-Band/Ka-band antennas. The mission requires two antennas, evaluated based on signal range, data transmission rate, power constraints, environmental resilience, and size/mass.

Signal range and data transmission rate each carry a 25% weight. High-Gain and X-band/Ka-band antennas excel here, with scores of 9 and 8 for range and 9 and 10 for data transmission, as both meet the 2Mbps rate requirement. Power constraints are weighted at 15%, given the limited power available per rover. Low-Gain and UHF antennas, needing minimal power, rank highest at 9 and 8. Environmental factors, also at 15%, saw Low-Gain antennas perform best, with a rating of 8 due to their resistance to radiation and temperature variations. Size/mass holds a 20% weight, as compact antennas benefit the system. Low-Gain and UHF antennas score 9 for their minimal size, aiding omni-directional signal transmission. Ultimately, the High-Gain antenna amassed the highest score of 74.50% based on the weighted factors, making it a top candidate for the mission.

The selected antennas based on this study shall include two X-Band Low-Gain antennas, one for each rover system, one X-Band High-Gain antenna for the SR only, which will be used for direct contact with the LO, and one UHF (Medium-Gain) antenna for the SSR only, which will be used for rover-rover system transmission and communication. The reason for choosing a combination of the trade study comparables comes down to the variability of the mission and its requirements and constraints. When used in their respective environments, each comparable acts appropriately to the respective criterion.

This next trade study (Appendix D, Table 2) evaluates Onboard Computer (OBC) options for the dual-rover system. Emphasis on weighted criteria includes processing power (30%), temperature range (25%), radiation tolerance (20%), power consumption (15%), and memory capacity (10%). The comparables reviewed are the RAD750, RAD5545, Arm Cortex-A53, and GR712RC.

Processing power holds the highest weight, as the OBC must efficiently process instrument data and maintain communication within precise timeframes. RAD5545 and Cortex-A53 achieved the highest ratings, with Cortex-A53 scoring 10 due to its processing capabilities under low-power constraints. Radiation tolerance, weighted at 20%, reflects the lunar environment's high radiation exposure; GR712RC, RAD5545, and RAD750 earned top ratings, with the RAD series capable of up to 100 Krad shielding. Power consumption saw comparable scores similarly, except the RAD5545, which scored slightly lower. Memory capacity saw all comparables perform well, with the RAD5545 excelling due to internal MRAM and SDRAM storage. Temperature range ratings were uniform across all options, as all models function between -55°C and +125°C. The RAD5545 achieved the highest overall score, at 79.00%, due to its balanced performance across these weighted categories.

The prospective OBC's to be selected will be the RAD5545 and RAD750 single-board computers, for the SR and SSR systems, respectively. Although the RAD750 has a lower score than the second highest scored comparable (GR712RC), it harbors a favorable balance between reliability, power consumption, and processing power. Due to this, it meets the appropriate constraints for the SSR system.

The next trade study (Appendix D, Table 3) focuses on the interfacing between instruments and equipment. Emphasis on criterias weighted are: data rate (25%), power consumption (25%), reliability/fault tolerance (30%), ease of integration (10%), and adoption within the industry (10%). The ideal interface for this mission would require high data rate connections between OBC and storage devices that are both reliable and have low power consumptions, hence the higher allocation of weight to stated criteria. The selected comparables include: SpaceWire, MIL-STD-1553, CAN Bus, RS-422/RS-485 and Ethernet. Of these, SpaceWire and MIL-STD-1553 interfacing amassed the highest scores of 79.00% and 77.50%, respectively.

SpaceWire excelled best in the data rate speed it can support, its ease of integration, especially with previously studied OBC's, and its adoption throughout the industry spectrum. MIL-STD-1553 proves to perform better in minimizing power consumption, reliability throughout the system it interacts with, and is also shown to be prevalent throughout the industry.

Both SpaceWire and MIL-STD-1553 interfacing shall be incorporated into the dual-rover system due to noted prospects as per the weighted categories.

The last trade study focuses on the storage of data collected from scientific instruments (Appendix D, Table 4). Emphasis on criterias weighted are: storage capacity (25%), read/write speed (25%), power consumption (25%), radiation tolerance (15%), and the size and mass (10%). The storage requirements call for appropriate capacity as per measurement data collected, high read/write speeds for storage and transmission readiness of data, and minimal power consumption, hence the higher allocation of weight to stated criteria. The selected comparables include: EEPROM, NANS Flash, SRAM, DRAM, MRAM, and SSD storage devices. Of these, SSD and NAND Flash storage units amassed the highest scores of 81.50% and 74.50%, respectively.

SSD excelled best in terms of storage capacity making it well suited for long-term storage needs. It also has fast read/write speeds that are essential for proper data storage of important information like scientific measurements. NAND Flash is also a competitor for the same criteria that SSD excelled in and may serve as a reliable backup. It also does well for size and mass compared to other devices.

After careful evaluation, it seemed apparent to include both SSD and NAND Flash to the dual-rover system with an additional storage device: EEPROM. This is to be allocated strictly for the OBC due to the requirement of including a storage device to meet the needs of firmware and software command allocation. This provides reliability and control for OBC operations.

1.5.5 Thermal Management Subsystem

1.5.5.1 Thermal Management Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req Met?
Thermal Control System (TCS)							
TCS-1	The system shall be maintained within allowable operating temperatures for all environmental conditions experienced on the lunar surface.	Ensures that all rover systems function optimally in extreme lunar conditions.	TCS-1	TCS-1.1, TCS-1.2	Analysis	Thermal Control System	Met
TCS-1.1	The surface system shall maintain an internal temperature of 17 to 30 ± 2 °C for the duration of the mission.	Ensures the surface rover is within operable temperature range with respect to the environmental conditions on the lunar surface.	TCS-1	TCS-1.1.1	Analysis	Thermal Control System	Met
TCS-1.1.1	The system shall incorporate passive heat distribution and management techniques to regulate the internal temperature of the surface system.	Ensures that the system manages heat loss/gain effectively while drawing virtually no power.	TCS-1.1	-	Inspection	Thermal Control System	Met
TCS-1.1.2	The system shall incorporate active heat distribution and management techniques to regulate the internal temperature of the surface system.	Ensures that the system effectively manages heat loss/gain at the cost of some power.	TCS-1.1	-	Inspection	Thermal Control System, CDH	Met

TCS-2	The systems shall maintain sensitive instrumentation and components within their operating temperature ranges.	Protects sensitive instruments from temperature based errors or damage.	MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9	TCS-2.1, TCS-2.2, TCS-2.3, TCS-2.4	Analysis	Thermal Control System, Payload, Power, Mechanical	Met
TCS-2.1	The NIRVISS spectrometer shall not exceed temperatures above 45°C and fall below -20 °C.	NIRVISS operates efficiently at temperatures lower than 0°C, as it significantly reduces thermal noise.	TCS-2	TCS-2.1.1	Analysis	Thermal Control System, Payload	Met
TCS-2.1.1	The system shall incorporate active heat management to maintain the NIRVISS spectrometer operational range from -20°C to 45°C.	In the lunar surface, where temperatures are relatively unstable ranging from -208°C to 250°C, active heat management will be necessary to combat fluctuating temperatures	TCS-2.1	-	Analysis	Thermal Control System, Payload, Power, CDH	Met
TCS-2.2	The Lunar Penetrating Radar (LPR) and LiDAR shall not exceed temperatures above 40 °C and below 0 °C.	Protecting such components from extreme temperatures ensures accurate measurements and prevents damage to sensitive components.	TCS-2	TCS-2.2.1	Analysis	Thermal Control System	Met
TCS-2.2.1	The system shall incorporate passive cooling to maintain the LPR, and LiDAR within its operable range of 0 °C-40 °C.	Proper insulation will ensure that the LPR and LiDAR remain within their operable ranges.	TCS-2.2	-	Analysis	Thermal Control System, Payload	Met

TCS-2.3	Critical CDH Components shall not exceed 125 °C and fall below -55 °C.	Operation in this range ensures that OBC processors, the most sensitive piece of CDH equipment, remain functional.	TCS-2	TCS-2.3.1	Analysis	Thermal Control System, Command and Data Handling	Met
TCS-2.3.1	The system shall incorporate passive cooling to maintain the temperature of CDH components.	Operation in this range ensures that electronic components function reliably without thermal stress and avoids mechanical failures of materials as a result	TCS-2.3, CDH-5	-	Inspection	Thermal Control System, CDH	Met
TCS-2.4	Sensitive Electronics within the rovers shall not exceed 35 C and fall below 15 C.	Operating in this range removes the possibility of thermal noise and thermal stress affecting sensitive electronics.	TCS-2	TCS-2.4.1	Analysis	Thermal Control System, Power System	Met
TCS-2.4.1	The system shall incorporate passive cooling to maintain the temperature of sensitive electronics.	Passive cooling components, particularly heat loops and radiators, can be effective at dissipating heat generation caused by electronics as they can gather heat in one area and be dissipated via IR.	TCS-2.4	-	Analysis	Thermal Control System, Power	Met

TCS-3	The systems shall protect sensitive instrumentation and components from damage caused by radiation.	Prevents degradation of instrumentation due to solar, cosmic, or lunar surface radiation exposure.	MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9	TCS-3.1	Demonstration	Thermal Control System	Met
TCS-3.1	The systems will have a net 0 W load entering and exiting.	Ensures that no radiation will enter the system to disrupt instrumentation and electronics.	TCS-3	TCS-3.1.1, TCS-3.1.2, TCS-3.1.3	Analysis	Thermal Control System	Met
TCS-3.1.1	The system shall incorporate insulation layers to protect against disruptions from radiation.	Insulation layers provide radiation balance such that heat loss/gain due to radiation is depreciable.	TCS-3.1	-	Inspection	Thermal Control System	Met
TCS-3.1.2	The system shall include radiation enclosures for electronics, providing redundancy in case radiation penetrates the rover's internal shielding.	Provides redundancy in case radiation penetrates the rover, shielding sensitive electronics.	TCS-3.1	-	Inspection	Thermal Control System, CDH, Power	Met

TCS-3.1.3	The system shall incorporate reflective thermal coating (absorptivity as close to 0 as possible) to minimize incoming solar radiation.	Reflective thermal coating deflects incoming solar radiation, reducing the heat load entering the rover.	TCS-3.1	-	Inspection	Thermal Control System	Met
TCS-4	The system shall include redundant thermal components to ensure continued operation in the event of a failure.	Enhances mission success probability by preventing singular points of failure.	MR-14	TCS-4.1	Inspection	Thermal Control System	Met
TCS-4.1	The system shall incorporate a backup heater and pump loops in the event an existing heater fails.	The heater and pump are the main sources of heating and cooling, especially for the surface rover, which is why it's imperative to reduce the risk of the surface rover failing due to a singular point.	TCS-4	-	Inspection	Thermal Control System, Power, CDH	Met
TCS-5	The system shall optimize energy consumption to maximize the rover's operational lifespan.	Ensures efficient use of limited power resources to ensure maximum lifetime during the mission duration.	MR-14	TCS-5.1	Demonstration	Thermal Control System, CDH, Power	Met
TCS-5.1	Each system individually shall not draw more than 239.2 W of power.	Utilizing more passive heat distribution than active heat distribution increases the longevity of the surface and subsurface rovers.	TCS-5	-	Analysis	Thermal Control System, Power, CDH	Met

TCS-6	The total mass of both thermal control systems shall not exceed 45.1 kg.	Ensures the system is optimized to be as lightweight as possible to traverse the lunar surface more efficiently.	Customer	TCS-6.1	Inspection	Thermal Control System, Mechanical	Met
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Table #13 Thermal Subsystem Surface Rover Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req Met?
Thermal Control System(TCS)							
TCS-1.2	The subsurface system shall maintain an internal temperature of 10 to 25 ± 2 °C for the duration of the mission.	Ensures subsurface rovers operate efficiently in stable temperature conditions.	TCS-1	TCS-1.1.1, TCS-1.2.1	Analysis	Thermal Control System	Met
TCS-1.2.1	The system shall incorporate active heat distribution and management techniques to regulate the internal temperature of the subsurface system.	Uses power to effectively manage heat loss/gain when necessary.	TCS-1.1	-	Inspection	Thermal Control System	Met
TCS-2	The systems shall maintain sensitive instrumentation and components within their operating temperature ranges.	Protects sensitive instruments from temperature based errors or damage.	MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9	TCS-2.1, TCS-2.2, TCS-2.3, TCS-2.4	Analysis	Thermal Control System	Met

TCS-2.1	The NIRVISS spectrometer and IR Camera shall not exceed temperatures above 45°C and fall below -20°C.	NIRVISS and IR cameras operate efficiently at temperatures lower than 0°C, as it significantly reduces thermal noise.	TCS-2	TCS-2.1.1	Analysis	Thermal Control System	Met
TCS-2.2	The Radiation Assessment Detector (RAD), Lunar Penetrating Radar (LPR), and LiDAR shall not exceed temperatures above 40°C and below 0°C.	Protecting such components from extreme temperatures ensures accurate radiation measurements and prevents damage to sensitive components.	TCS-2	TCS-2.2.1	Analysis	Thermal Control System	Met
TCS-2.2.1	The system shall incorporate passive cooling to maintain the LPR, and LiDAR within its operable range of 0°C - 40°C.	Proper insulation will ensure that the LPR and LiDAR remain within their operable ranges.	TCS-2.2	-	Analysis	Thermal Control System	Met
TCS-2.3	Critical CDH Components shall not exceed 125 °C and fall below -55 °C.	Operation in this range ensures that OBC processors, the most sensitive piece of CDH equipment, remain functional.	TCS-2	TCS-2.3.1	Analysis	Thermal Control System, Command and Data Handling	Met
TCS-2.3.1	The system shall incorporate passive cooling to maintain the temperature of CDH components.	Operation in this range ensures that electronic components function reliably without thermal stress and avoids mechanical failures of materials as a result	TCS-2.3, CDH-5	-	Inspection	Thermal Control System	Met

TCS-2.4	Sensitive Electronics within the rovers shall not exceed 35°C and fall below 15°C.	Operating in this range removes the possibility of thermal noise and thermal stress affecting sensitive electronics.	TCS-2	TCS-2.4.1	Analysis	Thermal Control System, Power System	Met
TCS-2.4.1	The system shall incorporate passive cooling to maintain the temperature of sensitive electronics.	Passive cooling components, particularly heat loops and radiators, can be effective at dissipating heat generation caused by electronics as they can gather heat in one area and be dissipated via IR.	TCS-2.4	-	Inspection	Thermal Control System	Met
TCS-3	The systems shall protect sensitive instrumentation and components from damage caused by radiation.	Prevents degradation of instrumentation due to solar, cosmic, or lunar surface radiation exposure.	MR-3, MR-4, MR-5, MR-6, MR-7, MR-8, MR-9	TCS-3.1	Demonstration	Thermal Control System	Met
TCS-3.1	The system will have a net 0 W heat load entering the rover.	Ensures heat balance in the system to prevent disruption of instrumentation and electronics.	TCS-3	TCS-3.1.1, TCS-3.1.2, TCS-3.1.3	Analysis	Thermal Control System	Met

TCS-3.1.1	The system shall incorporate insulation layers to protect against disruptions from solar/cosmic radiation.	Insulation layers provide radiation balance such that heat loss/gain due to radiation is depreciable.	TCS-3.1	-	Inspection	Thermal Control System	Met
TCS-3.1.2	The system shall include radiation enclosures for electronics, providing redundancy in case radiation penetrates the rover's internal shielding.	Provides redundancy in case radiation penetrates the rover, shielding sensitive electronics.	TCS-3.1	-	Inspection	Thermal Control System	Met
TCS-3.1.3	The system shall incorporate reflective thermal coating (absorptivity as close to 0 as possible) to deflect incoming solar radiation away from the rover.	Reflective thermal coating deflects incoming solar radiation, reducing heat load on the rover.	TCS-3.1	-	Inspection	Thermal Control System	Met
TCS-4	The system shall include redundant thermal components to ensure continued operation in the event of a failure.	Enhances mission success by preventing singular points of failure.	MR-14	TCS-4.1	Inspection	Thermal Control System	Met

TCS-4.1	The system shall incorporate a backup heater in the event an existing heater fails.	The heater is the main source of heating, especially for the surface rover, which is why it's imperative to reduce the risk of the surface rover failing due to a singular point.	TCS-4	-	Inspection	Thermal Control System	Met
TCS-5	The system shall optimize energy consumption to maximize the rover's operational lifespan.	Ensures efficient use of limited power resources to ensure maximum lifetime during the mission duration.	MR-14	TCS-5.1	Analysis	Thermal Control System	Met
TCS-5.1	The TCS shall not use more than 362 W.	Utilizing more passive heat distribution than active heat distribution increases the longevity of the surface and subsurface rovers.	TCS-5, EPS-3.2	-	Analysis	Thermal Control System	Met
TCS-6	The total mass of both thermal control systems shall not exceed 45.1 kg.	Ensures the rover is optimized to be as lightweight as possible to traverse the lunar surface more efficiently.	Customer	TCS-6.1	Inspection	Thermal Control System	Met

Table #14 Thermal Subsystem Subsurface Rover Requirements

Verification and Validation

TCS-1:

The verification method will involve analysis through Computational Fluid Dynamics (CFD) simulations.. The CAD designs of both rovers will be evaluated against the lunar environment to assess their robustness in withstanding thermal stress.

For validation, the rover will be placed in a thermal chamber to cycle through lunar thermal profiles. During this process, monitoring will focus on detecting any material or structural deformation, component failure, or changes in mobility performance.

TCS-1.1:

The verification method will involve analysis through heat flow diagrams. The net heat transfer of the rover on the lunar surface will be calculated based on the lunar environmental conditions to determine if the rover can operate within the specified parameters.

For validation, Computational Fluid Dynamics (CFD) simulations will be employed to support these calculations. The CAD designs of both rovers will be evaluated against the lunar environment to assess their robustness in withstanding thermal stress at the given temperature.

TCS-1.1.1:

The verification method will involve inspection to assess several modes of passive heat distribution and management components.

For validation, calculations of the heat flow diagram will be reviewed to ensure they justify the quantity and effectiveness of the passive heating and cooling devices.

TCS-1.1.2:

The verification method will involve inspection to assess various modes of active heat distribution and management components.

For validation, calculations of the heat flow diagram will be reviewed to ensure they adequately justify the quantity and effectiveness of the active heating and cooling devices.

TCS-1.2:

The verification method will involve analysis using heat flow diagrams. The net heat transfer of the rover in the lunar subsurface will be calculated based on the lunar environmental conditions to determine if the rover can operate within the specified parameters.

For validation, Computational Fluid Dynamics (CFD) and simulations will be employed to support these calculations. The CAD designs of both rovers will be evaluated against the

lunar environment to assess their robustness in withstanding the thermal stress at the given temperature.

TCS-1.2.1:

The verification method will involve inspection to assess various modes of active heat distribution and management components.

For validation, ensure that the calculations of the heat flow diagram justify the quantity of active heating and cooling devices, particularly if the temperature differential is significant.

TCS-2:

The verification method will involve analysis by simulating the lunar environments of both the surface and subsurface, while monitoring the respective rovers in those conditions. Computational Fluid Dynamics (CFD) analysis will be conducted to determine how the instruments respond to fluctuations in lunar temperature and how the thermal control system (TCS) adapts.

For validation, the rover will be placed in a simulated environment representing the lunar night cycle. The effectiveness of the thermal control system in preventing instrumentation and electronics from failure will be measured.

TCS-2.1:

The verification method will involve analysis through Computational Fluid Dynamics (CFD) simulations to verify whether the environmental temperatures align with the operational ranges of the instrument throughout the lunar day.

For validation, the instrument will be placed in a thermal chamber equipped with adequate insulation and cooling capabilities. Lunar thermal profiles will be cycled through while monitoring for component failure or any decline in data quality.

TCS-2.1.1:

The verification method will involve analysis through Computational Fluid Dynamics (CFD) simulations to ensure that the active thermal management system keeps the NIRVISS spectrometer within the specified temperature range under expected lunar conditions.

For validation, the spectrometer will be placed in a thermal chamber with controlled insulation and cooling capabilities. Simulated lunar thermal profiles, including both day and night cycles, will be cycled through to assess performance.

TCS-2.2:

The verification method will involve analysis through simulations using Computational Fluid Dynamics (CFD) to confirm that the thermal control system maintains the RAD,

LPR, and LiDAR instruments within the specified temperature range under expected lunar conditions.

For validation, a thermal vacuum chamber will be used to simulate lunar temperature extremes. Each instrument will be monitored to ensure they remain within operational limits during these tests.

TCS-2.2.1:

The verification method will involve analysis through simulations using Computational Fluid Dynamics (CFD) to confirm that the thermal control system maintains the RAD, LPR, and LiDAR instruments within the specified temperature range under expected lunar subsurface conditions.

For validation, a thermal vacuum chamber will be utilized to simulate lunar temperature extremes. Each instrument will be closely monitored to ensure they remain within operational limits throughout these tests.

TCS-2.3:

The verification method will involve analysis through thermal simulations to assess the heat dissipation and thermal environment of the CDH components. CFD will be used to predict temperature distributions and ensure they remain within specified limits.

For validation, CDH components equipped with passive cooling mechanisms will be subjected to temperature cycles that simulate expected operational conditions. Temperatures will be monitored to confirm that they remain within the specified range.

TCS-2.3.1:

The verification method will involve inspection to evaluate various modes of passive heat distribution and management for the CDH components.

For validation, ensure that the calculations of the heat flow diagram sufficiently justify the quantity and effectiveness of the passive cooling devices.

TCS-2.4:

The verification method will involve analysis through thermal simulations to assess the heat dissipation and thermal environment of the electronic components. Computational models will be used to predict temperature distributions and ensure they remain within specified limits.

For validation, the electronics will be placed in a thermal chamber and subjected to temperature cycles that simulate expected operational conditions. Temperatures will be monitored to confirm that they remain within the specified range.

TCS-2.4.1:

The verification method will involve inspection to assess various modes of passive heat distribution and management for critical electronics.

For validation, ensure that the calculations of the heat flow diagram adequately justify the quantity and effectiveness of the passive cooling devices.

TCS-3:

The verification method will be a demonstration conducted on the lunar surface. The rover will be equipped with multiple layers of insulation (MLI) and will include redundant features for sensitive electronics, such as radiation enclosures. The passive cooling system will incorporate a heat loop connected to a radiator to maximize heat dissipation through infrared radiation.

For validation, once the rover is deployed on the Moon, measurements will be taken to assess how effectively the rover adapts to the lunar environment.

TCS-3.1:

The verification method will involve analysis using heat flow diagrams to determine if the incorporation of active and passive heat flow management successfully reduces the net heat transfer to 0 W.

For validation, once the rover is completed, simulations will be conducted, and data will be recorded to compare with calculations, assessing whether there is any heat transfer.

TCS-3.1.1:

The verification method will involve inspection to assess whether the insulation layers around the rover are visibly compact and undamaged.

For inspection, once the rover is integrated, check for any damage to the insulation layers that may have occurred during the installation process. Additionally, verify that the correct number of layers has been applied.

TCS-3.1.2:

The verification method will involve inspection to observe and confirm that the enclosure fully houses all CDH components and other critical electronics, such as the lithium-ion battery.

For validation, calipers will be used to measure the volume of the enclosure, ensuring that all electronics fit comfortably within its boundaries.

TCS-3.1.3:

The verification method will involve inspection to observe the color of the painting, which should be white to maximize reflectivity.

For validation, calipers will be used to measure the thickness of the coating, ensuring it does not exceed a few millimeters to maintain proper adhesion while maximizing reflectivity.

TCS-4:

The verification method will involve inspection to assess the number of redundant features present in the rover. Specifically, the inclusion of backup heaters, which serve as the primary active heating element, is a crucial redundancy that requires a higher level of security.

For validation, after full integration, conduct a final inspection of the rover to ensure that the redundant features have been seamlessly integrated within the constraints of mass, volume, and budget, confirming that there is no additional capacity for more components

TCS-4.1:

The verification method will involve inspection to assess the heater's functionality by turning it on and off.

For validation, after the integration of all parts, activate the secondary heater to ensure it is functioning properly.

TCS-5:

The verification method will involve a demonstration, as the optimal performance of the rovers will be directly correlated with a longer mission duration.

For validation, after both rovers have been sent to the Moon, monitor their operation to ensure they function for their expected operational lifetime of 30 days.

TCS-5.1:

The verification method will involve analysis to calculate the power allocation for each subsystem.

For validation, ensure that passive systems are integrated into the rover to the maximum extent possible, thereby limiting the reliance on active systems and minimizing overall power consumption.

TCS-6: The verification method will involve inspection to measure all components of the thermal control system, ensuring they do not exceed 50 kilograms.

For validation, after full integration, measure all components of the system to confirm compliance with the specified mass requirements.

1.5.5.2 Thermal Management Subsystem Overview

Note: All equations references can be found in Appendix E

Surface Rover Overview

The surface rover, constructed from Aluminum Alloy 6061, has a rectangular prism chassis with dimensions of 0.75 m x 1.15 m x 0.25 m. For worst-case scenario analysis, we consider extreme lunar surface conditions during peak noon, with the sun directly overhead, and temperatures in the Marius Hills Pit reaching up to 250°C (481 K). The rover's internal temperature is set to 30°C (303 K) to ensure all instrumentation, electronics, Mechanical and Command and Data Handling (CDH) components operate within their required temperature ranges. In space, radiation is the primary mode of heat transfer, as there is no atmosphere for convection, and the lunar regolith's low thermal conductivity makes conduction negligible. The relevant parameters are provided in Table 15.

Known and Assumptions	
n radiating to space	1
n radiating to space/surface	4
n radiating to surface	1
space node temp, k	3
surface temp hot, k	481
surface temp cold, k	140
q_solar flux, W/m ²	1367
SA left_face, m ²	0.231
SA right_face, m ²	0.231
SA front_face, m ²	0.165
SA back_face, m ²	0.165
SA top_face, m ²	0.8625
SA bottom face	0.8625
emissivity base, e	0.4
absorptivity base, a	0.3
system temp, k	303
Stephan Boltzman Constant	0.0000000567
Known and Assumptions	

Table #15. Knowns and Assumptions of the Hot Case Heat Flow Map

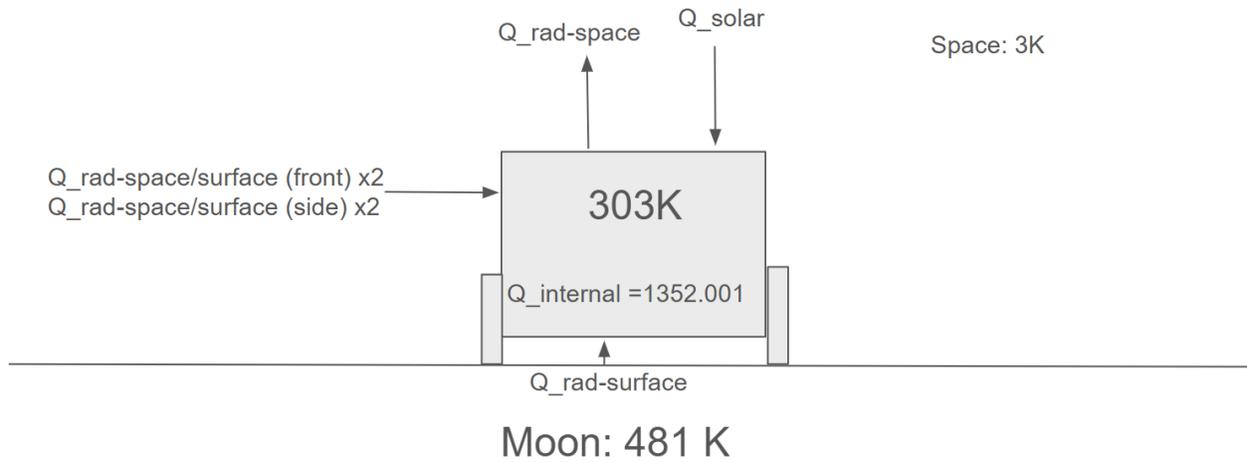


Figure #4. Hot Case Heat Flow Map of the Surface Rover

The heat flow map depicts the rover absorbs a solar flux, Q_{solar} on its top face, radiation $Q_{rad-surface}$ from the lunar surface to the bottom face, and radiation from both the ambient space and surface on all four sides, $Q_{rad-surface}$. Simultaneously, the rover is dissipating heat to the environment in the form of radiation, denoted as $Q_{rad-space}$.

The fundamental equation for radiative heat transfer is shown in Equation 1.

$$Q_{radiation} = \epsilon A \sigma (T_1^4 - T_2^4) \quad (1)$$

Hot Case, initial NO TCS implemented	
Q_solar, W	353.71125
Q_internal, W	1352.001
Q_rad-space, W	164.88
Q_rad-space/surface, W	-480.75
Q_rad-surface, W	-882.2044766
Q_in, W	3068.67

Q _{out} , W	164.88
Q _{net} , W	2903.78
If positive system is heating, if negative system is cooling. If 0 assume as stable	

Table #16 Hot Case Calculations with No TCS Applied

The calculations for each parameter listed in the table above are shown in Appendix E, based on the assumption that half of the 4 sides of the rover are absorbing radiation from space, while the other half absorbs it from the lunar surface. Thus, the total heat transfer of the rover can be denoted as $Q_{net} = Q_{in} - Q_{out} = 3018.58 W$, as outlined by equations (2) through (9).

The thermal control system (TCS) aims to keep the rover's temperature within its specified limits. For a stable internal temperature of 303 K, Q_{net} must be brought to zero. To achieve this, the TCS incorporates various passive cooling mechanisms, including an AZW/LA-II White Polished thermal coating⁸⁰ and 30-layer Aluminized Kapton multiple-layer insulation (MLI). The formula to calculate the effective emissivity of the MLI is as follows:

$$e^* = \left(\frac{2n}{e_{mylar}} - n - 1 + \frac{1}{e_1} + \frac{1}{e_2} \right)^{-1}$$

Where:

- $e_{mylar} = 0.3$
- N = number of layers
- e_1 and e_2 are the emissivity of surfaces 1 and 2 respectively = 0.4 (aluminum) and 0.9 (kapton)

When plugging values in, choosing n =30 layers will give an effective emittance of around 0.0005⁸¹.

The updated calculations with the applied changes are found in the table below:

Hot Case, with TCS	
Q_solar, W	106.113375
Q_internal, W	1352.001
Q_rad-space, W	370.98
Q_rad-space/surface, W	3.15
Q_rad-surface, W	-11.028
Q_in, W	1469.14
Q_out, W	358.39
Q_net, W	1110.75
If positive system is heating, if negative system is cooling. If 0 assume ss stable	

Table #17 Hot Case Calculations with TCS Applied

The absorptivity and emissivity of the AZW/LA-II White Polished thermal coating is given as $a = 0.09$ and $e = .9$ respectively. The low absorptivity indicates that the solar load absorbed is significantly lower than it would be without the thermal control system (TCS), as shown in Equation (10). Additionally, the high emissivity of the coating, at 0.9, suggests that the radiative heat transfer between the rover's top surface and space has nearly doubled, as illustrated in Equation (11). Finally, incorporating a layer of Multi-Layer Insulation (MLI) into the rover design enhances insulation, helping to minimize heat exchange with the surroundings, which is demonstrated by Equations (13) and (14).

The new total heat transfer of the rover can be written as:

$$Q_{net} = Q_{in} - Q_{out} = 1115.36 \text{ W} \quad (17)$$

By optimizing the system to achieve minimal heat gain and maximum heat dissipation, the overall heat transfer has been substantially reduced by more than half.

The current setup of the rover is still inadequate, however, as there are additional areas for improvement. Given that over 1 kW of heat needs to be dissipated, the loop heat pipe (LHP)—specifically the model designed by ARQUIMEA⁸²—coupled with a

radiator system, is an excellent solution capable of dissipating up to 1 kW of heat. The benefits are evident; if successfully implemented, the system could eliminate over 90% of the generated heat. For this application, the selected heat to be dissipated via the LHP is 856.76 W, which will be further detailed in the following calculations.

A loop heat pipe (LHP) is a two-phase system that passively transports heat over long distances to a designated location, such as a radiator, without the need for mechanical pumps. The LHP operates on the principle of phase-change heat transfer. At the evaporator, heat from the source causes the coolant to vaporize within the wick structure. Ammonia is the preferred coolant in this system due to its superior thermal properties compared to water—it has a lower boiling point, a higher heat transfer coefficient⁸³, and a greater vapor pressure⁸⁴. The high-pressure vapor then flows through the vapor line to the condenser, where it releases latent heat and condenses back into a liquid. The condensed liquid returns to the evaporator via the liquid line, driven by the capillary action of the wick. This wick generates the capillary pumping force necessary to circulate the fluid throughout the system. Additionally, the compensation chamber regulates the fluid inventory and balances the pressure, ensuring reliable operation under a wide range of conditions.

In this system, a radiator is the primary mode of passive heat rejection, for the loop heat pipe, facilitating heat dissipation in the form of infrared radiation (IR). The radiator functions not only as a condenser for the loop heat pipe, providing a large surface area for the vapor to condense back into liquid and re-enter the system, but also as a heat sink, enabling radiative heat transfer between its surface and the environment. The rover will employ a deployable radiator mechanism, allowing two radiators to extend from the rover to maximize heat dissipation. The radiator material will be copper (with an emissivity of 0.87⁸⁵), and its area will measure 0.323 m², as determined by the mechanical engineers.

The following table shows the final passive TCS applied to the hot case of the surface rover:

Hot Case, with additional TCS	
Q_solar, W	106.113375
Q_internal, W	509.851
Q_rad-space, W	639.58
Q_radiator	268.6
Q_rad-space/surface,	3.15

W	
Q_rad-surface, W	-11.028
Q_LHP, W	842.15
Q_in, W	626.99
Q_out, W	626.99
Q_net, W	0.00
If positive system is heating, if negative system is cooling. If 0 assume ss stable	

Table #18 Final Hot Case TCS for Surface Rover

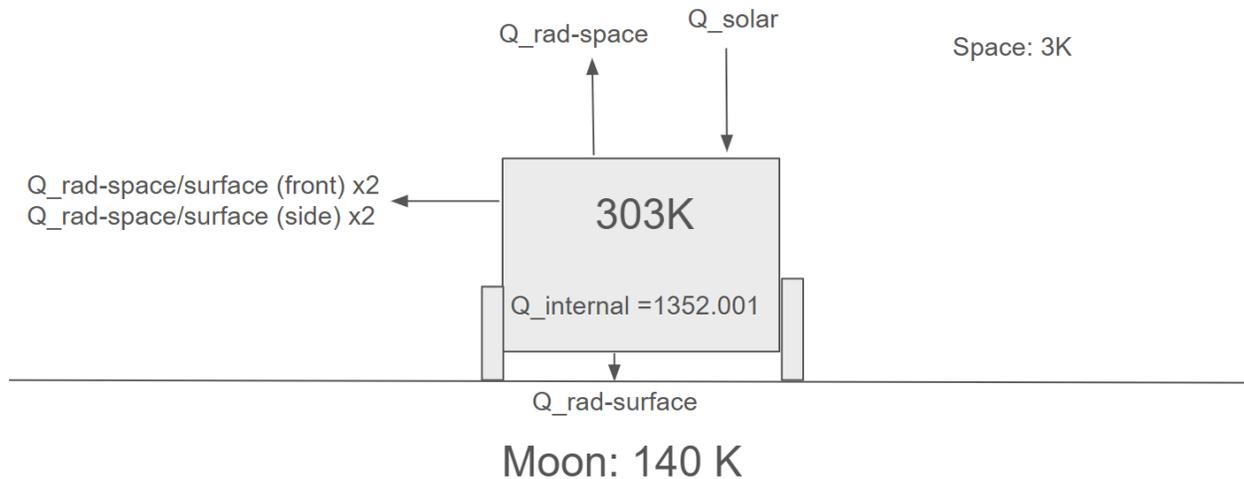


Figure #5 Cold Case Heat Flow Map for the Surface Rover

In the cold case, the thermal control system (TCS) derived from the hot case is applied to assess whether the rover is heating or cooling under the same conditions. The primary difference in the cold case calculations is the absence of solar load, as we assume the moon is positioned away from the sun, resulting in a surface temperature of 140 K instead of 481 K. By utilizing the same equations while removing the solar load factor and replacing 481 K with 140 K in Equations (18-23), the calculations are presented below:

Cold Case	
Q_solar, W	0
Q_internal, W	509.851
Q_radiator, W	268.6
Q_LHP, W	842.15
Q_rad-space, W	639.58
Q_rad-space/surface, W	0.74
Q_rad-surface, W	1.967
Q_in, W	509.85
Q_out, W	644.51
Q_net, W	-134.66
If positive system is heating, if negative system is cooling. If 0 assume ss stable	

Table #19 Cold Case Heat Calculations

The calculations indicate that 134.66 W of heat is lost to the system. Consequently, the TCS will employ the use of an active heating system—specifically, a Birk Manufacturing Polyimide-Traditional Heater—to heat the rover by 134.66 W to restore the rover to stability. This heater operates with a power range of 0.02 to 3.1 W/cm², requiring a maximum wattage of 66.5 W at its highest power density⁸⁶. Thus, the area of the electrical heater can be calculated to be approximately 43.44 cm².

Subsurface Rover Overview

For the subsurface rover, the operating environment is significantly different. The temperatures within the lava tubes are relatively stable, remaining around 17 °C (290 K) with only a 1 °C variation throughout the lunar day⁸⁷. Consequently, the hot and cold temperatures are defined as 290 K and 291 K, respectively. Additionally, the subsurface rover is considerably smaller in size compared to the surface rover, although it still utilizes the same material—Aluminum Alloy 6061. The total changes are summarized in the table below, reflecting the knowns and assumptions of the subsurface environment:

Known and Assumptions	
n radiating to space	1
n radiating to space/surface	4
n radiating to surface	1
space node temp, k	290
surface temp cold, k	290
surface temp hot, k	291
q_solar flux, W/m ²	1367
SA left_face, m ²	0.136322
SA right_face, m ²	0.136322
SA front_face, m ²	0.136294
SA back_face, m ²	0.136294
SA top_face, m ²	0.2025
SA bottom face	0.2025
emissivity base, e	0.4
absorptivity base, a	0.3
system temp, k	303
Stephan Boltzman Constant	0.000000567
n radiating to space	1

Table #20 Known and Assumptions of the Subsurface Rover

Since there is no sunlight in lava tubes, Q_{solar} is removed from the equation. Given that the rover is warmer than the lunar subsurface and that heat naturally flows from hot to cold, the heat flow map assumes that the rover is losing heat in the forms of $Q_{rad-space}$, $Q_{rad-space/surface}$, and $Q_{rad-surface}$. The surrounding environment is maintained at a consistent temperature of approximately 290 K. The resulting heat flow diagram is presented below:

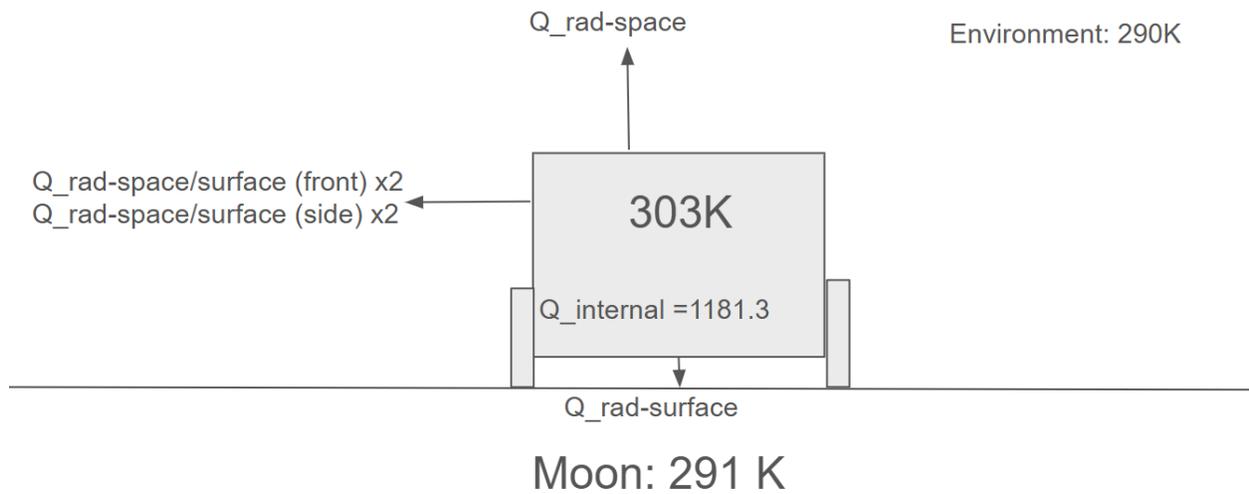


Figure #6 Subsurface Rover Hot case Heat Flow Map

Applying the same principle as described for the surface rover, with the same equations (3) - (9) the calculations for the heat flow map for the subsurface rover is presented in the table below. An important consideration is that there are now 20 layers of MLI instead of 30.

Hot Case, initial NO TCS implemented	
Q_solar, W	0
Q_internal, W	1181.301
Q_rad-space, W	6.23
Q_rad-space/surface, W	16.16
Q_rad-surface, W	5.777711761
Q_in, W	1181.301
Q_out, W	28.17
Q_net, W	1153.13
If positive system is heating, if negative system is cooling. If 0 assume as stable	

Table #21 First Iteration of the subsurface rover with no TCS applied

The system has visibly increased in terms of Q_{net} , but this is acceptable because the Multi-Layer Insulation (MLI) serves as a redundant feature for the subsurface rover, maintaining insulation and minimizing radiative heat transfer between the rover and its surroundings to protect critical components. Additionally, the application of white paint has enhanced the radiation expelled from the top surface of the rover, helping to balance the heat retained and the heat dissipated.

Hot Case, with TCS	
Q_solar, W	0
Q_internal, W	1181.301
Q_rad-space, W	12.46
Q_rad-space/surface, W	1.79
Q_rad-surface, W	0.072
Q_in, W	1181.30
Q_out, W	14.32
Q_net, W	1166.99
If positive system is heating, if negative system is cooling. If 0 assume ss stable	

Table #22 First Iteration of the subsurface rover with TCS applied

In the second iteration of the thermal control system (TCS), the heat loops and radiators are utilized. The heat loop is designed to dissipate the full 1 kW of heat. Using Equation (18), the radiative heat transfer $Q_{radiator}$ is calculated, with copper as the material and an area of 0.13 m², resulting in a value of 17.39 W. Consequently, $Q_{internal, new}$ and $Q_{rad-space}$ can be determined using Equations (19) and (20). The results are summarized in the table below:

Hot Case, with additional TCS	
Q_solar, W	0
Q_LHP, W	1000
Q_radiator, W	18.73037396
Q_internal,new W	181.301
Q_rad-space, W	31.19
Q_rad-space/surface, W	1.79
Q_rad-surface, W	0.078
Q_in, W	181.30
Q_out, W	33.05
Q_net, W	149.59
If positive system is heating, if negative system is cooling. If 0 assume ss stable	

Table #23 Second Iteration of the subsurface rover with TCS applied

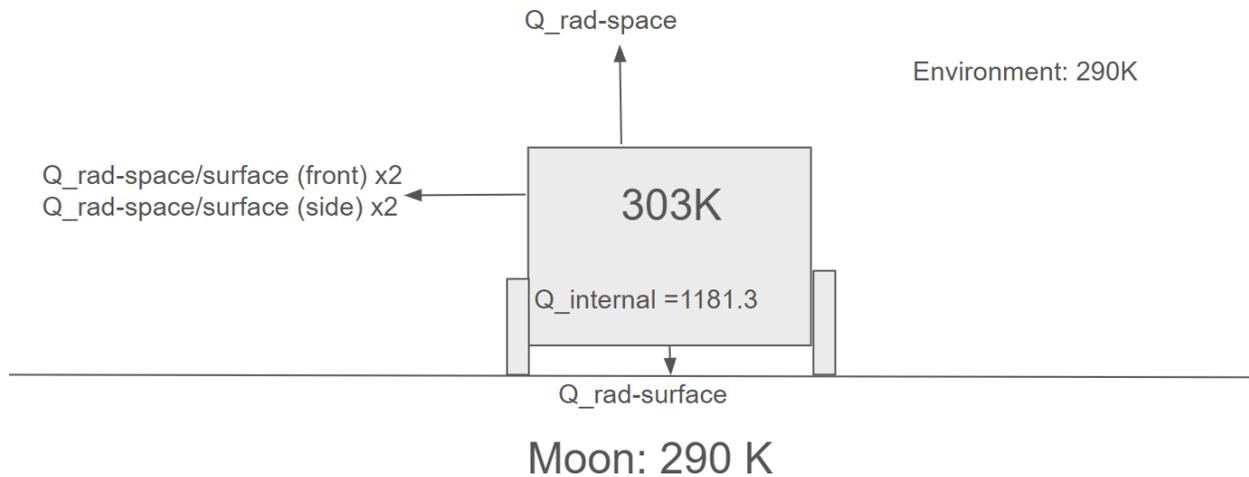


Figure #7 Cold Case Heat flow map of subsurface Rover

In the cold case, the same TCS determined in the previous table has been applied. The only difference is that the temperature is now 290K, which results in minimal variations in the values of $Q_{rad-space/surface}$ and $Q_{rad-surface}$. Nonetheless, the same procedure is applied as done in equations (10) - (14). The final values are found below:

Cold Case	
Q_solar, W	0
Q_internal, new W	181.301
Q_rad-space, W	31.19
Q_rad-space/surface, W	0.08
Q_rad-surface, W	0.078
Q_in, W	181.30
Q_out, W	31.60
Q_net, W	149.70
If positive system is heating, if negative system is cooling. If 0 assume as stable	

Table #24 Cold case applied

Since both the hot case and cold case values are positive, this indicates that the system is heating. Consequently, an active cooling system must be implemented to counteract the 149.7 W of heat. The chosen active cooling solution is a mechanical fluid loop controlled by pumps. This design is particularly convenient, as a fluid loop already exists within the system; only a pump needs to be installed along with the selection of the corresponding coolant. The selected pump is the Mars Pathfinder Pump, which consumes 10 watts of power and can provide a cooling load of 90-150 W⁸⁸. The coolant used in this system is CFC-11.

Technology Readiness Level (TRL)

Subassembly	TRL	Explanation
Surface Rover		
Active/Passive Heat Management		
MLI	8	Kapton has an impressive track record of previous space missions, including to the moon. Although some necessary testing will need to be conducted to ensure compliance with the amount of increased layers and the current mission needs, the core technology is effective at minimizing radiative heat transfer.
Thermal coating	8	The AZW/LA-II Thermal Coating display robust thermal properties and have been proven to be effective at minimizing solar degradation of previous spacecraft. However, specific lunar adjustments and testing are necessary to ensure the same performance on the lunar surface.
Radiator	8	The technology for deployable radiators have been utilized in previous lunar missions and has continuously proven to be a capable passive heat rejection tool. Additional testing will be necessary to adjust the radiator's specifications to the current mission location.
Loop Heat Pipe	7	Loop Heat Pipes are an effective passive heat management tool that have been used across various spacecraft. Their technology is desirable as they provide robust mechanical properties and heat transfer under minimal temperature differences. Some additional testing will be necessary to ensure high quality performance in the Marius Hills Pit.
Heater	6	Birk Manufacturing polyimide heaters provide high quality heating for a substantial range of temperatures. However, there is no record of it being used on space missions, so additional testing will be required to ensure high performance for the current mission needs.
Overall	6	
Subsurface Rover		
Active/Passive Cooling Management		
MLI	8	Kapton has an impressive track record of previous space missions, including to the moon. Although some necessary testing will need to be conducted to ensure compliance with the amount of decreased layers and the current mission needs, the core technology is effective at minimizing radiative heat transfer.
Thermal coating	8	White paint displays strong thermal properties in its ability to reflect solar radiation which have been demonstrated through previous space missions to the moon. Additional adjustment is required for the Marius Hills Pit.
Mechanically Pumped Fluid Loop	8	The Heat Rejection System of a radiator, loop heat pipe, and a pump has been demonstrated to be an effective method of active cooling as per a previous space mission to Mars. Additional testing will be required to demonstrate similar performance to the lunar conditions of the Marius Hills Pit.
Overall	8	

Table #25 TRL Of the components of the Surface and Subsurface Rover.

Surface Rover Thermal Equipment			
	Mass (kg)	Dimensions (mm)	Max Power Consumption (W)
MLI	.008862275	750 x 1050 x 220	0 W
Thermal Coating	.01426845	750 x 1050 x 220	0 W
Radiator	4.0449	22.5 x 21.12 x 12.38	0 W
Loop Heat Pipe	1	5000 length	0 W
Heater	~.006	14 x 18 x 1.0	66.5 W
Thermocouple	.001	304.8 (uncoiled)	0 W
Total	5.075030725		66.5 W

Table #26 SR Thermal Equipment

Subsurface Rover Thermal Equipment			
	Mass (kg)	Dimensions (mm)	Max Power Consumption (W)
MLI	.00451266776384	1807525.344 mm^2	0 W
Thermal Coating	.00353515805997	26750 mm^2	0 W
Mechanically Pumped Fluid Loop (including radiator)	40	1000	10 W
Thermocouple	.001	304.8 (uncoiled)	0 W
Total	40.0188036081	22 x 80 x 3.5	10 W

Table #27 SSR Thermal Equipment

1.5.5.3 Thermal Management Subsystem Trade Studies

The Heat Pipe Selection Trade Study (Appendix E, Table 1) aimed to select a heat pipe for the surface and subsurface rovers that balance strength, weight, flexibility, coolant compatibility, and thermal performance for the lunar environment. Criteria included wick compatibility (35%), operating temperature (30%), weight and flexibility (20%), and cost (15%). Wick compatibility was prioritized for efficient heat transfer, a crucial function of the thermal control system, while the operating temperature was weighted to ensure functionality in the lunar environment. Cost and weight were given less priority to emphasize heat transfer efficiency. Loop Heat Pipes emerged as the superior option due to their robust coolant compatibility, high thermal performance, and relatively lower cost, making them ideal for long-term lunar use.

The Thermal Coating Trade Study (Appendix E, Table 2) aimed to select a paint coating that passively dissipates heat on the lunar surface and subsurface. The criteria evaluated include reflectivity (30%), durability (20%), thermal performance (25%), cost (10%), and weight (15%). Reflectivity was prioritized to minimize heat absorption by the rover, while thermal performance was crucial to maximize radiation dissipation. Durability was essential to ensure the coating's viability in extreme lunar temperatures, and cost and weight were less critical, given the need for efficient heat management. For the surface rover, AZW/LA-II Silicate was chosen due to its superior thermal properties, despite its high cost, as it withstands harsher conditions. For the subsurface rover, white coating emerged as the best choice due to its similar thermal performance at a lower cost, which is suitable for the more stable subsurface environment.

The MLI Material Selection Trade Study (Appendix E Table 3) was crucial to determining an insulation layer capable of shielding against radiation on the lunar surface and subsurface. The criteria evaluated include weight and flexibility (20%), durability (25%), thermal insulation (40%), and cost (15%). Thermal insulation was prioritized to minimize radiative heat loss, particularly on the lunar surface, where extreme temperature differences make radiation a major factor. Weight, durability, and cost were considered secondary, as MLI effectiveness diminishes after a certain number of layers concerning both weight and cost efficiency. Durability was essential to ensure the material's longevity over the mission. Aluminized Kapton (5 mil thickness) scored highest overall, with its only drawback being a higher cost than the other options, which was deemed an acceptable tradeoff for optimal thermal performance.

The Radiator Material Selection Trade Study (Appendix E Table 4) was crucial to determining a passive heat management device for both the surface and subsurface rover that can operate as a condenser with the loop heat pipes. The criteria evaluated include thermal efficiency (25%), heat dissipation (20%), durability (20%), coolant compatibility (20%) and cost (15%). Thermal efficiency was prioritized to ensure high emissivity and passive operation without power input. Heat dissipation, durability, and coolant compatibility were equally weighted, as the radiator needs strong thermal properties, mission durability, and compatibility with the loop heat pipes. The cost was a

lesser factor, considered a tradeoff for achieving optimal thermal properties. Deployable radiators scored highest overall—though they were more expensive than the other options—and were deemed a worthwhile tradeoff for enhanced thermal performance.

The Resistive Heater Trade Study (Appendix E, Table 5) was crucial in determining the applicable active heat distribution and management for the surface rover. The criteria evaluated include temperature control (25%), energy efficiency (20%), durability (20%), weight impact (15%), and cost (20%). Temperature control was prioritized to ensure the system could reach thermal equilibrium, to avoid failure under thermal stress. Energy efficiency, durability, and cost were also key factors, as the heater needed to operate with minimal power draw and withstand harsh lunar conditions. Weight was the least critical factor due to the heaters' negligible mass compared to the overall rover, as they weighed only a few grams. Electric heaters scored highest, excelling in temperature control, energy efficiency, and durability, while also being lightweight and cost-effective, making them the optimal choice.

The Active Cooling Trade Study (Appendix E, Table 5) was crucial in determining the applicable active heat distribution and management for the subsurface rover. The criteria evaluated include temperature control (25%), energy efficiency (20%), durability (20%), weight impact (30%), and cost (10%). Given the subsurface rover's smaller size and strict mass constraints, weight was the top priority to avoid exceeding mass limits. Temperature control was also essential to maintain thermal equilibrium and prevent system failure under thermal stress. Energy efficiency, durability, and cost were secondary considerations, ensuring efficient operation with minimal power consumption and resilience to lunar conditions. Mechanically pumped loops scored the highest; although they are heavier, they are a valuable choice because they provide strong heat transfer and optimal energy efficiency.

1.5.6 Payload Subsystem

1.5.6.1 Payload Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
INS-1	The payload shall include a ground penetrating radar	There must be instrumentation to collect data about roof thickness in order to determine structural integrity of lunar caves	PAY-1	INS-1.1, INS-1.2	Inspection	Payload	Met
INS-1.1	The ground penetrating radar must have a depth range of greater than 60 m	The Marius Hills Pit is at a depth of 40 m and therefore the Ground Penetrating Radar must be have a depth penetration greater than 40 m with a factor of safety of 1.5	INS-1		Analysis	Payload	Met
INS-1.2	The ground penetrating radar must have a vertical resolution of less than 2 m	A vertical resolution of more than 2 m will lead to inaccurate measurements of roof thickness	INS-1		Analysis	Payload	Met
INS-2	The Lunar Penetrating Radar instrument must be kept between -10°C and 50°C	The Lunar Penetrating Radar must be kept between -10°C and 50°C to function correctly	PAY-1.2		Analysis	Payload	Met

INS-3	The payload shall include a laser altimeter	There must be instrumentation to map the lunar cave and the area around the pit	PAY-1	INS-3.1, INS-3.2, INS-3.3	Inspection	Payload	Met
INS-3.1	The laser altimeter must have a wavelength of 1064 nm	This wavelength is ideal for detection accuracy of mapping	INS-3		Analysis	Payload	Met
INS-3.2	The laser altimeter must have a repetition rate of 28 Hz or higher	A repetition rate of 28 Hz is a minimum for the accuracy desired on measurements	INS-3		Analysis	Payload	Met
INS-3.3	The laser altimeter must have a timing resolution greater than 0.5 ns	A minimum resolution of 0.5 ns is required for the accuracy desired on measurements	INS-3		Analysis	Payload	Met

Table #28 Payload Subsystem Requirements

1.5.6.2 Payload Subsystem Overview

The specific ground penetrating radar that will be used is the Lunar Penetrating Radar (LPR) that was used on the Chang'e-3 mission (Fang Guang-You et al. 2014, 1607). The LPR will be used to measure the width and roof thickness of the lunar cave. This will allow for calculations to estimate structural integrity of the lunar cave. The design of this instrument will be described below.

The Lunar Penetrating Radar is a ground penetrating radar that consists of two channels. Fang Guang-You et al. describes that channel one consists of two broadband monopoles as the antennas and each antenna is placed in a tubular radome to protect it from any damage. The length of each radome is described as 1150 mm and it has a diameter of 12 mm. As noted above, it is described that there are two of these radomes for each antenna. Fang Guang-You et al. also says “the antenna input impedance is designed to be 200 Ω , thus a 1:4 impedance transformer is connected to the input port of the antenna in order to transform the antenna impedance from 200 Ω to 50 Ω and match the impedance of the feed cable.” The center frequency of channel one is 60 MHz (Chunlai Li et al. 2015, 88). This corresponds to a penetration depth of 100 m or greater (Chunlai Li et al. 2015, 88). The low center frequency allows for a greater depth range, but leads to a lower vertical resolution of about 1 m (Chunlai Li et al. 2015, 88). However, this is predicted to be enough resolution to estimate roof thickness and width of a possible lunar cave. The bandwidth of the 1st channel is greater than or equal to 40 MHz (Chunlai Li et al. 2015, 88). Channel one will primarily be used to measure the roof thickness and width of the lunar cave. This is because the Marius Hills Pit has a depth of 40 m (Wagner et al. 2021) and so channel 2 may not be able to measure the complete roof thickness or width of the cave, whereas channel one can measure greater than 100 m (Chunlai Li et al. 2015, 88).

Fang Guang-You et al. describes that channel two consists of a set of bow tie antennas as the chosen antenna. This chosen antenna consists of three antenna elements that are placed side by side. One of the elements is used to transmit the waves while the other two receive them. According to Fang Guang-You et al. the antennas are “loaded by resistors in order to absorb the current reflected by the end of the set of antennas.” In order to improve performance, a rectangular conducting cavity is also added to the antennas. Fang Guang-You et al. also describes that the channel two antennas are placed on the bottom of the rover while the channel one antennas will protrude from the rover. Channel two operates at a higher center frequency of 500 MHz (Chunlai Li et al. 2015, 88). This is equivalent to a penetration of 30 m or greater (Chunlai Li et al. 2015, 88). Due to the higher center frequency there is greater vertical resolution, specifically less than or equal to 30 cm (Chunlai Li et al. 2015, 88). This leads to a more accurate and detailed measurement. This channel would give measurements with better resolutions of most of the roof thickness, which may be helpful in future scientific research.

The TRL of the LPR is designated as 8. This is because the LPR has already been used on a rover in the same environment, namely the lunar surface. This was done on the Chang'e-3 mission and the LPR was an instrument on board (Fang Guang-You et al. 2014, 1609). The

mission was successful and returned relevant data (Chunlai Li et al. 2015, 98). The TRL was not designated as 9 because it has yet to be used to find details of a lunar cave.

The overall TRL of the payload subsystem is a TRL of 5. This is because the NIRVSS spectrometer has a TRL of 5 and is the lowest TRL of all the instruments, so the whole subsystem has a TRL of 5.

The NIRVISS spectrometer is an obvious choice for the mission since it was designed for the exact measurements needed. NIRVISS stands for the Near Infrared Volatile Spectrometer Subsystem. It works in two primary ways: one is through active measurement and passive measurement.

Active measurement in the NIRVISS spectrometer means that it is activating its IR lamp which will illuminate the surrendering area. This will allow the NIRVISS to make measurements even in the dark. However it does require more power.

Passive measurement in the NIRVISS spectrometer is when it uses the ambient light to make measurements. Even though that is a little less accurate it is quite energy efficient especially if the rover is currently in sunlight.

The Radiation Assessment Detector (RAD) was the radiation detector that was equipped on the Mars Curiosity rover (Springer [94]). It has two separate parts, one to measure charged radiation and another to measure neutral radiation. Dual Detector Systems RAD has two functioning detectors. One of them is an SSD (Solid State Detector) and the other is a plastic scintillator which measures neutral radiation. This allows the RAD to continue to measure radiation even if one of the detectors becomes less accurate or fails. Another part of the RAD that makes it crucial to the mission is that it has completed a successful mission on Mars for almost twelve years. This means it is a very reliable device.

The IR camera that this subsystem has is the Leonardo DRS Tenum 640. This IR camera works like any other camera. However the one important distinction is that it is capable of seeing in infrared range. This lets it determine the surface temperature of anything that it looks at. Since this is the mission's thermometer it will be taking photos constantly throughout the lunar day in order to graph the temperature fluctuations.

The Laser Altimeter is the LiDAR System - REIGL VUX-1LR. Its main purpose is to give back data on the 3D structure of the cave. In order to do that it shoots a laser out which is then reflected by the surroundings and then is redetected by the LiDAR built-in detector. From this and the frequency shift of the light it can calculate the distance that the walls are from it. From this it will give amazing 3D data of the cave.

1.5.6.3 Payload Subsystem Trade Studies

For choosing the best laser altimeter, the weights were assigned based on the mission priorities and the environmental challenges. Wavelength and the pulse repetition rate were 25% since accurate topographic mapping and resolution are

important for understanding lunar details and detecting fine features. The mass was 20% since reducing the payload strain is important for rover mounted applications but it is not as important. The temperature and radiation tolerance is 30% reflecting the harsh lunar environment's extreme temperatures and high radiation levels, this ensures the altimeter can withstand these conditions for data integrity (Appendix F Table 2). The scoring was assigned on how well each altimeter met these criteria. The RIEGL VUX 1LR scored the highest since it had ideal ratings for wavelength, pulse rate, and mass making it best for rover deployment. It has an 8 for temperature and radiation tolerance because of its high durability but it is not space tested to the highest extent. ATLAS and LOLA scored lower due to their mass and wavelength limitations. As a result, the REIGL VUX 1LR has the highest overall score of 94% making it the best choice for lunar surface mapping, while ATLAS and LOLA got a 69.5% and a 57% respectively.

The trade study for the GPR (Appendix F Table 1) was done to choose a GPR that would be able to achieve all the desired science. The criterias that were used to determine the best GPR was the depth range, TRL, and vertical resolution. The depth range criteria was given 50% weight because without a sufficient depth range the cave may not even be detected. The measurements the GPR will obtain are the roof thickness and width of the cave. If the depth range is not large enough, the GPR will not be able to detect the entire roof thickness nor width of the cave because both of these will be deeper in the lunar subsurface than the GPR can penetrate. If the depth range is too high, the resolution is compromised and the cave may not be detected. The minimum depth requirement was chosen as 60 m in the STM because the pit is reported to be 40 m deep (Wagner et al. 2021) and so 60 meters includes this distance with a factor of safety of 1.5. The range for a score of 10 was put as a GPR that can penetrate up to any depth between 60 m to 100 m. Any depth penetration in this range would be ideal as it would be able to measure the whole lunar cave but does not penetrate too much deeper than the cave. A penetration that is deeper than the cave would lead to less resolution and a penetration less than 40 m would obviously not detect the full cave. The second criteria was vertical resolution. This is the resolution of the readings. This was given a weight of 30% because it does not hold as much importance as depth range but still holds significant importance because a resolution of less than 2 m, as required in the STM, may lead to a roof thickness measurement that is significantly inaccurate. The three GPR options were the Lunar Penetrating Radar (LPR), the Apollo Lunar Sounder System, and the Lunar Radar Sounder. The LPR was given a score of 9 because its depth penetration is a small amount greater than 100 m (Chunlai Li et al. 2015, 88). The Apollo Lunar Sounder System was given a score of 2 because it has a depth penetration of 1200 m which is too high for the pit that has a depth of 40 m (L. J. Porcello et al. 1974, 775). The Lunar Radar sounder has a penetration of greater than 2 km which is far too deep as well (NASA 2024, 1). The LPR was given a score of 8 for the vertical resolution criteria because it has a resolution of about 1 m (Chunlai Li et al. 2015, 88). The Apollo Lunar Sounder System was given a score of 1 because it had a resolution of 10 m (L. J. Porcello et al. 1974, 769). The Lunar Radar Sounder was given a score of 0 because it had a depth resolution of 75 m (NASA 2024, 1). Finally, the TRL was evaluated. The TRL was given a weight of 20%. The TRL is important because a higher TRL means higher change of the

instrument working as intended. It is not as important as other categories because an instrument can still function and achieve successful measurements even with a low TRL. The LPR was given a TRL of 8 because it has been used on a rover on the lunar surface which is the exact same way that this mission plans to use this instrument (Fang Guang-You et al. 2014, 1609). It was not given a TRL 9 because it has not been used to detect lunar caves. The TRL of the Lunar Radar Sounder was designated as 7 because it has been successfully used in space but from lunar orbit and not the surface on a rover (T. Ono et al. 2010, 145). The Apollo Lunar Sounder System was given the same score of 7 for the same reason of being used from lunar orbit (L. J. Porcello et al. 1974, 769).

Due to these scores, the LPR was chosen as our GPR because it had a score of 85% which was the highest score.

For the IR camera trade study the requirements for the STM were necessary. In this effort looking into first was the temperature range, since this was the most important and critical function of the IR camera. If the camera did not have the temperature range necessary it would not be included in the choices. After selections of multiple IR cameras the one that was the best fit for this mission was the Leonardo DRS Tenum 640. With its already tested temperature range and temperature resolution (Appendix F Table 5).

The trade study for the radiation detection instrument (Appendix F Table 3) was created in accordance with the mission statement. This was to measure the levels of radiation at the opening of the cave and inside of the cave. So the most important quality that this detector has was a large energy range to be able to detect as much different ionizing radiation as possible (Scot C. R. [90]). The second most important thing is that the radiation detector must have a high saturation limit. Saturation happens when radiation detectors get hit with over their specified amount of radiation. In this case it will not be able to accurately measure the levels of radiation and might damage the instrument. Lastly it must consume as little power as possible. Since it will be on for most of the time it will negatively affect the mission if it had a power consumption that was too large.

Finally the trade study for the one of the most important payload instruments which is the spectrometer (Appendix F Table 4). Since one of the mission statements is to see if there is life that exists in these caves at all then the spectrometer is the number one instrument for that. The specific range necessary for that is 1300-4000 nm so it was a requirement for the spectrometer to have that. Since the NIRVISS was designed perfectly for this range it was a clear fit. Second requirement that was needed to be imposed on the instrument was that it had enough spectral resolution. This means that it was able to see a small trace amount of the compounds in the samples it studies. The NIRVISS was also a clear fit for this since it was designed with the main purpose of finding water at the south pole of the moon (NASA [91]). The sensitivity, another requirement much like the spectral resolution, is also necessary in the measurement of small trace amounts of volatiles. Instead this time it is in the detector and not in the active emission where the sensitivity is needed.

1.5.7 Recovery and Redundancy

Mechanical

The lunar rover's mechanical system will be built with recovery and redundancy. However, due to the mass and volumetric constraints, redundancy for mechanical components was kept to a minimum. For redundancy, the rover will have six wheels, even though 4 is sufficient. This ensures that if 1 is out of use, there is still enough for the rover to move effectively. The SR will also have multiple anchor points for the purpose of lowering the SSR into the pit.

The rovers will have several modes of autonomous recovery. The drive motors will use thermocouple sensors to monitor temperature and automatically shut off the motor if the temperature rises above 150 degrees C. The navigation camera will reboot automatically, stopping at 5 reboots. If needed, it will drive backward using the rear navigation camera. The wheels, in case of slipping, will use a tachometer to measure RPM > XXX, if the readings are off nominal, the motors will stop and ramp up speed slowly from standstill. The drive motors will utilize sensors to detect failure of the motors. In case of a motor failure, if one motor fails, the others could automatically continue operating with reduced efficiency. During SR wheel deployment, sensors will determine wheel angle, and have malfunctioning leg joints lock into place if actuators fail, allowing for a stable stance. SSR legs will also utilize sensors to determine leg position and allow other legs to compensate for malfunctioning legs through adjustments in gait or redistribution of weight. Finally, the SR anchoring system will utilize sensors to detect anchor tension to detect failure early and use additional anchor points to stabilize.

Power

The lunar rover power system is designed with recovery and redundancy for the stability of operations. Due to the constraints related to cost and mass, it is not feasible to have duplicate solar panels for redundancy purposes. This classifies this system as a single point of failure. However, the solar arrays are highly and proven technology, because they have been flown and utilized on previous space missions and projects since 1958, including but not limited to the International Space Station and Europa Clipper^{1,2}. Overall, the high TRL and reliability of the solar panels show that it is safe to move forward without these redundant components. The power storage system also will not have redundancy due to the constraints related to the cost and mass of having two lithium-ion battery packs, since each battery pack has a mass of 40 kg. However, lithium-ion batteries are also a highly proven technology with a high technology readiness level, as they have been utilized on previous space technologies such as the Eurostar satellites, Lunar Reconnaissance Orbiter, Mars Rovers, Mars Landers, and more^{92,93}. However, the charge controller will be redundant and the technique of cross-strapping will be utilized, which allows the redundant unit to take over if one unit fails³. For instance, two charge controllers will be linked to the solar panel and battery pack, and if one charge controller fails, the

power will be transferred by the second charge controller, ensuring that the system remains functional in the event of failure of component function. Additionally, the assembly of the cable harnesses shall be redundant to provide power in the event of failure of the primary cable harness system.

For recovery of the solar panels, power monitors are integrated throughout the system which have predetermined thresholds for each component. When the performance of the solar panels falls below these thresholds, the monitor triggers a reset to stabilize the operations of the solar panel. This allows the system to quickly recover from minor issues, ensuring that operations remain sustained through challenges on the lunar surface.

CDH

Redundancy in the telecommunications subassembly includes the implementation of secondary antennas. For the SR system, the LGA serves as the secondary and redundant antenna to the HGA. When scenarios arise where the HGA is not able to direct itself to the LO or DSN, the LGA takes over for communication between all systems, thanks to its omni-directional nature, meaning it does not need to face any specific direction to send or receive signals. This is to ensure that constant communication is being held at all times throughout the life of the mission. The LGA on the SSR performs the same functions. The usage of MIL-STD-1553 as a secondary interface system along with its primary partner, SpaceWire, serves as a reliable and redundant structure around the transit of data throughout both rover systems. MIL-STD-1553 is slower but works in scheduled sequences of data delivery, excelling in data transit safety. As for the storage systems, both rovers utilize NAND Flash along with an SSD, precisely for reliable storage and the preparation of transmission of data. Partitioning both storage units and having the NAND act as a filter allows for streamlined and more efficient data sorting as well as a reliable and redundant system for data transmission.

In cases of overall system failure or malfunction, both rover systems must be able to autonomously act in accordance with such matter. The CDH subsystem provides such recovery for software failure through reboots that shall be automatically activated once the system senses abnormalities or turn-off functions. One way to ensure this is to provide a personal storage unit for the OBC that contains only information pertaining to the existing firmware and software, that may inject bootloader code for a system reset. This recovery can be done through the use of the systems EEPROM. This storage device allows for the system to read its data contents and overlap the systems code with the safety firmware.

Thermal

For the thermal system, the SR and SSR will have the following redundancies. The SR will have redundant heaters and pipes to aid recovery in case of failure. For the SSR, it will have redundant pumps and pipes for cooling in case of failure. The thermal system will also employ radiation enclosures to prevent degradation of critical CDH components and internal electronics

For SR recovery, CDH will detect anomalies in the Thermal Control System for the heater. If the heater suddenly stops working and the system determines a power drop, the system can assume the heater has died and will reconfigure to power the backup heater. In case of pipe failure in loop heat pipes, their software should pick up on the damaged pipe and stop all pipe flow to bypass fluid flow from the damaged pipe to the backup pipe. SSR will be similar to the SR except now the software detects changes in active cooling. If the pump stops working, software could start up a new pump. If a pipe is leaking, reroute flow by bypassing failed pipes to working pipes.

Payload

The payload instrumentation had the following redundancies. RAD has dual detector systems . One of them is an SSD (Solid State Detector) and the other is a plastic scintillator which measures neutral radiation. This allows the RAD to continue to measure radiation even if one of the detectors becomes less accurate or fails. The NIRVISS instrument has two laser diodes on its IR LED lamp for redundancy in case one either malfunctions or gets covered in dust. For the LPR, in the case of any projectiles or physical objects hitting and damaging the channel 1 antennas, tubular radomes are used to cover them and protect them. In addition, the channel 2 antennas may be affected by interference from the surroundings. In order to mitigate this, a rectangular conducting cavity is added to the antennas. For the IR camera, redundant pixel architecture in the image sensor allows for the camera to be able to accurately interpolate missing data from an image. This can take the form of dead pixels from individual pixel failure.

The payload instrumentation has the following autonomous recovery options. Built-in Data Backup was implemented in the RAD such that in case of data loss RAD has an internal storage which temporarily holds readings. This allows the RAD even in acute data loss to still perform nominally. Dual Illumination Sources allows the NIRVISS to continue to operate without one light source. The NIRVISS has an active illumination source (IR LED) and passive illumination source which is the background light levels. Redundant Data Logging Channels allow for the VUX-1LR LiDAR system to continue to upload data to its central computer from the laser and mirror even in the event of a single or multiple data logging channels returning error. For the LPR, in the case of

measurement data not being transferred correctly, the LPR will be programmed to detect that and send the data again until transferred correctly.

1.5.8 Interface Control

Surface Rover N²

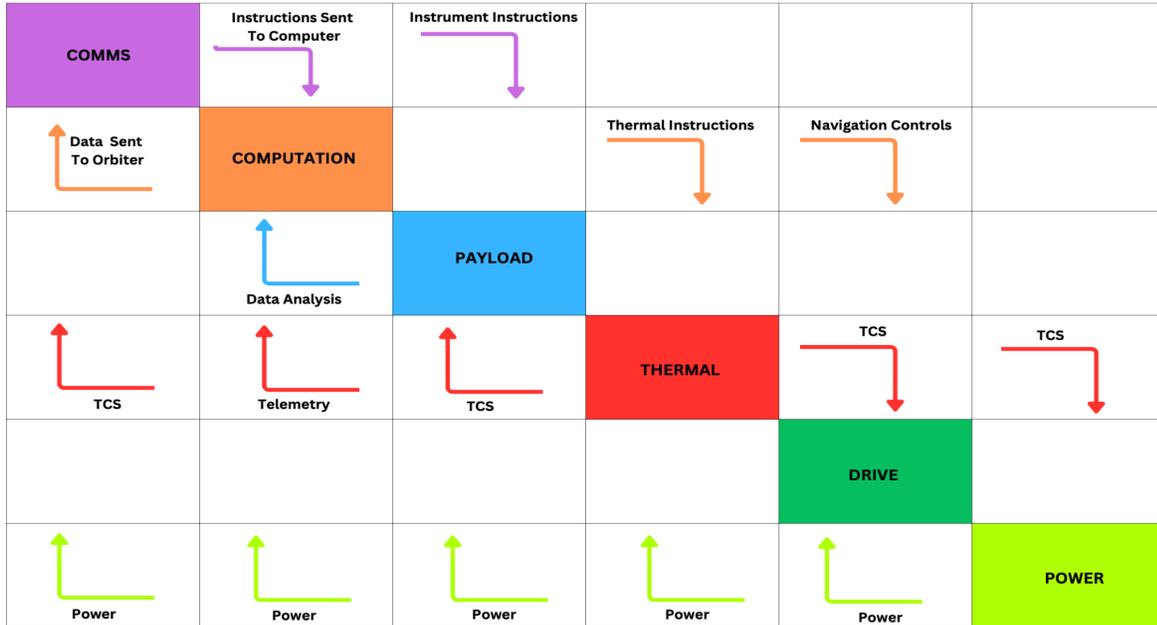


Figure #8 SR N² Diagram

Sub-Surface Rover N²

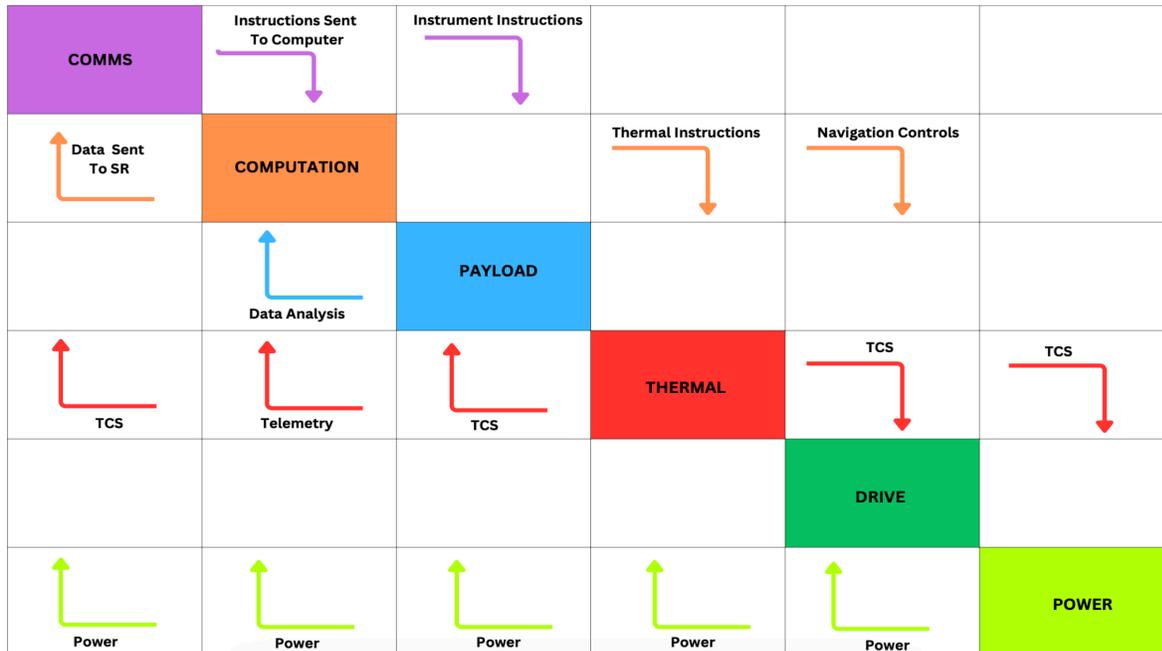


Figure #9 SSR N² Diagram

SR Block Diagram

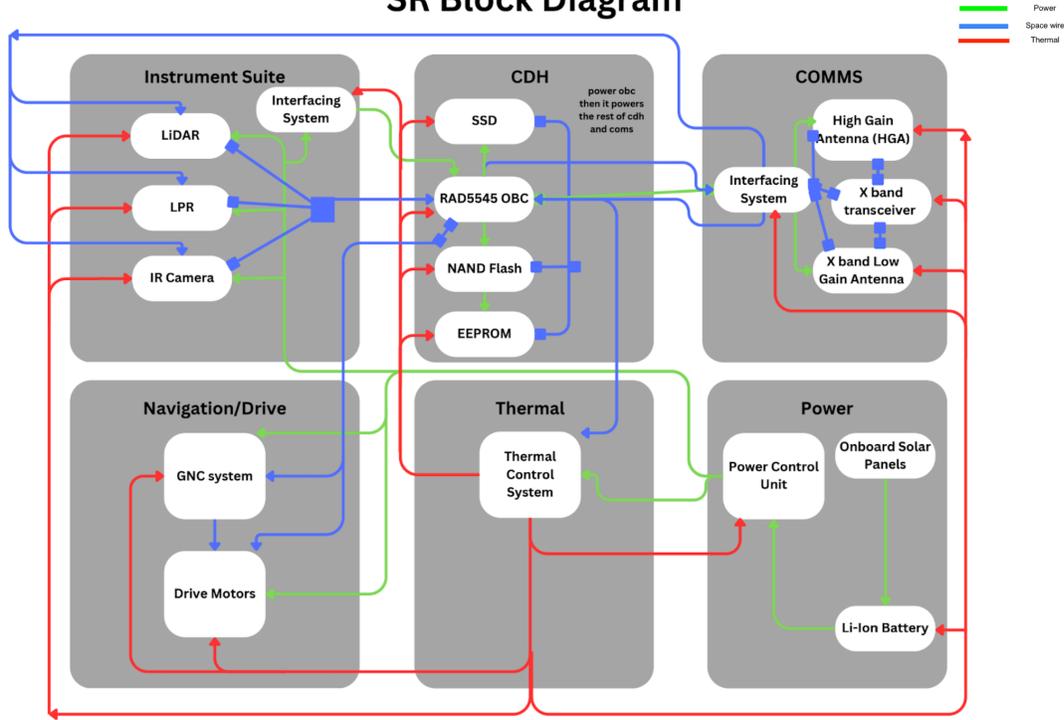


Figure #10 SR Block Diagram

SSR Block Diagram

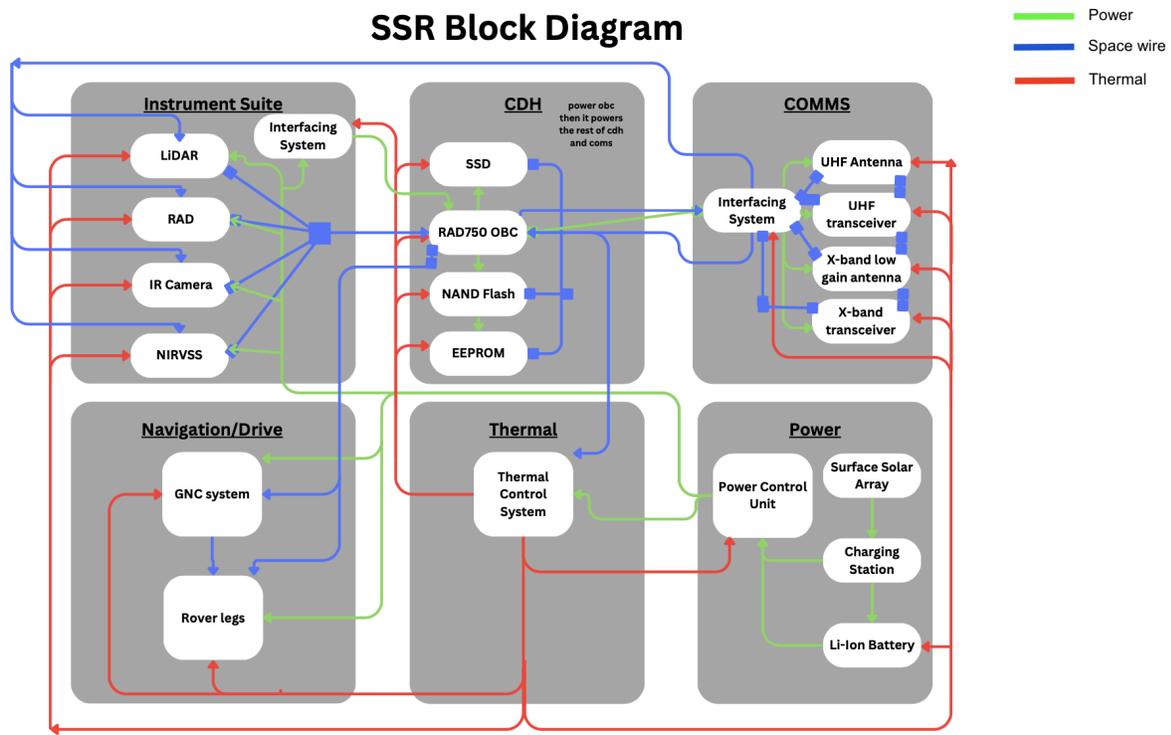


Figure #11 SSR Block Diagram

Surface Rover Interfacing

For power, the surface rover has onboard solar panels that charge a lithium ion battery, which in turn supplies power to the power control unit. The power is then directed to the thermal control system, GNC system, drive motors, instrument suite, and an interfacing system which then sends power to the systems computer, which then powers the rovers storage components as well as an interfacing system in the comms box. That interfacing system then powers all of the comms instruments. For thermal, the thermal control system interfaces with the power control unit, GNC system, drive motors, instrument suite, the onboard computer, storage components, interfacing systems in the instrument suite and comms box, and the comms components. The onboard computer communicates with the GNC system, drive motors, thermal control system, and interfacing system in the comms box via space wire. The interfacing system in the comms box communicates with the instruments in the instrument suite, and the instruments communicate with the onboard computer. Additionally, the GNC system also communicates with the drive motors. All of the comms components communicate with each other in the comms box. All communication is done via space wire.

Subsurface Rover Interfacing

For power, the subsurface rover connects to a charging station. The charging station is powered by a solar panel array on the surface deployed by the surface rover. The charging station charges the rovers lithium ion battery, which in turn supplies power to the power control unit. The power is then directed to the thermal control system, GNC system, the rovers robotic legs, instrument suite, and an interfacing system which then sends power to the systems computer, which then powers the rovers storage components as well as an interfacing system in the comms box. That interfacing system then powers all of the comms instruments. For thermal, the thermal control system interfaces with the power control unit, GNC system, the rovers robotic legs, instrument suite, the onboard computer, storage components, interfacing systems in the instrument suite and comms box, and the comms components. The onboard computer communicates with the GNC system, rovers robotic legs, thermal control system, and interfacing system in the comms box via space wire. The interfacing system in the comms box communicates with the instruments in the instrument suite, and the instruments communicate with the onboard computer. Additionally, the GNC system also communicates with the drive motors. All of the comms components communicate with each other in the comms box. All communication is done via space wire.

1.6 Risk Analysis

Identifying risks and subsequent mitigation strategies for relevant subsystems and instrumentation was done via research into the components, instruments, and similar designs or missions that have used similar architecture. These risks were put on a table to track and mitigate, and will be updated as new mitigation strategies or risks are derived. Mitigation strategies found or derived will be researched and added to the chart if chosen to mitigate the associated risk.

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Payload: RAD	1	5	NEW	R	Radiation overload	Active
2	Payload: NIRVSS	2	5	NEW	M	Regolith/dust covers LED's or sensors	Active
3	Payload: REIGL VUX-1LR	2	5	NEW	M	Thermal stress, system overheats	Active
4	Payload: LPR	4	3	NEW	M	Error readings due to repeated drive path	Active
5	Payload: Leonardo DRS Tenum 640	2	5	NEW	M	Thermal stress, system overheats	Active
6	Payload: Leonardo DRS Tenum 640	1	5	NEW	M	Radiation overload	Active
7	Mechanical	3	5	NEW	M	Tether failure	Active
8	Mechanical	2	4	NEW	M	Drive motor overheats	Active
9	Mechanical	1	5	NEW	M	Solar panel or CDH actuators fail to deploy panels or equipment	Active
10	Mechanical	2	3	NEW	M	Drivetrain motor fails	Active
11	Mechanical	2	3	NEW	M	Navigation cameras are damaged	Active
12	Mechanical	3	5	NEW	M	One or more subsurface rover legs malfunction	Active
13	Power	4	3	NEW	M	Dust coverage on solar panels	Active
14	Power	4	3	NEW	R	Radiation damages solar panels and batteries	Active
15	CDH	3	5	NEW	M	Radiation damages CDH components	Active
16	CDH	3	4	NEW	M	Thermal stress, system overheats or overcools	Active
17	Thermal	2	4	NEW	M	Regolith/dust covers thermal control surfaces	Active
18	Thermal	1	5	NEW	R	Micrometeoroid impact damages thermal system	Active

Table #29 Risk Table

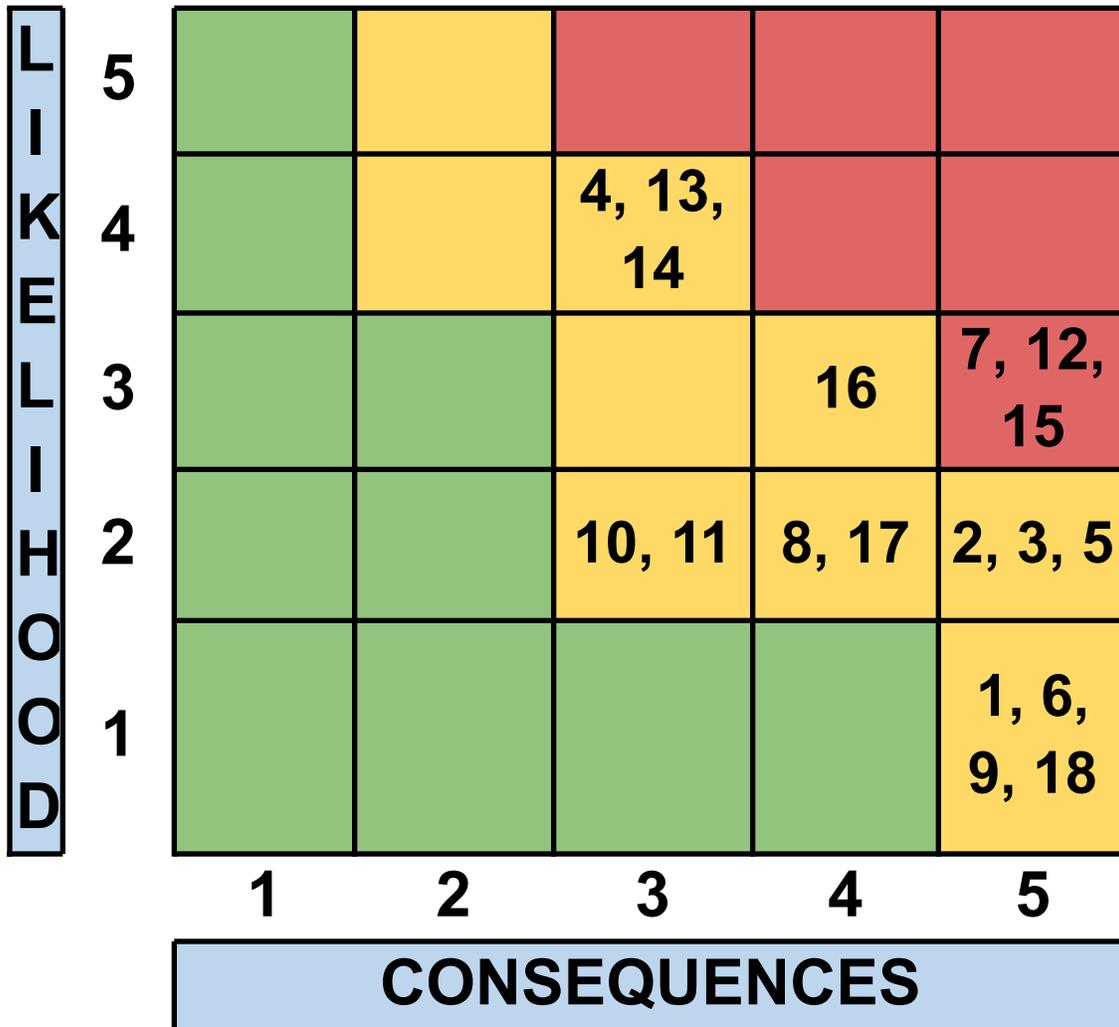
L = Likelihood (1-5)
1 = not likely 5 = extremely likely
C = Consequence (1-5)
1 = low consequence 5 = high consequence

LxC Trend
↓ - Decreasing (improving)
↑ - increasing (worsening)
→ - unchanged
NEW - added this month

Approach
A - accept
M- mitigate
W - watch
R - research

Criticality
HIGH
MED
LOW

Figure #12 Risk Matrix



Risk 1: Given there is little to no atmosphere on the Moon, resulting in a lack of protection from radiation, there is a possibility of radiation overload during a high radiation event like a solar flare. This would result in a radiation Overload on the detector. If the detector is overloaded with radiation, the detector can become oversaturated which could lead to data loss and or even damage to the instrument. This risk can be mitigated by the team keeping up to date with solar activity and powering the instrument off should a solar event occur. However, more research is needed here to increase confidence in this risk and mitigation strategy.

Risk 2: Due to the amounts of fine dust on the Moon, there is a possibility that the dust can cling to the LED lights and sensors, making them unable to shine light through and degrading the ability to get accurate readings. This would affect the instrument's ability to confidently complete the mission's science objectives. This risk can be mitigated by limiting rover speed to avoid dust pickup.

Risk 3: Given that the Moon has wide temperature fluctuations, there is a risk of thermal stress on the instrument, especially when under direct sunlight. This could result in thermal stress on equipment, which can affect the performance of the equipment and cause the lifespan to decrease. This risk can be mitigated by limiting operational hours and/or adding thermal shielding.

Risk 4: Given the subsurface rover will anchor near the pit then travel away from the pit to do science, and most likely it will come back near the pit, there is a risk that it travels a path that is sub-parallel or parallel to a path it has already taken. This can lead to misleading results of the measurements, leading to either misleading or incorrect data on the sublunar terrain. This risk can be mitigated by keeping the rover path in one direction and be aware of possible misleading results in sections where rover may have done similar paths multiple times.

Risk 5: Given that the Moon has wide temperature fluctuations, there is a risk of thermal stress on the instrument, especially when under direct sunlight. This could result in thermal stress on equipment, which can affect the performance of the equipment and cause the lifespan to decrease. This risk can be mitigated by limiting operational hours, and/or using thermal radiators to release heat effectively.

Risk 6: Given there is little to no atmosphere on the Moon, resulting in a lack of protection from radiation, there is a possibility of radiation damage to the instrument. High levels of Radiation can lower the performance of the instrument over time, leading to degradation of the IR data and compromising the science objectives. This risk can be mitigated by using a multi layer insulation (MLI) blanket to reflect the solar radiation.

Risk 7: Due to the abrasiveness of the lunar rocks and soil, there is a risk that the tether used to lower the SSR into the pit could be damaged or fail completely. The tether between the surface and subsurface rovers is responsible for physical support as well as power and data transmission and damage or failure of this tether could lead to catastrophic damage to the SSR, compromising mission success. Possible mitigation includes multiple tethers to reduce risk of failure and/or keeping the different transmission lines separate.

Risk 8: Given that the Moon has wide temperature fluctuations, there is a risk of thermal stress on the drive motors, especially when under direct sunlight. This could result in thermal stress on components, which can affect the performance of the motor and cause the motors to overheat. This could cause damage or malfunction, which could cause the rover to stop driving, compromising its ability to collect data. This risk could be mitigated by having thermocouple sensors that could sense a motor temp of >150 degrees C, triggering an automatic motor shut off.

Risk 9: Given that there are motors and actuators involved in deployment of solar panels or CDH equipment, there is a possibility of one of these failing to deploy the necessary equipment. This could lead to a lower power generation and/or communication issues or failure, leading to the rover not being able to operate or communicate. This risk could be mitigated by having manual overrides and/or smaller, secondary solar panels that deploy independently of the main array.

Risk 10: Given the rover will be traversing terrain, there is a possibility that one or more of the drivetrain motors fails or stops working. This could result in mobility issues with the rover, leading to reduced ability to move around and collect data with the instruments. This risk can be mitigated by having the other motors continue operating with reduced efficiency and/or activate a backup control algorithm to use the remaining functional motors for steering or movement.

Risk 11: Due to the presence of lunar rocks and the abrasiveness of the lunar regolith, there is a possibility of damage to the front navigation camera. This could result in diminished operability or seeing of the camera, leading to trouble navigating the rover effectively. This risk could be mitigated by rebooting the camera automatically. If rebooting is ineffective, another mitigation strategy is to drive the rover backward using a rear navigation camera.

Risk 12: Due to the SSR having four legs, there is a risk that one of the legs malfunctions or fails. This could lead to limited mobility or complete lack of mobility of the SSR. Loss of mobility would make the rover incapable of collecting data to complete the science objectives, compromising mission success. The risk could be mitigated by allowing other legs to compensate for the malfunctioning leg through adjustments in gait or redistribution of weight.

Risk 13: Given the lunar dust is known to be highly electrostatically charged, there is a possibility of lunar dust sticking to the surface of the solar panels. This could cause a decrease in efficiency, leading to poor power distribution. This risk can be mitigated by placing solar panels on vertical masts and implementing an electrostatic repulsion system.

Risk 14: Given there is little to no atmosphere on the Moon, resulting in a lack of protection from radiation, there is a risk of radiation impacting the efficiency of the solar panels and lithium-ion batteries. Radiation can damage the materials of solar arrays due to the defects created by ions or nuclei particles that strike the solar cells' wafers, causing lower than nominal power generation. This risk requires more research, but could potentially be mitigated by using metal coatings and using a Faraday cage to protect the components from the radiation.

Risk 15: Given there is little to no atmosphere on the Moon, resulting in a lack of protection from radiation, there is a risk of radiation damage to the CDH components/equipment. This could cause data corruption and system failure in the electrical and computer parts, leading to degraded or failed communication. Resolutions for data corruption include the usage of an EEPROM storage device for the specific use of firmware/software allocation of storage specific to the Onboarding Computer (OBC) in the backing-up of software during reboots when needed.

Risk 16: Given that the Moon has wide temperature fluctuations, and that the system is restrictive to the set temperature range of -55°C to $+125^{\circ}\text{C}$, there is a risk of thermal stress on the CDH components. This could pose a potential risk factor for components getting damaged or not working optimally or sufficiently enough for the mission requirements. This risk could be mitigated by enclosing the CDH components within a radiation and thermal blocking/shielding electrical housing unit.

Risk 17: Due to the amounts of fine dust on the Moon, there is a possibility that the dust can cling to and accumulate on thermal control surfaces. This could reduce their effectiveness, potentially causing overheating or cooling failures. The risk could be mitigated by using coatings to repel dust from critical surfaces or develop regular maintenance protocols for systems with self cleaning capabilities

Risk 18: Given that the lunar surface is susceptible to Micrometeoroid impacts, there is a small potential risk that a micrometeoroid strikes the rover, which could damage thermal control surfaces. This could lead to loss of insulation or cooling capacity for the rover. This risk requires more research, however, it could potentially be mitigated by the use of protective shielding and robust materials to minimize damage from impacts.

1.7 Programmatic

1.7.1 Team Organization

Reflecting on Team 18's performance, the team did an excellent job performing tasks swiftly and effectively, with a strong emphasis on collaboration and communication. The team has also taken a proactive approach to addressing obstacles and making timely choices to ensure project success.

First, to ensure a fair workload, Team 18 strives for weekly meetings to discuss the task at hand. The project manager does an impressive job explaining what the team objective is and making sure that each team member understands the task to be completed. Then, the workload is evenly distributed to members of the appropriate sections. The team leader of each section conducts checkups on each teammate to ensure that no task is too heavy by offering assistance and support.

Team 18's organization is simple yet incredibly successful. Starting with two project managers, Team 18 ensures that tasks are clearly stated and understood by all team members. They also check in to ensure that progress is made and that any impediments are overcome. Then there are three sectional leaders and their respective teams: the chief scientist on the science team, the lead systems engineer on the engineering team, and the deputy project manager of resources on the programming team. Each lead is responsible for routinely communicating with their team members to ensure that everyone is on track and has the resources they need to perform their duties.

Finally, each team receives a unique set of members. For example, the head scientist and scientists make up the science team, while the engineering team includes lead systems engineers, two mechanical engineers, electrical engineers, thermal engineers, and computer hardware engineers. The programming team includes a program analyst, a mission assurance specialist, and an outreach officer. Overall, the team organization is structured in a way that maximizes efficiency and collaboration among members with diverse expertise. This ensures that all aspects of the project are covered and that each team member can contribute their unique skills to the overall success of the mission.

Some team changes that I would recommend improving things in the future are to have monthly meetings. Everyone from different teams can learn from each other and work together to solve problems that arise across different parts of the team. Another beneficial adjustment would be to create a system for redistributing tasks if workloads

become uneven, hence reducing bottlenecks. Additionally, providing weekly updates to the entire team would make things clearer. Using a project management application can help everyone stay on top of tasks and deal with issues as they arise.

Hurricane Milton has caused a severe interruption for Team 18, as the majority of our members are from Florida. The lack of communication limited group members' cooperation. However, the group overcame this difficulty by holding virtual meetings and conducting daily check-ins to guarantee deadlines were fulfilled. Project managers and section leaders, for example, played a key role in staying in touch with each member and providing assistance as needed. The crew also managed to keep the work in order, allowing the most vital duties to continue uninterrupted. Team 18 demonstrated tenacity and adaptability in the face of adversity, resulting in a successful project despite the challenges brought by Hurricane Milton.

1.7.2 Cost Estimate

Phase C (~2 year)		
Personnel Salary/yr	Mechanical Engineering: x2	\$81,500
	Electrical Engineering:	\$86,520
	Thermal Engineer:	\$105,000
	Computer Hardware Engineer:	\$106,000
	Scientist: x2	\$115,000
	Program Analyst:	\$104,000
	Mission Assurance Specialist:	\$109,000
	Outreach Officer:	\$64,000
	PM:	\$146,500
	DPMR:	\$126,000
	Chief Scientist:	\$134,000
Lead System Engineer:	\$126,000	
Travel	Estimate of Travel Cost:	\$100,000
Outreach	Estimate of Outreach Cost:	\$40,000
Total Cost		\$3,140,040

Phase D (~2 year)		
Personnel Salary/yr	Mechanical Engineering: x2	\$85,500
	Electrical Engineering:	\$90,520
	Thermal Engineer:	\$110,000
	Computer Hardware Engineer:	\$111,000
	Scientist: x2	\$113,000
	Program Analyst:	\$105,300
	Mission Assurance Specialist:	\$110,800
	Outreach Officer:	\$68,500
	PM:	\$151,200
	DPMR:	\$128,900
	Chief Scientist:	\$136,700
Lead System Engineer:	\$128,100	
Travel	Estimate of Travel Cost:	\$100,000
Outreach	Estimate of Outreach Cost:	\$80,000
Total Cost		\$3,256,040

Phase F/E (~1 year)		
Personnel Salary/yr	Mechanical Engineering: x2	\$87,800
	Electrical Engineering:	\$93,700
	Thermal Engineer:	\$115,100
	Computer Hardware Engineer:	\$114,100
	Scientist: x2	\$117,000
	Program Analyst:	\$106,800
	Mission Assurance Specialist:	\$114,400
	Outreach Officer:	\$70,600
	PM:	\$156,000
	DPMR:	\$129,100
	Chief Scientist:	\$138,600
Lead System Engineer:	\$128,500	
Travel	Estimate of Travel Cost:	\$50,000
Outreach	Estimate of Outreach Cost:	\$40,000
Total Cost		\$1,666,500

Table #30 Phase C through E Cost Estimates

Direct Costs			
CER Category	Instrument	Manufacturing Cost	Testing Cost
Body Mounted In-Situ Instrument	Radiation Detector	\$3,600,000.00	\$1,100,000.00
Body Mounted In-Situ Instrument	NIRVSS	\$26,200,000.00	\$7,900,000.00
Body Mounted In-Situ Instrument	Laser Altimeter: LiDAR System - REIGL VUX-1LR x2	\$20,100,000.00	\$6,000,000.00
Body Mounted In-Situ Instrument	Lunar Penetrating Radar (LPR)	\$11,500,000.00	\$3,500,000.00
Body Mounted In-Situ Instrument	IR Camera: Leonardo DRS Tenum 640 x2	\$11,200,000.00	\$3,400,000.00

Table #31 Direct Costs

Subsystem Costs	
Category	Estimated Cost
Mechanical/Structures Subsystem	\$10,400,000.00
Thermal/Fluids Subsystem	\$7,500,000.00
Electronics Subsystem	\$18,300,000.00
Software Subsystem	\$2,500,000.00
Total Cost	\$38,700,000.00

Table #32 Subsystem Costs

Wrap Costs	
Category	Estimated Cost
Instrument Management	\$4,541,272
Instrument Systems Engineering	\$3,273,400
Instrument Product Assurance	\$6,580,776
Instrument Integration & Test	\$23,744,582
Total	\$38,140,030

Table #33 Wrap Costs

Total Cost (~5 years)		
Personnel	Salary Total:	\$7,652,580
Travel	Travel Total:	\$250,000
Outreach	Outreach Total:	\$160,000
Instruments	System Model CERs:	\$103,900,000
Tests	Testing Facility Costs:	\$31,300,000.00
Subsystems	Subsystem Model CERs:	\$38,700,000.00
Wraps	Wrap CERs:	\$38,140,030
Total Cost		\$220,102,610

Table #34 Direct Costs

Table #30 shows the salary breakdown for each member of our team throughout the different phases of our mission. The average yearly salary was calculated using the budget template spreadsheet provided. An estimated increase in yearly salary was added as well to account for any promotions or/and inflation. The travel costs were estimated for each member which are 14 in total plus any technicians needed. The cost includes transportation, lodging, meals, and any other necessary accommodations such as car rentals. The table also includes outreach costs while it's expected to be lower in price as social media is likely to be used. The amount put is a high estimate and if not used for that category; will go to another expense such as travel.

NASA's cost estimating tool MCCET was used to generate the values in Table #31. In this table the different types of instruments that are necessary for the objective of the mission are presented along with their final manufacturing and testing facility cost per unit. This table highlights the direct costs needed for the success of the mission. Table #32 shows each subsystem's allocated budget and Table #33 shows everything instruments related. Both tables were calculated using the CERs equations and the MCCET provided as well.

A simple summary of the total estimated costs is shown in table x.5. The table shows the total personnel salaries, travel expenses, outreach budget, and direct costs such as instruments and testing. The total cost calculated meets the stakeholder requirements which is under \$425 million. As the team progresses further a better and more accurate estimate will be made and updated.

1.7.3 Schedule Estimate

Schedule Estimate Relation Category	Instrument	Time in Months
Planetary, in situ Instruments	Radiation Detector	27.5
Planetary, in situ Instruments	NIRVSS	37.0
Planetary, in situ Instruments	Laser Altimeter: LiDAR System - REIGL VUX-1LR x2	35.6
Planetary, in situ Instruments	Lunar Penetrating Radar (LPR)	32.8
Planetary, in situ Instruments	IR Camera: Leonardo DRS Tenum 640 x2	27.6

Table #35 Instrument Manufacturing/testing Estimate

Milestones	Assigned to	Start Date	End Date
Start of Phase C	-	12/20/2024	10/9/2026
Finalize Designs	Engineering	Present	6/20/2025
Design Analysis	Science, Engineering	6/30/2025	12/30/2025
Confirm Cost and Schedule	Programmatic	12/30/2025	1/15/2026
Start Manufacturing Instruments	Technicians	1/1/2026	-
Review/Update Documents	Engineering Science Programmatic	1/15/2026	4/24/2026
CDR Submission/ Presentation	Engineering Science Programmatic	5/3/2026	5/5/2026
Review/Update Documents	Engineering Science Programmatic	6/25/2026	9/27/2026
SIR Submission/ Presentation	Engineering Science Programmatic	10/5/2025	10/9/2025
Start of Phase D	-	12/1/2026	12/1/2029
Radiation Detector	Technicians	1/1/2026	4/15/2027

Manufacturing/ Testing			
IR Camera: Leonardo DRS Tenum 640 Manufacturing/ Testing	Technicians	1/1/2026	4/16/2027
Assemble Parts	Engineering	4/18/2027	6/1/2027
Preliminary Components Test	Engineering, Science	6/10/2027	8/10/2027
Review/ Update Documents	Engineering Science Programmatics	8/22/2027	10/11/2027
Lunar Penetrating Radar (LPR) Manufacturing/ Testing	Technicians	1/1/2026	10/12/2027
ORR Submission/ Presentation	Engineering Science Programmatics	10/30/2027	11/2/2027
Laser Altimeter: LiDAR System - REIGL VUX-1LR Manufacturing/ Testing	Technicians	1/1/2026	12/8/2027
NIRVSS Manufacturing/ Testing	Technicians	1/1/2026	1/12/2028
Final System Assembly	Engineering, Technicians	2/1/2028	8/1/2028
Final System Testing	Engineering, Technicians	8/14/2028	2/1/2029
Launch Prep	Engineering Technicians Science	3/1/2029	11/15/2029
Launch Date	Programmatics, Engineering	12/1/2029	12/1/2029
Start of Phase E/F	-	12/1/2029	12/1/2030
Post-launch Checks	Programmatics, Engineering	12/1/2029	12/5/2029
Arrival on the Lunar Surface	Programmatics	12/5/2029	12/5/2029
Surface Mission	Science, Engineering	12/5/2029	11/14/2030
End of Mission	-	12/1/2030	12/1/2030

Table #36 Schedule Milestones

The estimated time for manufacturing and testing each of the science instruments is shown in Table #35. These estimations were calculated using the MCCET tool provided. The category for the SERs used is shown in the table as well.

The milestones along with who it is assigned to including start and end date is presented in table #36. This is the schedule that the team will follow to achieve a launch date by the 1st of December, 2029 and landing on the lunar surface approximately no more than 5 days after the launch date. A more detailed schedule will be done and updated with the subtasks and specific team members in each subteams assigned to each appropriate task when the team progresses through their mission. The dates in this table were estimated using the Gantt Chart template and the data collected from the MCCET combined

1.7.4 Change Control

Approach to Change Control RFAs, ADVs, and CCB's by Your Team

RFAs: Requests for Action are submitted when an issue or improvement is identified by a team member. The RFA is then sent to the Change Control Board, or CCB, for review. Subsystem leads and other key personnel (the people who have the big picture of the mission) are part of the CCB..

ADV's are handled as high-priority recommendations to be dealt with as soon as possible. Unlike RFAs, which are considered and debated, an ADV would usually have time-sensitive concerns such as safety risks or critical system updates that require immediate action.

Change Control Board (CCB): The CCB will evaluate the RFAs and/or ADVs. They assess the risk associated with the change, cost, and benefits of offering the change and grant approval or rejection of the change accordingly. They build in measures to ensure that all subsystems are aware of and prepared for the impacts of the change.

Are RFAs and ADVs treated alike or differently?

Differentiated: RFAs are recommendations or requests for changes that can be debated and prioritized according to their impact and urgency. The CCB reviews them during their periodic meetings.

ADV's are handled as a matter of more urgency, though. They are issued in cases where the implementation of the change is urgently required either to prevent mission failure or as a result of changes brought about by the promulgation of new laws. What this means is that ADVs skip the time-consuming review process of RFAs for quicker dispensation.

How Do You Follow Up on the Implementation of Feedback?

Tracking System: Implement any kind of project management tool, like a shared

document or a versioning system, in which RFAs and ADVs can be tracked. Each RFA/ADV will have a unique ID, status of the RFA/ADV, assigned team members, and deadlines.

Weekly Progress Meetings: The status of all RFAs and ADVs will be reported in the regular team meeting. This is where the subsystem leads communicate about the status of changes. A shared task board-e.g., an online tool like Trello or a Gantt chart-can indicate the status of each change.

How Do You Delegate Tasks Related to Feedback?

Subsystem Leads: Once a change has been approved by the CCB, the tasks are forwarded to the appropriate subsystem lead. He delegates special responsibilities among his team.

Cross-Subsystem Coordination: If the feedback involves more than one subsystem, a task force is organized or a joint meeting of the teams concerned is held for proper coordination.

What If a Change Affects Multiple Subsystems?

Impact Analysis: The impact thus is analyzed and performed by CCB. The lead of each subsystem determines how the change impacts his system, and changes are effected across the board. This may be updating design documents, recalibration of instruments, or change in other subsystem parameters.

Integration Testing: This type of testing occurs after changes are implemented and integrated, ensuring the adjustments across a variety of subsystems work in cohesion as wanted. Verification processes are carried out first to ascertain whether changes have introduced new problems.

How is it confirmed that all required actions have been taken?

Verification and Validation Process: Each subsystem will maintain an individual checklist, which must be signed off after changes are implemented. The CCB tracks these checklists to ensure all steps are complete.

Final Approval by CCB: After observing that all necessary changes have been made and verified, the CCB gives its final approval to make certain that all feedback has been acted upon.

1.8 Conclusion

The SRR is a critical milestone for the mission. In this review, instruments were selected via trade studies, TRL determined for the vehicle and all of its components, vehicle systems were baselined, cost and schedule estimated with greater detail, landing site chosen, and system/vehicle risks were identified. N² charts and block diagrams were also used to further outline the vehicle's system and component integration. This review sets the next stepping stone for the mission.

Given more time, more attention would be paid to refining the CAD of the rovers, both surface and subsurface. This is a goal going forward. The next milestones are to further outline and baseline the mission's cost and schedule, which will begin immediately. Much more detail and work will be put into the fine details of this part of the mission design.

References

1. Perkins, Robert. 2023. "In a First, Caltech's Space Solar Power Demonstrator Wirelessly Transmits Power in Space." California Institute of Technology. June 1, 2023. <https://www.caltech.edu/about/news/in-a-first-caltechs-space-solar-power-demonstrator-wirelessly-transmits-power-in-space>.
2. "NASA's Europa Clipper Gets Set of Super-Size Solar Arrays - NASA." 2024. NASA. NASA. August 27, 2024. <https://www.nasa.gov/missions/europa-clipper/nasas-europa-clipper-gets-set-of-super-size-solar-arrays/>.
3. "Cross-Strapping | European Cooperation for Space Standardization." 2019. Ecss.nl. 2019. https://ecss.nl/item/?glossary_id=868.
4. Williams, Matt. 2024. "New Study Addresses How Lunar Missions Will Kick up Moondust." Phys.org. March 4, 2024. <https://phys.org/news/2024-03-lunar-missions-moondust.html>.
5. BAE. "BAE Systems Products: Satsearch." the global marketplace for the space industry. Accessed October 29, 2024. <https://satsearch.co/suppliers/bae-systems/products>.
6. cFS-NASA. "Core Flight System." NASA. Accessed October 29, 2024. [https://cfs.gsfc.nasa.gov/#:~:text=The%20core%20Flight%20System%20\(cFS,and%20a%20component%20based%20design](https://cfs.gsfc.nasa.gov/#:~:text=The%20core%20Flight%20System%20(cFS,and%20a%20component%20based%20design).
7. ESA. "SpaceWire." ESA. Accessed October 29, 2024. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Onboard_Computers_and_Data_Handling/SpaceWire#:~:text=The%20SpaceWire%20standard%20offers%20many,on%20the%20Bepi%20Colombo%20platform.
8. IQSpaceCom. "Multi Frequency Easy Made." XLINK. Accessed October 29, 2024. <https://www.iq-spacecom.com/products/xlink#configurations>.
9. MAE. "Avionics Designers Plan for Another Decade with the 1553 Databus." Military Aerospace, March 1, 2004. <https://www.militaryaerospace.com/computers/article/16710545/avionics-designers-plan-for-another-decade-with-the-1553-databus>.

10. Mellor, Chris. "Fresh Details on Mars Perseverance Rover's Storage Tech." The Register® - Biting the hand that feeds IT, June 15, 2023.
https://www.theregister.com/2023/06/15/mars_perseverance_rover_space_ssd/#:~:text=Sequential%20Read%20%2D%20300%20MBps,C%20to%2085%C2%B0C.
11. NASA SPINOFF. "Communicating via Long-Distance Lasers." NASA, December 12, 2020. <https://spinoff.nasa.gov/satellite-laser-communications>.
12. NASA. "Perseverance Rover Components - NASA Science." NASA, n.d.
<https://science.nasa.gov/mission/mars-2020-perseverance/rover-components/>.
13. SatSearch. "TRX-U Satellite UHF Transceiver." satsearch. Accessed October 29, 2024. <https://satsearch.co/products/aac-clyde-trx-u-satellite-uhf-transceiver>.
14. Taylor, Jim, Andre Makovsky, Andrea Barbieri, Ramona Tung, Polly Estabrook, and A. Gail Thomas . Mars exploration rover telecommunications - descanso, July 29, 2016.
https://descanso.jpl.nasa.gov/monograph/series13/DeepCommo_Chapter7--141030.pdf
15. WNDRVR. "Wind River's VxWorks Powers Mars Science Laboratory Rover, Curiosity." Wind River. Accessed October 29, 2024.
<https://www.windriver.com/news/press/news-10901#:~:text=Wind%20River's%20VxWorks%20enables%20precise%2C%20complex%20landing,has%20successfully%20powered%20countless%20space%2Dexploration%20products%20globally>.
16. WOTM. "WOTM-Radiation." NASA, February 8, 2008.
<https://www.nasa.gov/history/alsj/WOTM/WOTM-Radiation.html>.
17. Fang, Guang-You, Bin Zhou, Yi-Cai Ji, Qun-Ying Zhang, Shao-Xiang Shen, Yu-Xi Li, Hong-Fei Guan, et al. "Lunar Penetrating Radar Onboard the Chang'E-3 Mission." Research in Astronomy and Astrophysics 14, no. 12 (December 2014): 1607–22.
<https://doi.org/10.1088/1674-4527/14/12/009>.
18. Wagner, R.V et al., Catalog of Lunar Pits. 2021
19. Li, Chunlai, Jianjun Liu, Xin Ren, Wei Zuo, Xu Tan, Weibin Wen, Han Li, et al. "The Chang'e 3 Mission Overview." Space Science Reviews 190, no. 1–4 (May 7, 2015): 85–101. <https://doi.org/10.1007/s11214-014-0134-7>.
20. Ono, T., A. Kumamoto, Y. Kasahara, Y. Yamaguchi, A. Yamaji, T. Kobayashi, S. Oshigami, et al. "The Lunar Radar Sounder (LRS) Onboard the Kaguya (SELENE) Spacecraft." Space Science Reviews 154, no. 1–4 (July 2010): 145–92.
<https://doi.org/10.1007/s11214-010-9673-8>.

21. Porcello, L.J., R.L. Jordan, J.S. Zelenka, G.F. Adams, R.J. Phillips, W.E. Brown, S.H. Ward, and P.L. Jackson. "The Apollo Lunar Sounder Radar System." *Proceedings of the IEEE* 62, no. 6 (1974): 769–83. <https://doi.org/10.1109/proc.1974.9517>.
22. NASA. Lunar Radar Sounder (LRS) - the NSSDCA. Accessed October 30, 2024. <https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=2007-039A-06>.
23. Roncoroni, G., et al. "Deep Learning Driven Interpretation of chang'e-4 lunar penetrating radar." *Icarus*, vol. 421, Oct. 2024, p. 116219, <https://doi.org/10.1016/j.icarus.2024.116219>.
24. Abracon. 2024. "Supercapacitor Lifetime Explained Abracon." *Abracon*.
<https://abracon.com/uploads/resources/Supercapacitor-Lifetime-Explained.pdf>.
25. Amphenol Communications Solutions. 2024. "Amphenol Communications Solutions." Amphenol-Cs.com. Amphenol Communications Solutions. 2024.
<https://www.amphenol-cs.com/product-series/millipacs-high-temperature.html>.
26. Astrodyne TDI. 2024. "Addressing Power Challenges with Power Distribution Units." Astrodynetdi.com. 2024.
<https://www.astrodynetdi.com/blog/addressing-power-challenges-with-power-distribution-units>.
27. Atrenne. 2024. "Harnessing the Power of Backplanes in Modern Computer Systems - Atrenne." Atrenne. March 28, 2024.
<https://www.atrenne.com/blog/harnessing-the-power-of-backplanes/#>.
28. Battery University. 2010a. "BU-107: Comparison Table of Secondary Batteries." Battery University. September 2, 2010.
<https://batteryuniversity.com/article/bu-107-comparison-table-of-secondary-batteries>.
29. Battery University. 2010b. "BU-209: How Does a Supercapacitor Work?" Battery University. September 11, 2010.
<https://batteryuniversity.com/article/bu-209-how-does-a-supercapacitor-work>.
30. Battery University. 2010c. "BU-802b: What Does Elevated Self-Discharge Do?" Battery University. September 26, 2010.
<https://batteryuniversity.com/article/bu-802b-what-does-elevated-self-discharge-do>.

31. CablesPlus USA. 2024. "Rack Mount (PDU) Power Distribution Unit | Shop."
Cablesplususa.com. 2024.
<https://store.cablesplususa.com/power-distribution-units-pdu/>.
32. Cableteque. 2024. "Reliability vs. Cost: Investing in Quality Wire Harness Validation vs. Cutting Corners." LinkedIn.com. March 25, 2024.
<https://www.linkedin.com/pulse/reliability-vs-cost-investing-quality-wire-harness-validation-y7ree/>.
33. Consolidated Electronic Wire & Cable. 2024. "Understanding Wire Harnesses."
Conwire.com. 2024. <https://www.conwire.com/cable-wiring-harnesses/>.
34. Dever, Tim. n.d. "Development of a High Specific Energy Flywheel Module, and Studies to Quantify Its Mission Applications and Benefits Tim Dever / NASA GRC."
<https://ntrs.nasa.gov/api/citations/20150009522/downloads/20150009522.pdf>.
35. Di Buono, Antonio, Neil Cockbain, Peter R. Green, and Barry Lennox. 2020. "The Effects of Total Ionizing Dose Irradiation on Supercapacitors Deployed in Nuclear Decommissioning Environments." *Journal of Power Sources* 479 (December): 228675. <https://doi.org/10.1016/j.jpowsour.2020.228675>.
36. Dragonfly Energy. 2021. "Why Does Energy Density Matter in Batteries?" Dragonfly Energy. December 22, 2021.
<https://dragonflyenergy.com/why-does-energy-density-matter-in-batteries/>.
37. EG Solar. 2021. "10 Kwh Rechargeable Lithium Ion Battery for Energy Storage | OSM." EG Solar. September 4, 2021.
<https://osmbattery.com/portfolio-items/10-kwh-rechargeable-lithium-ion-battery-for-energy-storage/>.
38. Enel X. 2024. "What Is Solar Panel Energy Efficiency?" Enel X. Enel X. 2024.
<https://corporate.enelx.com/en/question-and-answers/are-solar-panels-energy-efficient>.
39. EPEC Engineered Technologies. n.d. "Lithium vs NiMH Battery Packs - Cost Effective Battery Pack Designs." Wwww.epectec.com. Accessed October 31, 2024.
<https://www.epectec.com/batteries/lithium-vs-nimh-battery-packs.html>.

40. EPTAC Staff. 2023. "Components, Challenges, and the Role of Quality Standards in Cable Harness Assembly." Eptac.com. August 11, 2023.
<https://www.eptac.com/blog/quality-standards-in-cable-harness-assembly-quality-control-measure>.
41. European Space Agency. 2019. "Nobel-Winning Lithium-Ion Batteries Powering Space." Www.esa.int. European Space Agency. October 15, 2019.
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Nobel-winning_lithium-ion_batteries_powering_space.
42. Ferriday, T.B., and Peter Hugh Middleton. 2021. "Alkaline Fuel Cell Technology - a Review." *International Journal of Hydrogen Energy* 46 (35): 18489–510.
<https://doi.org/10.1016/j.ijhydene.2021.02.203>.
43. FQ-Wire Harness. 2024. "How Much Does It Cost to Replace a Wiring Harness?" LinkedIn.com. May 2024.
https://www.linkedin.com/posts/fq-wire-harness_how-much-does-it-cost-to-replace-a-wiring-activity-719635060350411616-bTNP/.
44. Hickman, J. Mark, Henry Curtis, and Geoffrey Landis. 1990. "Design Considerations for Lunar Base Photovoltaic Power Systems NASA Design Considerations for Lunar Base Photovoltaic Power Systems." *National Aeronautics and Space Administration*.
<https://ntrs.nasa.gov/api/citations/19910004946/downloads/19910004946.pdf>.
45. Huynh, Co, Liping Zheng, and Patrick McMullen. 2007. "Thermal Performance Evaluation of a High-Speed Flywheel Energy Storage System." *IEEE Xplore*, January. <https://doi.org/10.1109/iecon.2007.4459898>.
46. INSIGHT Staff. 2022. "Spotlight on Lessons Learned: Cable Harness Wiring and Connector Anomalies Caused by Induced Damage in Human Spaceflight Vehicles | APPEL Knowledge Services." Appel.nasa.gov. APPEL Knowledge Services. January 31, 2022.
<https://appel.nasa.gov/2022/01/31/spotlight-on-lessons-learned-cable-harness-wiring-and-connector-anomalies-caused-by-induced-damage-in-human-spaceflight-vehicles/>.

47. Inverter. 2024. "100A 12V/24V/48V PWM Solar Charge Controller." Inverter.com. 2024.
https://www.inverter.com/100a-pwm-solar-charge-controller?affiliate=ads&gad_source=1&gclid=Cj0KCQjw1Yy5BhD-ARIsAl0RbXbk1avOs2q5YWKpj2zw42wbmgTsfFPXYOmJUrh14tia1Sb2NnLx3owaAkXxEALw_wcB.
48. Jet Propulsion Laboratory. n.d. "FAQ | Mission." NASA's Europa Clipper.
<https://europa.nasa.gov/mission/faq/>.
49. Kamarudin, S.K., W.R.W. Daud, A. Md.Som, M.S. Takriff, and A.W. Mohammad. 2006. "Technical Design and Economic Evaluation of a PEM Fuel Cell System." *Journal of Power Sources* 157 (2): 641–49.
<https://doi.org/10.1016/j.jpowsour.2005.10.053>.
50. Kato, N, T Murao, K Fujii, T. Aoiki, and S. Muroyama. 2002. "1 KW Portable Fuel Cell System Based on PEFCs." *IEEE Xplore* 18 (November): 209–13.
<https://doi.org/10.1109/telesc.2000.918440>.
51. Keim, Robert. 2024. "Supercapacitor." Eepower.com. eepower.com. 2024.
<https://eepower.com/capacitor-guide/types/supercapacitor>.
52. Koehler, Uwe. 2019. "Nickel Cadmium Battery - an Overview | ScienceDirect Topics." [Www.sciencedirect.com](https://www.sciencedirect.com/topics/engineering/nickel-cadmium-battery). 2019.
<https://www.sciencedirect.com/topics/engineering/nickel-cadmium-battery>.
53. Krause, Frederick C, Juan Pablo, Simon C Jones, Erik J Brandon, Eric Darcy, C Iannello, and Ratnakumar V Bugga. 2021. "Performance of Commercial Li-Ion Cells for Future NASA Missions and Aerospace Applications." *Journal of the Electrochemical Society* 168 (4): 040504–4.
<https://doi.org/10.1149/1945-7111/abf05f>.
54. Layton, Julia. 2005. "How Robotic Vacuums Work." HowStuffWorks. November 3, 2005. <https://electronics.howstuffworks.com/gadgets/home/robotic-vacuum.htm>.
55. Leita, Gabriele, and Benedetto Bozzini. 2024. "Impact of Space Radiation on Lithium-Ion Batteries: A Review from a Radiation Electrochemistry Perspective." *Journal of Energy Storage* 100 (August): 113406.
<https://doi.org/10.1016/j.est.2024.113406>.

56. Lenovo. 2021. "What Is a Backplane? An In-Depth Guide | Lenovo US."
Lenovo.com. 2021. <https://www.lenovo.com/us/en/glossary/backplane/>.
57. Marketing, Metric. 2024. "The Pros and Cons of Nickel-Cadmium Batteries." City Labs. March 4, 2024. <https://citylabs.net/nickel-cadmium-batteries/>.
58. Marshall, Max Bair. 2023. "Solar Panel Output Voltage." ShopSolar.com. Shop Solar. November 7, 2023.
<https://shopsolarkits.com/blogs/learning-center/solar-panel-output-voltage>.
59. NASA Jet Propulsion Laboratory. 2024. "Meet Europa Clipper's Solar Array 'Wings.'" YouTube. August 27, 2024. <https://www.youtube.com/watch?v=7sa96nLa5QQ>.
60. National Aeronautics and Space Administration. n.d. "3.0 Power - NASA." National Aeronautics and Space Administration.
<https://www.nasa.gov/smallsat-institute/sst-soa/power-subsystems/>.
61. Nayak, Anish K., Babu Ganguli, and Pulickel M. Ajayan. 2023. "Advances in Electric Two-Wheeler Technologies." *Energy Reports* 9 (December): 3508–30.
<https://doi.org/10.1016/j.egy.2023.02.008>.
62. Ni, Meng. 2005. "Current Status of Fuel Cell Technologies." *Energy Exploration & Exploitation* 23 (3): 207–14. <https://doi.org/10.1260/014459805774852083>.
63. NJ.gov. n.d. "Batteries vs. Flywheels." Nj.gov. nj.gov.
https://www.nj.gov/bpu/pdf/publicnotice/stakeholder/Omnes%20Energy%20BATTERIES%20vs%20FLYWHEELS_March%2019%202019.pdf.
64. Oehm, Cody. 2022. "How to Charge Lithium Ion Battery with Solar Panel." ShopSolar.com. Shop Solar. July 15, 2022.
<https://shopsolarkits.com/blogs/learning-center/how-to-charge-lithium-ion-battery-with-solar-panel>.
65. Office of Energy Efficiency & Renewable Energy. 2024. "Fuel Cell Basics." Energy.gov. 2024. <https://www.energy.gov/eere/fuelcells/fuel-cell-basics#>.
66. Office of Energy Efficiency and Renewable Energy. 2019. "Types of Fuel Cells." Energy.gov. 2019. <https://www.energy.gov/eere/fuelcells/types-fuel-cells>.

67. Panlkouich , John. 1967. "Solar Array Regulators of Explorer Satellites XII, XIV, XV, XVIII, XXI, XXVI, XXVIII, and Ariel 1." *National Aeronautics and Space Administration*.
<https://ntrs.nasa.gov/api/citations/19670020697/downloads/19670020697.pdf>.
68. Perkins, Robert. 2023. "In a First, Caltech's Space Solar Power Demonstrator Wirelessly Transmits Power in Space." California Institute of Technology. June 1, 2023.
<https://www.caltech.edu/about/news/in-a-first-caltechs-space-solar-power-demonstrator-wirelessly-transmits-power-in-space>.
69. Raya-Armenta, José Maurilio, Najmeh Bazmohammadi, Juan C. Vasquez, and Josep M. Guerrero. 2021. "A Short Review of Radiation-Induced Degradation of III–v Photovoltaic Cells for Space Applications." *Solar Energy Materials and Solar Cells* 233 (December): 111379. <https://doi.org/10.1016/j.solmat.2021.111379>.
70. Schneider Electric. 2024. "Rack Power Distribution Unit (PDU) Safety Information | Schneider Electric." Se.com. Schneider Electric. 2024.
https://www.se.com/us/en/download/document/990-3433_EN/.
71. "Specific Energy of Batteries Worldwide 2023 | Statista." 2023. Statista. 2023.
<https://www.statista.com/statistics/1422973/specific-energy-of-battery-energy-systems/>.
72. Spectrolab - A Boeing Company. n.d. "XTE-SF (Standard Fluence) Space Qualified Triple Junction Solar Cell." *Spectrolab*. Spectrolab. Accessed October 31, 2024.
https://www.spectrolab.com/photovoltaics/XTE-SF_Data_Sheet.pdf.
73. Tang, Xingwang, Yujia Zhang, and Sichuan Xu. 2023. "Temperature Sensitivity Characteristics of PEM Fuel Cell and Output Performance Improvement Based on Optimal Active Temperature Control." *International Journal of Heat and Mass Transfer* 206 (June): 123966.
<https://doi.org/10.1016/j.ijheatmasstransfer.2023.123966>.
74. TE Connectivity. 2024. "Cabled Backplane Systems the High-Speed Alternative to Print Circuit Boards (PCBs)." TE Connectivity. September 22, 2024.
<https://www.te.com/en/industries/data-centers-ai/insights/high-speed-alternative-to-pcbs.html?tab=pgp-story>.

75. "The Energy Density of a Lithium-Ion Battery." 2024. Wwww.ufinebattery.com. January 27, 2024.
<https://www.ufinebattery.com/blog/what-is-the-energy-density-of-a-lithium-ion-battery/>.
76. Thunder Said Energy. n.d. "Lithium Ion Batteries: Energy Density?" Thunder Said Energy. Thunder Said Energy.
<https://thundersaidenergy.com/downloads/lithium-ion-batteries-energy-density/>.
77. U.S Department Of Energy. 2015. "Fuel Cells." U.S Department Of Energy.
<https://www.energy.gov/eere/fuelcells/articles/fuel-cells-fact-sheet>.
78. Vertiv. 2022. "Your Guide to Buying a Power Distribution Unit (PDU)." Vertiv.com. February 24, 2022.
<https://www.vertiv.com/en-emea/about/news-and-insights/articles/educational-articles/your-guide-to-buying-a-power-distribution-unit-pdu/>.
79. VR, Akshay. 2023. "Unleashing the Potential of Solar Energy for Space Exploration." Republic of Solar. March 21, 2023.
<https://arka360.com/ros/solar-energy-space-exploration-potential-challenges/#>.
80. "AZW/LA-II Ultra-Low Solar Absorptance White Thermal Control Paint / Coating." n.d. Wwww.aztechnology.com. <https://www.aztechnology.com/product/2/azw-la-ii>.
81. "THERMAENGINEER.COM WEBSITE." 2024. Thermalengineer.com. 2024.
https://www.thermalengineer.com/library/effective_emittance.htm.
82. "Loop Heat Pipes for Space Applications | ARQUIMEA." n.d. Wwww.arquimea.com.
<https://www.arquimea.com/products/loop-heat-pipes-satellite-space/>.
83. Leonard, Becca. n.d. "Understanding Loop Heat Pipes | Advanced Thermal Solutions." <https://www.qats.com/cms/2014/08/04/understanding-loop-heat-pipes/>.
84. "Types of Heat Pipes." 2020. Celsia. December 3, 2020.
<https://celsiainc.com/heat-sink-blog/types-of-heat-pipes/>.
85. "Emissivity of Common Materials." n.d. Wwww.omega.co.uk.
<https://www.omega.co.uk/literature/transactions/volume1/emissivitya.html>.

86. “HK699 | Polyimide Thermofoil™ Heaters | Minco.” 2015. Minco.com. 2015.
http://catalog.minco.com/catalog3/d/minco/?c=products&cid=3_1-polyimide-thermofoil-heaters&id=HK6909&unit=metric.
87. Horvath, Tyler, Paul O. Hayne, and David A. Paige. 2022. “Thermal and Illumination Environments of Lunar Pits and Caves: Models and Observations from the Diviner Lunar Radiometer Experiment.” *Geophysical Research Letters* 49 (14).
<https://doi.org/10.1029/2022gl099710>.
88. Birur, Gajanana, Gani Ganapathi, Anthony Paris, Mike Pauken, Keith Novak, and Glenn Tsuyuki. 2004. “Mechanically Pumped Fluid Loops for Spacecraft Thermal Control: Pradeep Bhandari.”
<https://tfaws.nasa.gov/TFAWS04/Website/program/Speakers/TFAWS2004PresentationonMechLoops-v1.pdf>.
89. “Density.” n.d. Precision Ceramics USA.
<https://precision-ceramics.com/materials/properties/density/>.
90. Scot C. R. Rafkin “RAD – The Radiation Assessment Detector for MSL”
https://srag.jsc.nasa.gov/Publications/Workshop_2006-04/RAD_RAFFIN_2006.pdf
91. Dr. Anthony Colaprete “Near InfraRed Volatiles Spectrometer System (NIRVSS) - NASA Space Science Data Coordinated Archive”
<https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=VIPER++++-03>
92. Krause, Frederick C, Juan Pablo, Simon C Jones, Erik J Brandon, Eric Darcy, C Iannello, and Ratnakumar V Bugga. 2021. “Performance of Commercial Li-Ion Cells for Future NASA Missions and Aerospace Applications.” *Journal of the Electrochemical Society* 168 (4): 040504–4. <https://doi.org/10.1149/1945-7111/abf05f>.
93. “Nobel-Winning Lithium-Ion Batteries Powering Space.” 2019. [Www.esa.int](http://www.esa.int). October 15, 2019.
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Nobel-winning_lithium-ion_batteries_powering_space.
94. Hassler, D.M., Zeitlin, C., Wimmer-Schweingruber, R.F. et al. The Radiation Assessment Detector (RAD) Investigation. *Space Sci Rev* 170, 503–558 (2012).
<https://doi.org/10.1007/s11214-012-9913-1>

Appendices

Appendix A

CAD Drawings

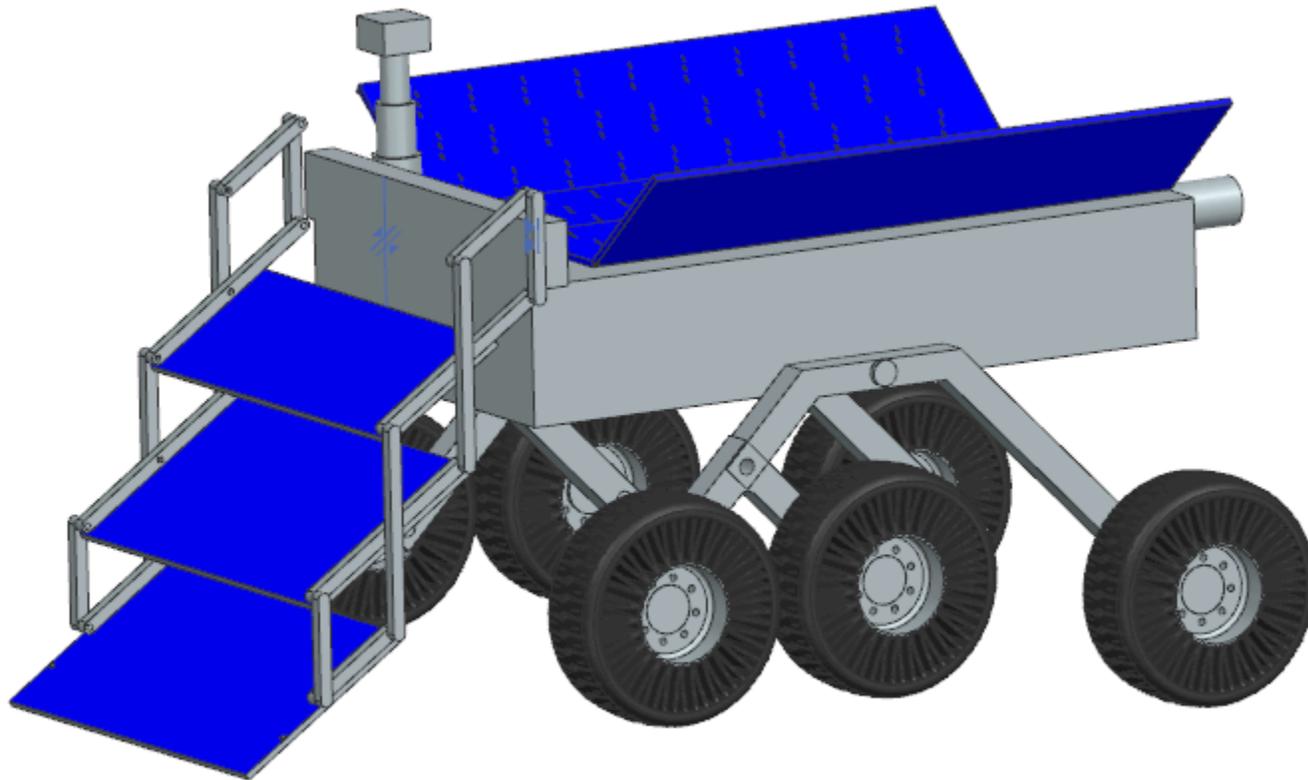


Figure A.1 Surface Rover Assembly

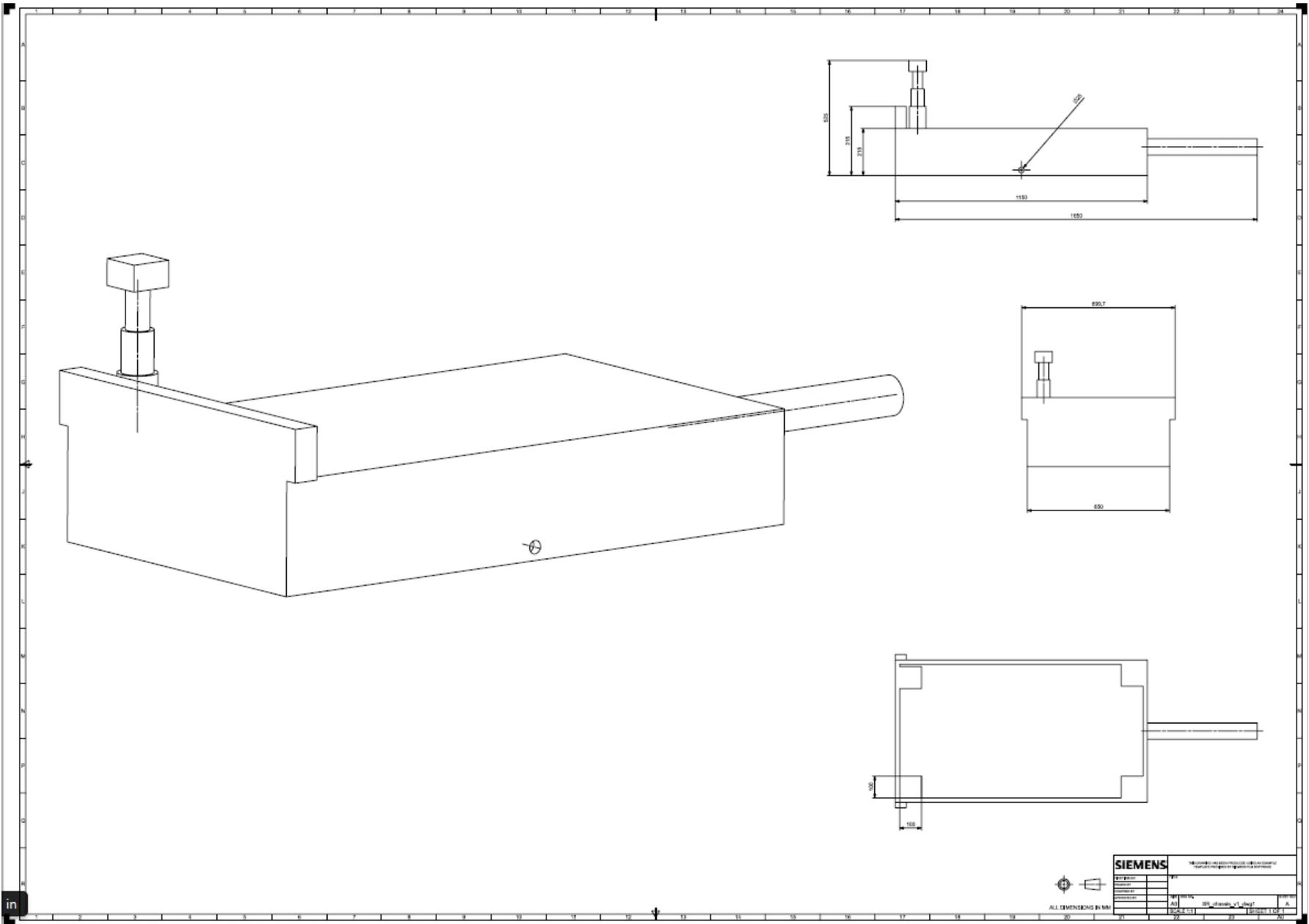


Figure A.2 Surface Rover Assembly Drawing

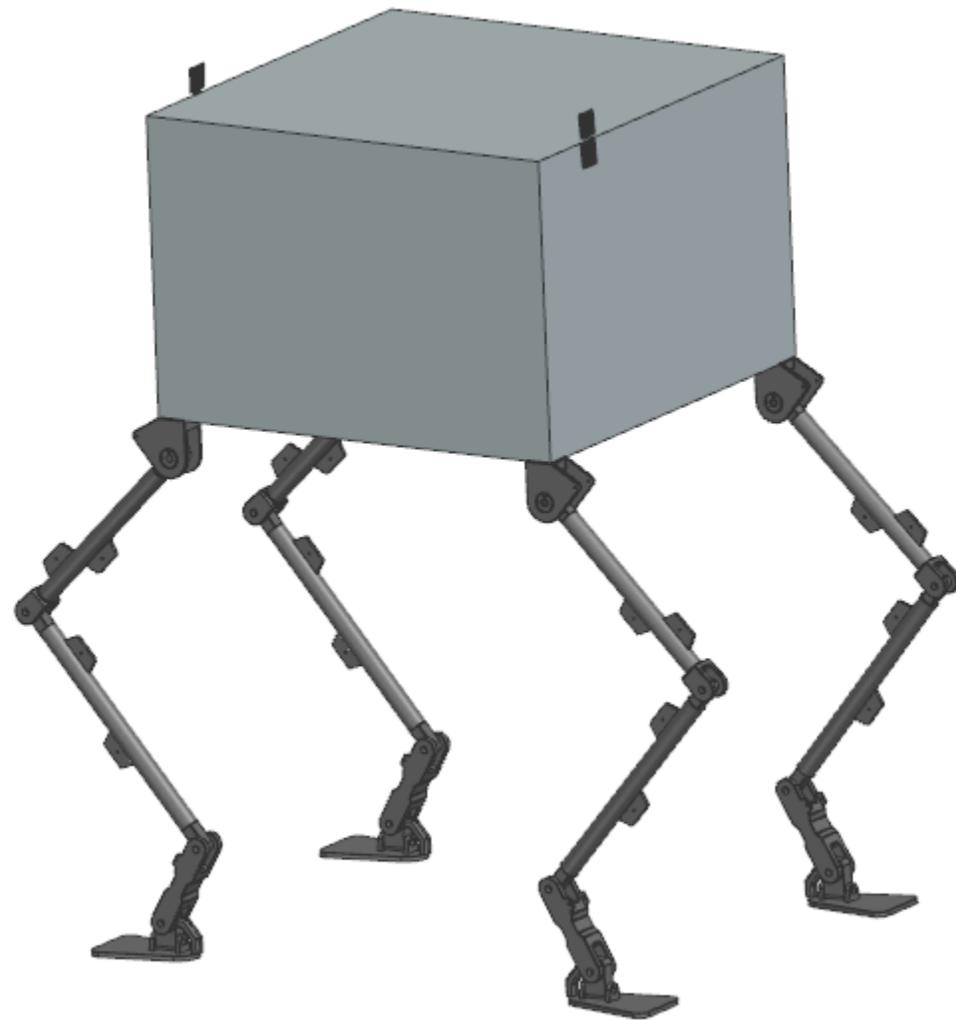


Figure A.4 Subsurface Rover Assembly

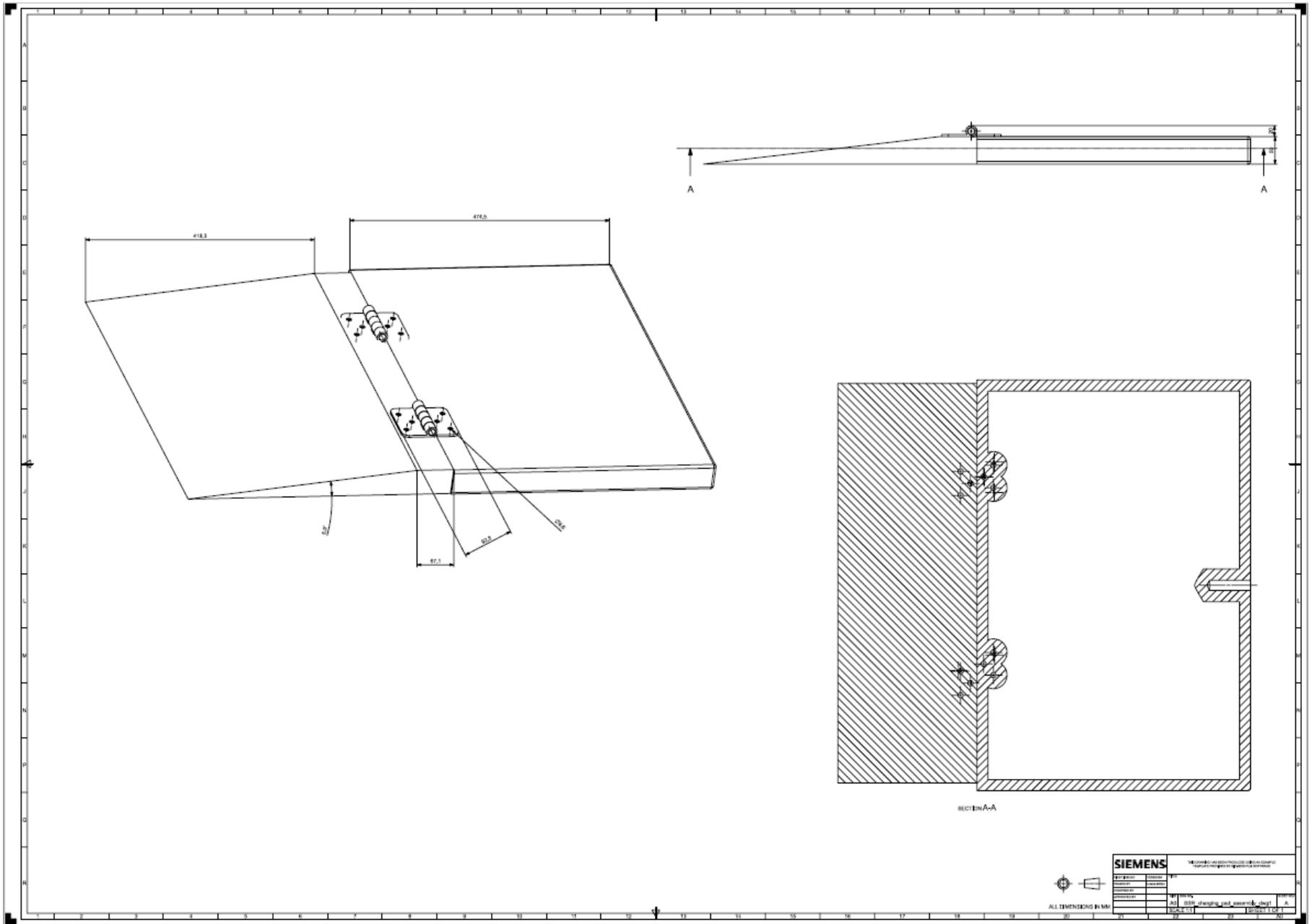


Figure A.6 Subsurface Rover Charging Pad Drawing

Appendix B
Mechanical Subsystem Trade Studies

Appendix B Table 1:

Material							
Criteria	Explanation	Grade	Weight	Aluminum Alloy (6061)	Titanium Alloy (Ti-6Al-4V)	Carbon Fiber	Stainless Steel
Weight	Effect on rover's overall weight and mobility (% of rover weight)	10 = <20% 5 = 20-30% 1 = 30-35% 0 = >35%	30%	8	6	9	5
Strength	Ability to withstand mechanical stress, shocks, and impacts (strength-to-weight ratio)	10 = High specific strength and solid 5 = Average specific strength, pretty solid 1 = Lower specific strength but not brittle 0 = Low specific strength and brittle	35%	7	9	6	2

Cost	Affordability in material costs and repairs	10 = Great cost 5 = moderate 1 = expensive but still feasible 0 = over budget (can't allocate the finances for it)	20%	10	4	6	7
Repairability	Ease of repair in lunar conditions, good corrosion resistance and melting point	10 = Can experience temp fluctuations, great corrosion resistance 5 = Decent corrosion resistance 0 = Can't experience varying temps	15%	7	5	4	6
		TOTALS:	100%	79.00%	65.00%	66.00%	45.00%

Appendix B Table 2:

Subsurface Rover Suspension Design									
Criteria	Explanation	Grade	Weight	Rocker Bogie	Rocker Bogie with Treads for Front Wheel	Full Tank Treads	Spider-like Suspension	Rocker Bogie Lambda Suspension	Similar to Asagumo Rover (4 legs, small)
Obstacle Clearance	The suspension should allow the rover to traverse large obstacles, such as rocks or uneven terrain, without compromising stability or mobility.	10 = can scale vertical obstacle 5 = can scale 45 degree obstacle with ease 1 = gets over pebble 0 = fail	18%	7	8	6	9	8	2
Shock Absorption	The suspension should minimize vibrations and impacts from uneven terrain to protect both the rover and mounted instruments.	10 = can handle extreme shocks without damage or discomfort 5 = can absorb moderate shocks effectively 1 = minimal shock absorption, uncomfortable on rough terrain	18%	8	9	7	8	7	6

Payload Accommodation	The suspension should allow sufficient space and mounting options for all required science instruments, ensuring secure and vibration-isolated placement.	10 = ample room plus extra 5 = can barely carry instruments 1 = Cannot fit instruments 0 = Fail	14%	7	7	7	5	7	5
Volume Compliance	The suspension system must fit within the specified stowed volume constraints (2 m x 1.25 m x 1.25 m).	10 = fits within volume requirements within the tolerance of 10% 5 = fits within volume requirements within the tolerance of 1% 1 = barely fits volume requirements 0 = Fail	10%	4	3	4	4	3	8

Minimize d Mass	The suspension should be designed to minimize mass, contributing to the overall system's weight efficiency without sacrificing performance.	10 = <250 kg 5 = 300 kg 1 = exactly 350 kg 0 = Fail	10%	5	4	3	4	5	9
Maneuve rability	The suspension should allow for efficient turning and steering, enabling smooth navigation in tight or irregular lunar environments.	10 = Large amount of control and a large turning radius 5 = medium 1 = slow turning with a small amount of flexibility for terrain 0 = Fail	14%	3	3	2	7	3	7

Modularity	The suspension can be adapted or modified for different rover designs.	10 = Very modifiable 5 = Some tunability 1 = Very limited modification is possible 0 = Fail	8%	6	7	5	6	4	8
Design Simplicity	The system should aim for low complexity to reduce the risk of failure, facilitate ease of assembly, and ensure reliability during the mission.	10 = very simple with few considerations 5 = more variables in calculations, but not terrible 1 = Extremely complex 0 = Fail	8%	6	6	7	1	5	8
		TOTALS:	100%	40.40%	40.20%	36.00%	41.80%	40.40%	43.80%

Appendix B Table 3:

Subsurface Rover Mobility System						
Criteria	Explanation	Grade	Weight	Traditional Wheels	Tracks	Articulated Legs
Terrain Adaptability	The system should effectively traverse diverse lunar terrains, including soft regolith, rocks, and slopes, without significant loss of traction.	10 = high 5 = medium 1 = low 0 = Fail	17.5%	6	8	10
Load-Bearing Capability	The mobility system must support the rover's weight, including payload and science instruments, without compromising mobility or performance.	10 = high 5 = medium 1 = low 0 = Fail	25%	1	1	10
Climbing and Stability	The mobility system must provide reliable climbing capability, enabling the rover to ascend and descend steep slopes.	10 = high 5 = medium 1 = low 0 = Fail	25%	1	1	10
Energy Efficiency	The mobility system should minimize energy consumption while maintaining reliable movement across the lunar surface and in the pit.	10 = high 5 = medium 1 = low 0 = Fail	10%	9	5	4
Modularity	The mobility system should be modular to allow for easy replacement or repair in case of damage.	10 = high 5 = medium 1 = low 0 = Fail	10%	8	5	4

Stability	Able to remain stable, especially on inclined surfaces (<~45 degrees) and during turning maneuvers	10 = high 5 = medium 1 = low 0 = Fail	12.5%	7	8	9
		TOTALS:	100%	41.25%	39.00%	86.75%

Appendix B Table 4:

Surface Rover Mobility System						
Criteria	Explanation	Grade	Weight	Traditional Wheels	Tracks	Articulated Legs
Terrain Adaptability	The system should effectively traverse diverse lunar terrains, including soft regolith, rocks, and slopes, without significant loss of traction.	10 = Best for navigating rugged surfaces 5 = Good on flat surfaces, may struggle with rough terrain 1 = Low adaptability for rough surfaces, hard to turn and climb	25%	6	8	10
Load-Bearing Capability	The mobility system must support the rover's weight, including payload and science instruments, without compromising mobility or performance.	10 = high 5 = medium 1 = low 0 = Fail	25%	10	8	7

Energy Efficiency	The mobility system should minimize energy consumption while maintaining reliable movement across the lunar surface.	10 = Low power requirements 5 = High power use, which may be due to weight or complex movements 0 = Fail	15%	9	5	4
Durability	The mobility system should be designed to withstand the abrasive lunar dust and extreme temperature fluctuations for extended operational periods.	10 = high 5 = medium 1 = low 0 = Fail	15%	10	8	7
Steering Precision	The mobility system should provide precise and efficient turning capability to navigate through tight spaces and avoid obstacles.	10 = high 5 = medium 1 = low 0 = Fail	10%	8	6	7
Modularity	The mobility system should be modular to allow for easy replacement or repair in case of damage.	10 = high 5 = medium 1 = low 0 = Fail	10%	7	6	8
		TOTALS:	100%	83.50%	71.50%	74.00%

Appendix B Table 5:

Drivetrain System						
Criteria	Explanation	Grade	Weight	Electric Motor	Hydraulic Systems	Mechanical Gearboxes
Torque and Power Delivery	The drivetrain should provide sufficient torque to overcome lunar terrain obstacles (e.g., regolith, slopes, rocks).	10 = High power delivery 5 = Medium power delivery, not as efficient 1 = Low power delivery, not very efficient 0 = Fail	30%	10	5	4
Weight	Impact of system weight on overall rover mass (kg)	10 = Lightweight 5 = Medium weight 1 = Bulkier 0 = Fail	25%	9	4	1
Control Responsiveness	The drivetrain must ensure smooth and responsive power delivery, allowing precise control for both low-speed maneuvering and faster traversal.	10 = Excellent control for maneuvering 5 = Descent control, not as precise 1 = Limited 0 = Fail	20%	10	6	6

Durability	The drivetrain should be able to withstand wear and tear in harsh lunar conditions	10 = Few failure points, very durable 5 = Can be vulnerable to some harsh environments 0 = Unable to withstand harsh conditions	25%		2	2
		TOTALS:	100%	72.50%	42.00%	31.50%

Appendix C
Power Subsystem Trade Studies

Appendix C Table 1:

Power Generation						
Criteria	Explanation	Grade	Weight	Solar Array	Proton Exchange Membrane Fuel Cell	Alkaline Fuel Cells (AFC)
Cost	Ensure that the system remains under the budget.	10 = \$500,000 or less 5 = \$1 million 1 = \$2 million 0 = Greater than \$2 million	10%	4	10	10
Reliability	The system shall be reliable to meet the mission requirements.	10 = Extremely reliable 5 = Moderately reliable 1 = Low reliability 0 = Not reliable	20%	10	6	8

Radiation Tolerance	Ability to tolerate levels of radiation on the lunar surface.	10 = Tolerates high levels of radiation without degradation. 5 = Tolerates medium levels of radiation with minor degradation. 1 = Minimal levels of radiation tolerance and significant degradation in high radiation environments 0 = Fails in high radiation environments	15%	6	5	1
Temperature Tolerance	Ability to tolerate changes in temperature on the surface of the moon between -150°C and 140°C.	10 = Working performance in the full range of temperatures between -150°C and 140°C. 5 = Operational for most temperatures on the lunar surface. 1 = Operates for minimal ranges in temperature on the lunar surface. 0 = Fail	15%	7	3	5
Efficiency	This is the percentage of the total energy absorbed that can be converted into electricity.	10 = 100% 5 = 50% 1 = 10% 0 = 0%	20%	3	5	5

Safety	Safety challenges associated with the power generation technology.	10 = low safety risk 5 = medium safety risk 1 = high safety risk 0 = Fail	10%	8	5	5
Mass	Ensure that the mass of the electrical power generator does not exceed 350 kg.	10: Fits within 2 m x 1.25 m x 1.25 m and weighs less than 350 kg 0: Does not fit within physical or mass constraints for mission	10%	8	6	6
		TOTALS:	100%	65.50%	55.00%	56.00%

Appendix C Table 2:

Power Storage Method Selection						
Criteria	Explanation	Grade	Weight	Batteries	Supercapacitors	Flywheels
Cost	The costs of operation and maintenance of the power storage method must not result in the lunar rover exceeding the \$450 million budget.	10 = Less than \$100 per KWh 5 = \$5000 per KWh 1 = \$10,000 per KWh 0 = Greater than \$1,000 per KWh	10%	8	2	6
Size & Mass	The total mass and size of the components contained within the energy storage system, including the storage system, casing, and other materials necessary for operation.	10: Fits within 2 m x 1.25 m x 1.25 m and weighs less than 350 kg 0: Does not fit within physical or mass constraints for mission	10%	9	3	5
Operating Temperature Range	Ability to tolerate changes in temperature on the surface of the moon between -150°C and 140°C.	10 = Working performance between -150°C and 140°C 5 = Working performance between 0°C and 80° C 1 = Operates between 0°C and 20° C 0 = Fail	15%	6	5	5

Specific Energy	The total amount of electrical energy stored per unit weight, which is measured in W/kg.	10 = Greater than 150 Wh/kg 5 = 80-90 Wh/kg 1 = 30-40 Wh/kg 0 = Less than 30 Wh/kg	20%	9	3	5
Radiation Tolerance	Ability to tolerate levels of radiation on the lunar surface.	10 = Tolerates high radiation without degradation. 5 = Tolerates medium levels of radiation with minor degradation. 1 = Minimal levels of radiation tolerance and significant degradation in high radiation. 0 = Fails in high radiation environments	15%	5	8	5
Lifetime (Cycles)	The amount of charge and discharge cycles the power storage method can complete before decreasing in functionality.	10 = 1800 or Greater 5 = 1200 1 = 600 Cycles 0 = Less Than 600 Cycles	30%	9	3	5
TOTALS:			100%	78.50%	39.50%	51.00%

Appendix C Table 3:

Batteries For Power Storage						
Criteria	Explanation	Grade	Weight	Nickel- Cadmium	Nickel-metal hydride	Lithium Ion
Lifetime (Cycles)	The amount of charging and discharging cycles the battery can complete before losing functionality and deteriorating in performance.	10 = 1800 or Greater 5 = 1200 1 = 600 Cycles 0 = Less Than 600 Cycles	15%	4	1	8
Energy Density (Watt Hours / Liter)	The amount of energy stored in the battery per unit volume, describing how much energy the battery holds relative to the volume.	10 = Greater Than 400 Wh/L 5 = 250 Wh/L 1 = 100 Wh/L 0 = Less Than 100 Wh/L	30%	3	5	9
Specific Energy (Watt Hours / Kilogram)	The amount of energy the battery contains per unit mass.	10 = Greater than 150 Wh/kg 5 = 80-90 Wh/kg 1 = 30-40 Wh/kg 0 = Less than 30 Wh/kg	25%	3	5	10
Self-Discharge Rate	The ability for a battery to retain stored energy over time and resist self-discharge.	10 = Slow (Less Than 5% in 24 Hours) 5 = Medium (10% in 24 Hours) 1 = Fast (15% in 24 Hours) 0 = Fail (Greater Than 15% in 24 Hours)	20%	5	3	9

Battery Cell Voltage (Operating)	The difference in electrical potential between two terminals, determined by chemical reactions within cells.	10 = 4 V 5 = 2 V 1 = 0.5 V 0 = 0 V	10%	4	4	9
		TOTALS:	100%	34.00%	38.00%	84.00%

Appendix C Table 4:

Power Management and Distribution (PMAD)						
Criteria	Explanation	Grade	Weight	Cable Harness	Backplane	Power Distribution Unit
Mass and Size	Ensure that the mass adheres to the 350 kg mass requirement and has a configuration that fits within 2 m x 1.25 m x 1.25 m.	10: Fits within 2 m x 1.25 m x 1.25 m and weighs less than 350 kg 0: Does not fit within physical or mass constraints for mission	15%	10	10	10
Reliability	The likelihood that the system will perform the necessary functions at any given time without failure.	10 = highly reliable 5 = medium reliability 1 = low reliability 0 = not reliable	30%	9	8	7
Safety	The ability of the component to minimize hazards and mitigate risks.	10 = Low Safety Risk 5 = Medium Safety Risk 1 = High Safety Risk 0 = Unsafe	30%	9	7	5
Operating Temperature Range	Ability to tolerate changes in temperature on the surface of the moon between -150°C and 140°C through proper insulation.	10 = Working performance between -150°C and 140°C 5 = Working performance between 0°C and 80° C 1 = Operates between 0°C and 20° C 0 = Fail	15%	8	6	2

Cost	Ensure that the power management and distribution system adheres to the budget of \$450 million and minimizes expenses.	10 = Low cost 5 = Medium Cost 1 = High Cost 0 = Fail	10%	6	7	5
		TOTALS:	100%	87.00%	76.00%	59.00%

Appendix D

CDH Subsystem Trade Studies

Appendix D Table 1:

Rover Antennas for Inter- and Intra- Communications							
Criteria	Explanation	Grade	Weight	High-Gain Antenna (HGA)	Low-Gain Antenna (LGA)	UHF Antenna	X-band/Ka-band Antennas
Signal Range	Distance the antenna can effectively cover	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	4	4	8
Data Rate Requirements	Amount of data to be transmitted (telemetry, imagery, etc.)	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	3	5	10
Power Constraints	Usage of power for communication systems	10 = low usage of power, 1 = high usage of power 0 = Fail	15%	6	9	8	5
Environmental Factors	Handling of Radiation and temperature fluctuations	10 = handles well 1 = handles bad 0 = Fail	15%	7	8	7	6
		TOTALS:	100%	74.50%	61.00%	63.00%	69.50%

Appendix D Table 2:

Rover Onboarding Computers (OBC) Selection							
Criteria	Explanation	Grade	Weight	RAD750 single-board computer	RAD5545 single-board computer	Arm Cortex-A53	GR712RC
Processing Power	Required for real-time data processing (e.g., navigation, scientific instruments)	10 = high processing power 1 = low processing power 0 = Fail	30%	7	8	10	6
Radiation Tolerance	Ability to operate in high-radiation environments	10 = high, 5 = medium 1 = low 0 = Fail	20%	8	9	4	10
Power Consumption	Average and peak power consumption under nominal and full-load operation	10 = low consumption of power 1 = high consumption of power 0 = Fail	15%	8	7	8	8
Memory Capacity	Amount of onboard memory for temporary data storage and processing	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	9	8	8

Temperature Range	Operational temperature range in extreme environments	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	7	5	7
		TOTALS:	100%	73.50%	79.00%	70.50%	75.50%

Appendix D Table 3:

Interface for Communication Between Instruments, Equipment, and OBC								
Criteria	Explanation	Grade	Weight	SpaceWire	MIL-STD-1553	CAN Bus	RS-422/RS-485	Ethernet
Data Rate	The rate of speed the interface can support	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	5	6	6	10
Power Consumption	The power required by the data interface during operations	10 = low power consumption 1 = high power consumption 0 = Fail	25%	7	8	9	8	5

Reliability/ Fault Tolerance	The ability of the interface to operate in high-radiation and other extreme conditions	10 = high, 5 = medium 1 = low 0 = Fail	30%	9	10	8	8	6
Ease of Integration	Complexity of integrating the interface with the rover subsystems	10 = low complexity 1 = high complexity 0 = Fail	10%	7	6	9	8	6
Industry Adoption	Popularity and adoption in space applications	10 = high, 5 = medium 1 = low 0 = Fail	10%	10	9	7	7	7
		TOTALS:	100%	79.00%	77.50%	77.50%	74.00%	68.50%

Appendix D Table 4:

Data Collection Storage for Scientific Instruments and Equipment Instructions									
Criteria	Explanation	Grade	Weight	EEPROM	NAND Flash	SRAM	DRAM	MRAM	SSD
Storage Capacity	Total data storage capacity needed to handle mission data	10 = high, 5 = medium 1 = low 0 = Fail	25%	4	8	3	6	7	9
Read/Write Speed	Required speed for data access, logging, and processing	10 = high, 5 = medium 1 = low 0 = Fail	25%	4	7	9	9	8	9
Power Consumption	The power consumption of the storage system during operation	10 = low power consumption 1 = high power consumption 0 = Fail	25%	9	8	6	5	6	8

Radiation Tolerance	Ability to operate in high-radiation environments without data loss or corruption	10 = high, 5 = medium 1 = low 0 = Fail	15%	9	6	9	4	6	7
Size & Mass	Physical footprint and weight constraints for integration	10 = small physical footprint 1 = large physical footprint 0 = fail	10%	9	8	6	7	7	6
		TOTALS:	100%	65.00%	74.50%	64.50%	63.00%	68.50%	81.50%

Appendix E

Thermal Management Subsystem Calculations

Hot Case, No TCS Applied Calculations

$$Q_{solar} = q_{solar} * A_{top\ face} * absorptivity = 1440 * .8625 * 0.3 = 372.6\ W \quad (2)$$

$$Q_{internal} = 1352.001\ W \text{ (calculated from electrical)} \quad (3)$$

$$Q_{rad-space} = \epsilon * \sigma * A_{top\ face} * (T_1^4 - T_2^4) = .4 * 5.67 * 10^{-8} * .8625 * (303^4 - 3^4) = 164.88\ W \quad (4)$$

$$Q_{rad-space/surface} = 2(\epsilon * \sigma * ((1/2) * A * (T_1^4 - T_{space}^4)) + \epsilon * \sigma * ((1/2) * A * (T_1^4 - T_2^4)))$$

$$Q_{rad-space/surface} = - 576.66\ W \quad (5)$$

$$Q_{rad-surface} = \epsilon * \sigma * A_{bottom\ face} * (T_1^4 - T_2^4) \\ = .4 * 5.67 * 10^{-8} * .8625 * (303^4 - 481^4) = - 882.204\ W \quad (6)$$

$$Q_{in} = Q_{solar} + Q_{internal} - Q_{rad\ space-surface} - Q_{rad-surface} = 3183.46\ W \quad (7)$$

$$Q_{out} = Q_{rad\ space} = 164.88\ W \quad (8)$$

$$Q_{net} = Q_{in} - Q_{out} = 3183.46\ W - 164.88\ W = 3018.58\ W \quad (9)$$

$$e^* = \left(\frac{2n}{e_{mylar}} - n - 1 + \frac{1}{e_1} + \frac{1}{e_2} \right)^{-1} \quad (10)$$

Hot Case, First Iteration of TCS Applied Calculations

$$Q_{solar, new} = q_{solar} * A_{top\ face} * absorptivity = 1440 * .8625 * 0.9 = 111.78\ W \quad (11)$$

$$Q_{rad-space, new} = \epsilon * \sigma * A_{top\ face} * (T_1^4 - T_2^4) = .9 * 5.67 * 10^{-8} * .8625 * (303^4 - 3^4) = 370.98\ W \quad (12)$$

$$\begin{aligned} Q_{rad-space/surface, new} &= 2(\epsilon * \sigma * ((1/2) * A * (T_1^4 - T_{space}^4)) + \epsilon * \sigma * ((1/2) * A * (T_1^4 - T_2^4))) \\ &= 2.88\ W \end{aligned} \quad (13)$$

$$\begin{aligned} Q_{rad-surface, new} &= \epsilon * \sigma * A_{bottom\ face} * (T_1^4 - T_2^4) \\ &= .005 * 5.67 * 10^{-8} * .8625 * (303^4 - 481^4) = -11.028\ W \end{aligned} \quad (14)$$

$$Q_{in} = Q_{solar} + Q_{internal} - Q_{rad\ space-surface} - Q_{rad-surface} = 1474.81\ W \quad (15)$$

$$Q_{out} = Q_{rad\ space} = 359.45\ W \quad (16)$$

$$Q_{net} = Q_{in} - Q_{out} = 1474.81\ W - 359.45\ W = 1115.36\ W \quad (17)$$

Hot Case, Final Iteration of TCS Applied Calculations

$$Q_{radiator} = \epsilon * \sigma * A_{bottom\ face} * (T_1^4 - T_2^4) = .87 * (5.67 * 10^{-8}) * .8625 * (303^4 - 3^4) = 268.6\ W \quad (18)$$

$$Q_{internal, new} = Q_{internal, new} - Q_{LHP} = 1352.001\ W - 846.76\ W = 505.241\ W \quad (19)$$

$$\begin{aligned} Q_{rad-space} &= \epsilon * \sigma * A_{top\ face} * (T_1^4 - T_2^4) + Q_{radiator} \\ &= 0.9 * 5.67 * 10^{-8} * .8625 * (303^4 - 3^4) = 639.5\ W \end{aligned} \quad (20)$$

Thus, the final total heat transfer of the rover in the hot case can be denoted as $Q_{net} = Q_{in, new} - Q_{out, new}$, where :

$$Q_{in, new} = Q_{solar, new} + Q_{internal, new} - Q_{rad\ space-surface, new} - Q_{rad-surface, new} = 628.05W \quad (21)$$

$$Q_{out, new} = Q_{rad\ space} = 628.05W \quad (22)$$

$$Q_{net} = Q_{in, new} - Q_{out, new} = 628.05\ W - 628.05W = 0\ W \quad (23)$$

Cold Case, TCS Applied Calculations

$$Q_{solar, new} = 0\ W \text{ (No sun)} \quad (24)$$

$$Q_{internal, new} = Q_{internal, new} - Q_{LHP} = 1352.001\ W - 846.76\ W = 505.241W \quad (25)$$

$$Q_{rad-space} = \epsilon * \sigma * A_{top\ face} * (T_1^4 - T_2^4) + Q_{rad} = .9 * 5.67 * 10^{-8} * .8625 * (303^4 - 3^4)$$

$$= 639.5\ W \quad (26)$$

$$Q_{rad-space/surface, new} = 2(\epsilon * \sigma * ((1/2) * A * (T_1^4 - T_{space}^4)) + \epsilon * \sigma * ((1/2) * A * (T_1^4 - T_2^4)))$$

$$Q_{rad-space/surface, new} = 0.89\ W \quad (27)$$

$$Q_{rad-surface, new} = \epsilon * \sigma * A_{bottom\ face} * (T_1^4 - T_2^4)$$

$$= .005 * 5.67 * 10^{-8} * .8625 * (303^4 - 140^4) = 1.967\ W \quad (28)$$

Area of Heater Calculations:

$$A_{electrical\ heater} = Q_{net} / \text{Power Density} = 138.32 / 3.1 = 43.4386228\ cm^2$$

Mass Calculations for MLI

Surface Rover:

Outer Layer: Kapton

$$\text{Surface Area (SA)} = 2(115 * 75 + 115 * 25 + 75 * 25) = 26750 \text{ cm}^2$$

Thickness of Kapton = .0127 cm

Weight of Kapton = .019 g/cm²

For 5 mil thickness: $\text{Mass} = \text{SA} * \text{thickness} * \text{weight}$

$$= 26750 * .019 * .0127 = 6 \text{ grams}$$

Inner Layer: Double Aluminized Kapton

Thickness of Kapton = .0025 mm (1 mil)

Weight of Kapton = .0036 g/cm²

For 5 mil thickness: $\text{Mass} = \text{SA} * \text{thickness} * \text{weight}$

$$= 26750 * .025 * .0036 = 2.405 \text{ grams}$$

Total Mass for Surface Rover: 8.86 grams.

Subsurface Rover:

Outer Layer: Kapton

$$\text{Surface Area (SA)} = 1807525.3444 \text{ mm}^2 = 18075.253444 \text{ cm}^2$$

Thickness of Kapton = .0127 cm

Weight of Kapton = .019 g/cm²

For 5 mil thickness: $\text{Mass} = \text{SA} * \text{thickness} * \text{weight}$

$$= 18075.253444 * .019 * .0127 = 4.36155 \text{ grams}$$

Inner Layer: Double Aluminized Kapton

Thickness of Kapton = .0076 mm (0.3 mil)

Weight of Kapton = .0011 g/cm²

For 5 mil thickness: $\text{Mass} = \text{SA} * \text{thickness} * \text{weight}$

$$= 18075.253444 * .0076 * .0011 = 0.151109 \text{ grams}$$

Total Mass for Subsurface Rover: 4.5126677 grams.

Thermal Coating Mass Calculations

Surface Rover:

$$\text{Surface Area (SA)} = 2(115 * 75 + 115 * 25 + 75 * 25) = 26750 \text{ cm}^2$$

$$\text{Volume} = (\text{SA}) * (\text{thickness})$$

- Typical coating assumes 7-13 mils of thickness
- Assume 7 mil
- Since AZW/LA-II is a ceramic coating⁸⁹, density is between 2 – 6 g/cm^2
 - Assume 3 g/cm^2

$$\text{For 7 mil thickness: Mass} = SA * \text{thickness} * \text{density}$$

$$= 26750 * .007 * .0254 * 3 = 14.26845 \text{ grams}$$

Subsurface Rover:

$$\text{Surface Area (SA)} = 1807525.3444 \text{ mm}^2 = 18075.253444 \text{ cm}^2$$

$$\text{Volume} = (\text{SA}) * (\text{thickness})$$

- Typical coating assumes 7-13 mils of thickness
- Assume 7 mil
- Density of white paint is 1.1 g/cm^2

$$\text{For 7 mil thickness: Mass} = SA * \text{thickness} * \text{density}$$

$$= 26750 * .007 * .0254 * 1.1 = 3.535 \text{ grams}$$

Thermal Management Subsystem Trade Studies

Appendix E Table 1: Trade Studies for the Heat Pipe Selection for Passive Heat Management

Heat Pipe Selection						
Criteria	Explanation	Grade	Weight	Copper Heat Pipes	Aluminum Heat Pipes	Loop Heat Pipes
Weight and Flexibility	Impact on overall system weight and design flexibility.	10 = high, 5 = medium 1 = low 0 = Fail	20%	6	8	7
Wick Compatibility	A variety of coolants are available, each with specific suitability based on operating temperatures. Different coolants function optimally within certain temperature ranges, as the wick material and fluid may exhibit varying thermal properties at extreme limits.	10 = high compatibility, 5 = medium 1 = low 0 = Fail	35%	4	2	9
Operating Temperature	Different material combinations used in heat pipes are limited to specific operating temperature ranges, as the wick material and internal fluid may exhibit varying thermal properties at extreme temperatures. Factors considered in this section include thermal expansion coefficients, thermal conductivity, and materials testing reports.	10 = high, 5 = medium 1 = low 0 = Fail	30%	8	7	9

Cost	Overall cost of implementation	10 = low cost, 5 = medium 1 = high cost 0 = Fail	15%	8	9	6
		TOTALS:	100%	62.00%	57.50%	81.50%

Table 2: Trade Studies for Thermal Coating Selection for Passive Heat Management

Thermal Coating Selection						
Criteria	Explanation	Grade	Weight	White Paint	Aerogel Coating	AZW/LA-II Silicate
Reflectivity	Assessing material reflectivity is essential to limit radiation penetration and ensure efficient thermal instrument operation.	10 = high reflectivity, 5 = medium 1 = low 0 = Fail	30%	8	6	9
Durability	Resistance to abrasion and environmental degradation.	10 = high durability, 5 = medium 1 = low 0 = Fail	20%	7	8	9
Thermal Performance	Ability to manage heat through reflection, insulation, or conduction	10 = high thermal performance, 5 = medium 1 = low 0 = Fail	25%	7	9	9
Cost	Overall cost of implementation	10 = low cost	10%	9	6	2

Weight	Impact on overall system weight and design flexibility since it will cover most of the rover	10 = high weight, 5 = medium 1 = low 0 = Fail	15%	9	7	8
		TOTALS:	100%	78.00%	73.00%	81.50%

Table 3: Trade Studies for MLI Selection for Passive Heat Management

MLI Material Selection						
Criteria	Explanation	Grade	Weight	Aluminized Mylar	Aluminized Kapton	Kapton
Weight and Flexibility	Impact on overall system weight and design flexibility.	10 = high, 5 = medium 1 = low 0 = Fail	20%	9	8	8
Durability	Resistance to environmental degradation and mechanical impacts	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	9	7
Thermal Insulation	Effectiveness in minimizing radiative heat transfer	10 = high, 5 = medium 1 = low 0 = Fail	40%	8	9	9
Cost	Overall cost of implementation	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	6	7
		TOTALS:	100%	79.50%	83.50%	80.00%

Table 4: Trade studies for Radiator Material Selection for Passive Heat Management

Radiator Material Selection						
Criteria	Explanation	Grade	Weight	Flat-Plate Radiator	Deployable Radiators	Variable Emittance Radiators
Thermal Efficiency	Impact on overall system weight and design flexibility.	10 = very lightweight	25 %	6	8	8
Heat Dissipation	Effectiveness in maximizing radiative heat transfer	10 = high durability 5 = medium 1 = low 0 = Fail	20 %	7	9	8
Durability	Resistance to environmental degradation and mechanical stress.	10 = high, 5 = medium 1 = low 0 = Fail	20 %	9	8	7
Cost	Overall cost of implementation	10 = low cost	15 %	9	7	8
Coolant compatibility	Various coolants are available, each suited to specific temperature ranges, as wick materials and fluids vary in thermal properties at extreme limits. Key factors include thermal expansion, conductivity, and materials testing reports.	10 = highly compatible 5 = medium 1 = low 0 = Fail	20 %	7	8	9
		TOTALS:	100 %	74.50%	80.50%	80.00%

Table 5: Trade Studies for Resistive Heater Selection for Active Heat Management

Resistive Heater Selection						
Criteria	Explanation	Grade	Weight	Resistive Heaters	PTC Heaters	Ceramic Heaters
Temperature Control	Ability to maintain precise temperature, ensuring components operate within optimal ranges. This is crucial for preventing overheating or undercooling in sensitive systems.	10 = highly precise 5 = medium 1 = low 0 = Fail	25%	8	7	8
Energy Efficiency	Power consumption relative to performance, indicating how effectively the heater converts energy into heat. Efficient heaters reduce power usage and extend mission duration.	10 = very efficient 5 = medium 1 = low 0 = Fail	20%	7	8	9

Durability	Resistance to environmental and mechanical impacts, ensuring long-term reliability in harsh conditions. Durable heaters minimize maintenance and replacement needs.	10 = very durable 5 = medium 1 = low 0 = Fail	20%	8	9	8
Weight Impact	Influence on overall system weight, affecting payload capacity and fuel efficiency. Lightweight designs are preferred for space applications to reduce launch costs.	10 = minimal impact 5 = medium 1 = low 0 = Fail	15%	9	7	8
Cost	Overall cost of implementation, including manufacturing and operational expenses. Cost-effective solutions are essential for budget-constrained missions.	10 = low cost 5 = medium 1 = low 0 = Fail	20%	9	6	7
TOTALS:			100%	81.50%	74.00%	80.00%

Table 6: Trade Studies for Active Cooling

Active Cooling Selection						
Criteria	Explanation	Grade	Weight	Mechanically Pumped Fluid Loops	Vapor Compression Systems	Thermoelectric Coolers
Temperature Control	Ability to maintain precise temperature, ensuring components operate within optimal ranges. This is crucial for preventing overheating or undercooling in sensitive systems.	10 = highly precise	25%	9	8	9
Energy Efficiency	Power consumption relative to performance, indicating how effectively the heater converts energy into heat. Efficient heaters reduce power usage and extend mission duration.	10 = very efficient	20%	8	6	7
Durability	Resistance to environmental and mechanical impacts, ensuring long-term reliability in harsh conditions. Durable heaters minimize maintenance and replacement needs.	10 = very durable	20%	9	8	8

Weight Impact	Influence on overall system weight, affecting payload capacity and fuel efficiency. Lightweight designs are preferred for space applications to reduce launch costs.	10 = minimal impact	25%	6	7	6
Cost	Overall cost of implementation, including manufacturing and operational expenses. Cost-effective solutions are essential for budget-constrained missions.	10 = low cost	10%	7	6	7
		TOTALS:	100%	78.50%	71.50%	74.50%

Testing Facility Costs				
Test	Testing details [4]	Testing requirements	Test Duration	Cost
Thermal Vacuum (TVAC)	TVAC testing simulates a spacelike environment by removing air and pressure in an enclosed chamber. The component inside then goes through cycles of very hot and very cold temperatures.	Cleanroom facility, 24/7 testing staff, fixtures, and liquid Nitrogen	Minimum time of 2 weeks and up to 3 months	All tests combined is ~30% of the overall instrument cost
Electromagnetic Interference (EMI)	Spacecraft may experience conducted and radiated EMI from onboard systems or from Electrostatic Discharge (ESD) events caused by spacecraft charging. The risk of this occurring can be determined through this testing	Cleanroom facility, 24/7 testing staff, and fixtures	Average of 1 to 2 weeks	
Vibration Testing (VIBE)	This testing ensures that the spacecraft will survive the launch vibration environment and can provide vibration response data (e.g., accelerometry) for validation and refinement of structural analysis models.	Non-cleanroom facility, full-time testing staff, and fixtures	Takes an average of 90-180 minutes while on the shake table. This does not include the setup and disassembly time which could take around 3-7 days.	
Ambient Testing	All other component testing is done throughout the entire development process.	Lab facility with cleanroom and non-cleanroom, 24/7 testing staff, equipment, and fixtures	Duration of full testing and integration phase	

Appendix F

Payload Subsystem Trade Studies

Appendix F Table 1:

Ground Penetrating Radar						
Criteria	Explanation	Grade	Weight	Lunar Penetrating Radar	Apollo Lunar Sounder System	Lunar Radar Sounder
Depth Range	INS-1.1 Depth range is how deep the LPR can measure. If the depth range is not large enough, the GPR will not be able to detect the entire roof thickness nor width of the cave because both of these will be deeper in the lunar subsurface than the GPR can penetrate.	10 = between 60 and 100 m of depth penetration 5 = can measure less than 20 or greater than 200 m in depth 1 = can measure less than 10 m or greater than 2km 0 = measures less than 5 m or greater than 5 km in depth	50%	9	2	1

Vertical Resolution	INS-1.2 Vertical resolution is the resolution of the readings. This holds importance because a resolution that is too low may lead to a roof thickness measurement that is significantly inaccurate.	10 = less than 0.5 m 5 = vertical resolution between 4 and 5 m 1 = vertical resolution between 9 and 10 m 0 = Vertical resolution greater than 10 m	30%	8	1	0
TRL	A higher TRL will give a higher chance of the instrument working as intended and thus a higher change of achieving the desired science	9 = TRL 9 5 = TRL 5 1 = TRL 1	20%	8	7	7
		TOTALS:	100%	85.00%	27.00%	19.00%

Appendix F Table 2:

Laser Altimeter						
Criteria	Explanation	Grade	Weight	REIG L VUX-1 LRion 1	Adva nced Topo graph ic Laser Altim eter Syste m (ATLA S)	Lunar Orbite r Laser Altim eter (LOL A)
Wavelength	INS-3.1 Wavelength affects the detection accuracy of mapping small details and penetrating lunar dust	10 = Meets ideal wavelength (1064 nm) 5 = Close to 1064nm but not exact 1 = Okay but different 0 = Fail	25%	10	5	5
Pulse Repetition rate	A higher rate means better mapping resolution, which is necessary for detailed terrain analysis.	10 = High rate (adjustable to 28 Hz) 5 = Moderate rate 1 = low rate 0 = insufficient	25%	10	10	5

Mass	For rover-mounted applications, lower mass is important since it lessens payload strain.	10 = Ideal for rover mounting (<5kg) 5 = Moderate rate (<10kg) 1 = Heavy 0 = Too Heavy	20%	10	1	1
Temperature and Radiation Tolerance	INS 3.2 For guaranteed long-term performance, it must withstand severe lunar temperatures and radiation.	10 = High tolerance, space tested 5 = Meets basic lunar needs, not space tested 1 = limited tolerance, not ideal for moon 0 = not ideal for lunar conditions	30%	8	10	10
		TOTALS:	100%	94.00%	69.50%	57.00%

Appendix F Table 3:

The Radiation Assessment Detector (RAD)						
Criteria	Explanation	Grade	Weight	Radiation Assessment Detector (RAD)	Anton-type 302 (Explorer 1)	Geiger Counter carried on Luna 2
Sensitivity Range	INS-4.1 This is the energy range of radiation that can be detected by the detector. This is to measure the levels of harmful radiation that are able to	10 = 0.2-1 MeV 8 = 300KeV - 9 MeV 1 = Out of Range	50%	9	8	6

	permeate through the cave ceiling.	0 = Fails				
Saturation Limit	INS-4.2 With radiation detectors it is necessary that their saturation limit be larger than most the radiation levels they will be exposed to. Otherwise the measurements will be inconclusive.	10 = 100000 CPS 5 = 50000 CPS 1 = 10000 CPS 0 = Fails	30%	9	6	6
Power Consumption	Radiation detectors require a constant stream of power when operating (Watts). It is necessary that this power draw is as small as possible to diminish its load on the batteries when in operation.	10 = 2 W 8 = 4 W 1 = 6 W 0 = 10 W	20%	8	7	7
		TOTALS:	100%	88.00%	72.00%	62.00%

Appendix F Table 4:

Spectrometer						
Criteria	Explanation	Grade	Weight	NIRV SS	Air-L USI	AVIRI S-3
Wavelength Range	INS 5.1 Wavelength of light picked up is what allows the spectrometer to see the materials in the sample. Water and carbon dioxide fall in the range of 1300-3400nm.	10 = 1300-4000nm 7 = 1600-3400nm 1 = Out of Range 0 = Fails	60%	10	7	6

Spectral resolution	Spectral resolution is required for the accuracy of measurement. The spectral resolution should be much smaller than the wavelength range.	10 = 10-50 nm 5 = 51-100 nm 1 = 101-1000nm 0 = >1000nm	20%	9	5	7
Sensitivity	Sensitivity is the smallest intensity of light that can be measured by this device. This is incredibly important especially if there are small trace amounts of water or carbon dioxide in the sample it's measuring. Measured as a ratio of the active lighting of the device.	10 = 0.1 (w/w) 7 = 0.5 (w/w) 4 = 1 (w/w) 0 = >5 (w/w)	20%	8	7	7
		TOTALS:	100%	94.00%	66.00%	64.00%

Appendix F Table 5:

IR Camera						
Criteria	Explanation	Grade	Weight	Leonardo DRS Tenu m 640	Panc am	FLIR Systems Boson Model No. 640.
Temperature Range	INS-6.3 Temperature Range is the range at which the device is able to measure the temperature. This means what is the IR wavelength that its pixels can measure. The grade is based on the Kelvin.	10 = 230-350 K 7 = 250-325 K 1 = Out of Range 0 = Fails	60%	9	7	6
Temperature Resolution	Temperature Resolution is the smallest amount of temperature variation the	10 = <= 0.05 K 5 = 0.1 K	20%	10	10	7

	camera can pickup. The grade is based on Kelvin as well.	1 = 0.5-1 K 0 = > 1 K				
TRL	A higher TRL gives the mission a greater chance of success. The grade is based on the TRL.	9 = 9 TRL 5 = 5 TRL 1 = 1 TRL	20%	7	7	6
		TOTALS:	100%	88.00%	76.00%	64.00%