Preliminary Design Review (PDR)

L'SPACE Mission Concept Academy Summer 2024

Destination: Lunar Water-Ice Strategic Science Investigation

Team #17

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August 12, 2024

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Acronym	Abbreviations
CDH	Command & Data Handling
ConOps	Concepts of Operations
DPMR	Deputy Project Manager of Resources
EPS	Electrical Power System
ISRU	In-Situ Resource Utilization
JMARS	Java Mission-planning and Analysis for Remote Sensing
L'SPACE	Lucy Student Pipeline Accelerator and Competency Enabler
MEC	Mechanical
MCR	Mission Concept Review
MR	Mission Requirements
NASA	National Aeronautics and Space Administration
Obj.	Objectives
Obs.	Observation
PAY	Payload
Phys. Par.	Physical Parameters
PSR	Permanently Shadowed Regions
Reqs.	Requirements
RGA	Residual Gas Analyzer
RTG	Radioisotope Thermoelectric Generator
SAM	Sample Analysis at Mars
SSIT	Solid Sample Intake Tube
STM	Science Traceability Matrix
TBD	To Be Determined
TBR	To Be Resolved
TCS	Thermal Control System
TRL	Technology Readiness Level
VAPoR	Volatile Analysis by Pyrolysis of Regolith
VIPER	Volatiles Investigating Polar Exploration Rover

1. Mission Definition Review

1.1. Mission Statement

The intended goal of this mission is two primary objectives. One is to determine water ice abundance in lunar regolith as a part of determining volatile components in the vicinity of and inside lunar permanently shadowed regions (PSRs). The second is to determine the isotopic variation of lunar regolith due to ancient solar and cosmic ray activity from other sources like supernovas, which may have caused accretion of various volatiles like nitrogen and sulfur. For water ice, the mission will gather data like concentration and depth on volatiles in lunar regolith in the form of water ice compounds and other signs of water ice formation such as water weathering. For isotopic measurements, the mission will gather data on solar-affected volatiles in the regolith like nitrogen isotope content and sulfur accretion. These datasets will be acquired via rover instruments and payload collection systems deployed from the relevant orbiter/lander system for the manned Artemis III mission. Water ice content will help NASA and other lunar expeditions determine the presence and content of critical water supplies in PSRs available for future in-situ resource utilization (ISRU) capabilities for future lunar development. It will also contribute to the scientific knowledge of previous lunar history and planetary development through geologic history and analysis. Isotopic analysis in the regolith will contribute towards knowledge of the history of ancient solar activity through variations in the relevant isotopes chronologically through the regolith, furthering scientific understanding of the Sun’s behaviors.

1.2. Science Traceability Matrix

The Science Traceability Matrix further outlines the Scientific Objectives of the overall Mission Goals. The first Mission Goal is determining the water ice abundance in lunar regolith within and around Permanently Shadowed Regions (PSRs). The Scientific Objectives of this Mission Goal are to determine concentration of water ice present in the lunar regolith and to determine the depth of water ice present in the lunar regolith to determine feasibility of use of water ice. Addressing these two goals will determine both the presence and amount of water ice in PSRs, to determine feasibility for use in deriving oxygen. The Scientific Objectives will be measured through the identification of the concentration of water ice molecules in a 0.5 cubic meter volume, which will be observed through spectral readings within the 300-900 nm range. Additionally, the depth of water ice samples will be measured in the range of ten centimeters to one meter. The second Mission Goal is to investigate isotopic variations in lunar regolith to understand ancient solar and cosmic ray activity, which will be framed through the science objectives of determining whether solar activity has affected isotope variation in the lunar regolith and determining the extent of helium deposits in the lunar regolith. To determine whether solar activity has impacted lunar deposits, spectral analysis will be completed in the 100-500 nm range to determine if deposits of isotopes Carbon 13, 14, 15, Nitrogen 14, 15, and Sulfur 32, 24 are present in the lunar regolith. The presence of Helium-3 is not only indicative of solar activity on the Moon, but also poses an interesting opportunity to develop energy on the moon through nuclear fusion. PSRs may be particularly rich in the isotope Helium-3 due to extremely low temperatures. The presence of Helium-3 will be measured through spectroscopy at the 0.42-3.0 μm range. The objectives within the Science Traceability Matrix are key to guiding the mission direction and Scientific Objectives, while adhering to stakeholder goals of determining water ice and isotopic deposits in PSRs on the Moon.

<table>
<tr><th rowspan="2">Science Goals</th><th rowspan="2">Science Objectives</th><th colspan="2">Science Measurement Requirements</th><th rowspan="2" colspan="2">Instrument Performance Requirements</th><th rowspan="2">Predicted Instrument Performance</th><th rowspan="2">Instrument</th><th rowspan="2">Mission Requirements</th></tr>
<tr><th>Physical Parameters</th><th>Observables</th></tr>
<tr><td rowspan="6">Determine the water ice abundance in lunar regolith within and around Permanently Shadowed Regions (PSRs)</td><td rowspan="3">Determine concentration of water ice present in the lunar regolith.</td><td rowspan="3">Identify water ice molecules in a 0.5 cubic meter volume.</td><td rowspan="3">Collect absorbance spectra of solid H2O in the 300-900 nm range.</td><td>Mass Range:</td><td>1-1000 amu</td><td>1 - 1050 amu</td><td rowspan="3">VAPoR Flight System TOF-MS Mass Spectrometer</td><td rowspan="5">The system shall determine water ice abundance in the lunar regolith.</td></tr>
<tr><td>Sensitivity:</td><td>3 x 10^-4 (counts/second)/ (particle/cc)</td><td>3 x 10^-4 (counts/second)/ (particle/cc)</td></tr>
<tr><td>Spatial Resolution :</td><td>600-1000 nm</td><td>300-1000 nm</td></tr>
<tr><td rowspan="3">Determine the depth of water ice present in the lunar regolith to determine feasibility of use of water ice.</td><td rowspan="3">Identify maximum depth of present water ice.</td><td rowspan="3">Detects absorbance spectra in depth samples in the 300-900 mn collected every 10 cm until 1 m.</td><td>Mass Range:</td><td>1-300 amu</td><td>1-350 amu</td><td rowspan="3">VAPoR Flight System Residual Gas Analyzer</td></tr>
<tr><td>Pressure:</td><td>~10^-5 to 10^-8 torr</td><td>~10^-5 to 10^-8 torr</td></tr>
<tr><td>Sensitivity:</td><td>4 x 10^-2 (counts/second)/ (particle/cc)</td><td>4 x 10^-2 (counts/second)/ (particle/cc)</td><td>The system shall gather water ice compounds and formations in the lunar regolith.</td></tr>
<tr><td>Investigate isotopic variations in lunar regolith</td><td>Determine if solar activity has affected isotope</td><td>Identify deposits of Carbon 13, 14, 15,</td><td>Collect absorbance spectra of carbon,</td><td>Mass Range:</td><td>1-300 amu</td><td>1-350 amu</td><td>VAPoR Flight System Residual Gas Analyzer</td><td>The system shall gather water ice compounds and formations in the</td></tr>
</table>

to understand ancient solar and cosmic ray activity	variation in the lunar regolith	Nitrogen 14, 15, Sulfur 32, 34.	nitrogen, and sulfur isotopes deposited by solar wind in the 100-500 nm range.	Pressure:	~10^-5 to 10^-8 torr	~10^-5 to 10^-8 torr		lunar regolith.
				Sensitivity:	4 x 10^-2 (counts/second)/ (particle/cc)	4 x 10^-2 (counts/second)/ (particle/cc)		
	Determine the extent of helium deposits in the lunar regolith.	Identify deposits of Helium-3 in lunar regolith within PSRs.	Detects the presence of He-3 isotopes in the 0.42-3.0 μm range.	Mass Range:	1 - 1000 amu	1 - 1050 amu	VAPoR Flight System TOF-MS Mass Spectrometer	The system shall determine the isotopic variation of lunar regolith.
				Sensitivity:	3 x 10^-4 (counts/second)/ (particle/cc)	3 x 10^-4 (counts/second)/ (particle/cc)		
				Spatial Resolution:	600-1000 nm	300 - 1000 nm		

Table 1.2.1: Science Traceability Matrix for MCA Team #17 Mission

The table above demonstrates the specific science goals, objectives, measurements, and instruments described within the Science Traceability Matrix. It goes into detail about instrument performance and expected measured outcome of the spacecraft's scientific measurements.

1.3 Summary of Mission Location

Shackleton Crater, situated near the Moon's south pole, is a prime target for the lunar surface mission due to its unique scientific and strategic value. Named after Antarctic explorer Ernest Shackleton, this crater likely harbors significant water ice deposits in its permanently shadowed regions, as indicated by data from the Lunar Reconnaissance Orbiter and the Lunar Crater Observation and Sensing Satellite. The presence of water ice is crucial for understanding its distribution and accessibility, offering insights into lunar geology and providing a potential resource for future lunar habitation including the production of: water, oxygen and even fuel ignitor.

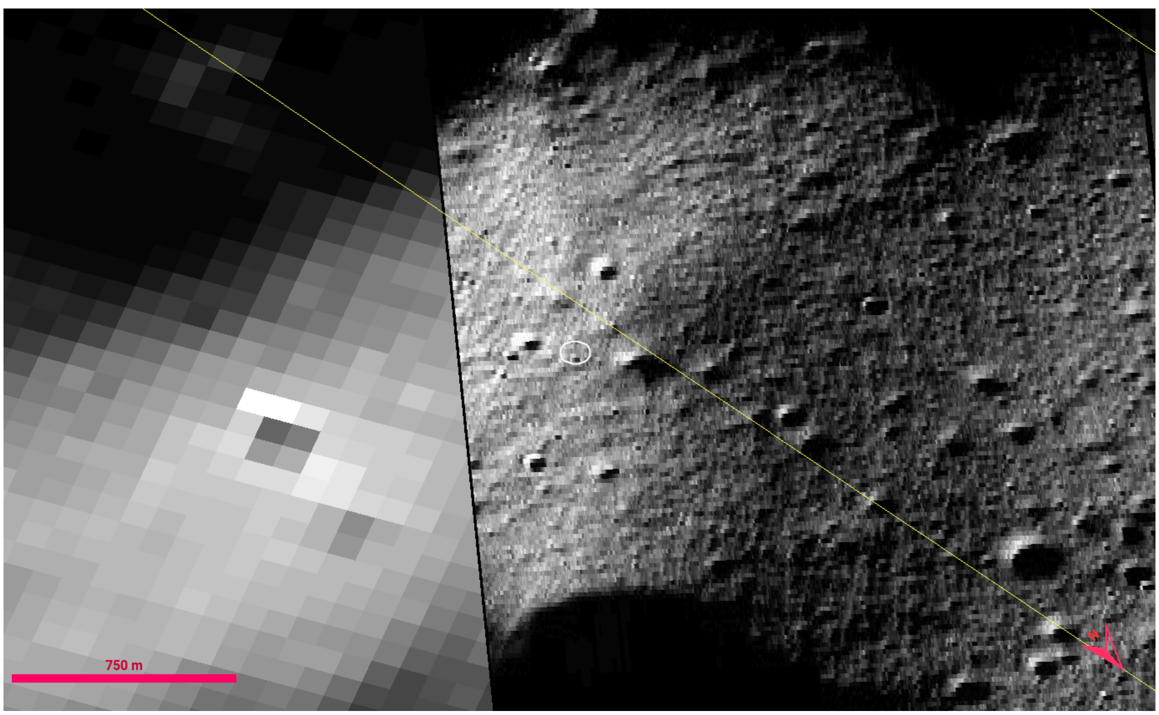
Scientifically, Shackleton's structure offers valuable information about the Moon's geological history. By studying the composition and stratigraphy of the regolith and underlying bedrock, we can learn about the processes that have shaped the lunar surface over billions of years. The potential for preserving microbial life in these shadowed lunar regions adds an astrobiological interest as well, enhancing our understanding of life's resilience in extreme environments and informing the search for life on other celestial bodies.

Strategically, the crater's rim receives nearly continuous sunlight, making it ideal for establishing solar power arrays. This constant availability of solar energy is critical for supporting long-term surface operations and potentially human habitats, ensuring a sustainable energy source. The stable temperatures in the permanently shadowed areas of Shackleton Crater are advantageous for preserving volatiles like water ice and reducing thermal stress on mission equipment, thereby increasing the longevity and reliability of the mission.

Shackleton's location near the lunar south pole provides extended periods of daylight, facilitating surface operations and energy management. The south pole's unique lighting conditions are beneficial for future exploration missions, offering logistical advantages for establishing a base of operations. Shackleton Crater's strategic position could serve as a gateway for further exploration of the Moon's polar regions and beyond.

The mission objectives would focus on detecting and analyzing water ice, conducting detailed geological surveys, and monitoring environmental conditions to assess the suitability for future human missions. Using ground-penetrating radar, spectrometers, and drilling equipment, the mission would aim to locate, extract, and study water ice deposits, providing critical data for future resource utilization. Detailed geological mapping would help understand the crater's formation and evolution, identifying regions of scientific interest. Environmental monitoring would measure temperature variations, radiation levels, and other parameters to ensure the safety and success of future lunar operations.

The JMARS images of the landing site are pictured below in Figure 1.3.1. The landing site has a radius of 50 meters and is about 3.7 kilometers from the permanently shadowed region in the landing region, Peak Near Shackleton. The exact location of the landing site is -88.811°N, 128.585°E on the south pole of the moon. This landing site has a maximum slope of 13.987 degrees, which meets the slope requirement for the site. Furthermore, the distance from the permanently shadowed region is less than 10 kilometers which will allow for the vehicle to traverse to the science site.



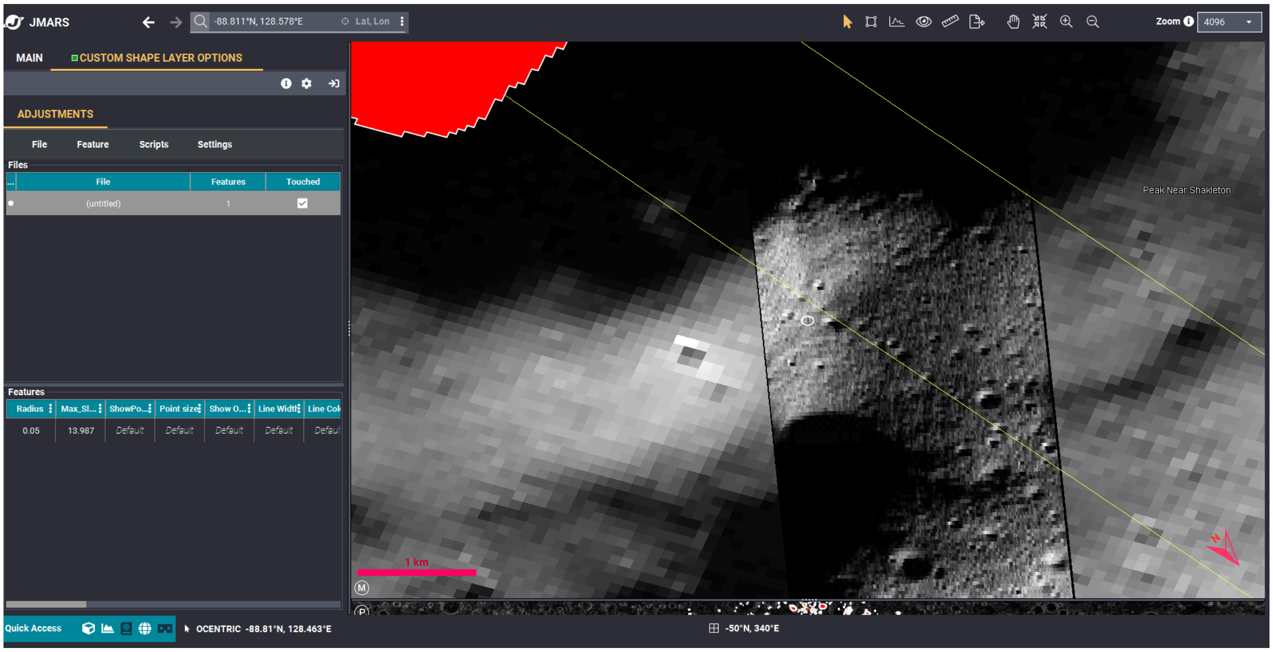


Figure 1.3.1: JMARS images of the landing site in the region the Peak Near Shackleton

1.4 Mission Requirements

The customer constraints for the system require that the system remains under a budget of $225M, and is ready for launch by September 1st, 2028. The system must be confined to a volume of 1.5m x 1.5m x 1.5m before deployment, must not exceed a mass of 85kg, and cannot use a Radioisotope Thermoelectric Generator (RTG). The entire system cannot contain more than 5g of radioactive material.

For mission success, the system must additionally be able to determine water ice abundance, isotopic variation, and volatile components near the permanently shadowed regions (PSRs). The system cannot contain more than 2 science instruments and must be able to communicate with the spacecraft orbiting the moon in a circular polar orbit at 100km.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mission Reqs							
MR-1	The system shall determine water ice abundance in the lunar regolith.	Provided by the Mission Document	Customer	ESP-2, CDH-2	Demonstration	Payload	Met
MR-2	The system shall determine the isotopic variation of lunar regolith.	Provided by the Mission Document	Customer	ESP-2, CDH-2	Demonstration	Payload	Met
MR-3	The system shall gather water ice compounds and formations in the lunar regolith.	Provided by the Mission Document	Customer	ESP-2, CDH-2	Demonstration	Payload	Met

MR-4	The system shall determine volatile components in and around lunar permanently shadowed regions(PSRs).	Provided by the Mission Document	Customer	TCS-1, ESP-2, CDH-2	Demonstration	Payload	Met
MR-5	The mission shall not exceed a cost of $225M, not including launch or cruise costs.	Provided by the Mission Document	Customer		Inspection	Payload	Met
MR-6	The system shall be ready for launch by September 1st, 2028.	Provided by the Mission Document	Customer		Inspection	Payload	Met
Mechanical Reqs							
MEC-1	The system shall be confined to a volume of 1.5m x 1.5m x 1.5m cubic feet before deployment.	Provided by the Mission Document	Customer		Inspection	All	Met
MEC-2	The system shall not exceed a total mass of 85kg.	Provided by the Mission Document	Customer		Inspection	All	Met
MEC-3	The system shall not contain more than 5g of radioactive material.	Provided by the mission Document	Customer		Inspection	All	Met

Electrical Power System (EPS) Reqs							
EPS-1	The system shall not contain a Radioisotope Thermoelectric Generator (RTG) or derivative of such.	Provided by the Mission Document	Customer		Inspection	Payload	Met
ESP-2	The system shall power all necessary components for mission completion.	The system will require power to complete mission requirements	MR-1, MR-2, MR-3, MR-4		Demonstration	All	Not Met
Payload Reqs							
PAY-1	The system shall not contain more than 2 science instruments.	Provided by the Mission Document	Customer		Inspection	Payload	Met
Command & Data Handling Reqs (CDH)							
CDH-1	The system communicates directly with the designated orbiting spacecraft.	Provided by the mission document	Customer	CDH-1.1	Test	Communications	Met

CDH-1.1	The system must transmit communications to a distance necessary to reach the orbiting spacecraft in a circular polar orbit at 100km.	Allows communication with orbiting spacecraft	CDH-1		Test	Communications	Not Met
Thermal Control System Reqs (TCS)							
TCS-1	System shall regulate itself to an appropriate temperature range for functionality of all components.	Temperatures in shadowed regions of the moon can range from 88-100K	MR-4		Analysis	Thermal Control System	Not Met

Table 1.4.1: Mission Requirements Overview and Verification Status for Lunar Exploration Project

1.5 Concept of Operations

The key tasks to be included in the mission are the retrieval and analysis of samples of the lunar regolith. The primary phases of the mission are surface deployment, traversal, science analysis and data uplink.

In the initial surface deployment of the rover, the payload system will need to run an instrumentation check to ensure that all components are working. Communications and telemetry will also be checked to assure data collected can be relayed to the orbiting satellite.

During traversal, the components of the mechanical subsystem will be used to navigate to the edge of the PSR containing the science site, where the rover will stop and the electrical subsystem will complete functions necessary to ensure there is adequate power to the rover. The solar panels will generate power to fill the batteries before entering the PSR. Once the batteries are fully charged, the rover will continue traversing to the science site. It is estimated to take about 9 hrs to fully charge the batteries using solar while still maintaining systems from freezing. The rover would travel to site 1 at an average speed of 3 km/day for about 17 km. Taking about 6 days for the transverse process. It will send a telemetry signal every 2 hours to the orbiting satellite to actively communicate with the ground ops.

Once the rover arrives at the science site, the payload subsystem will collect samples and analyze them to determine the isotopic variation of the lunar regolith as well as the concentration and depth of volatiles in lunar regolith as well as signs of water ice formation such as water weathering. The TRIDENT drill will be used to dig samples from the lunar regolith. The Cold Operable Lunar Deployable (COLD) arm will be used to place samples into the VAPOR system’s Solid Sample Intake Tube. From the Solid Sample Intake Tube, samples are placed into six pyrolysis crucible ovens and heated to 1400 degrees Celsius to release any noble gasses within the samples, which are then analyzed by the VAPOR system.

Once the samples have been collected and analyzed, the CDH subsystem will transmit the collected data to the orbiting satellite, which will then send the collected data back to Earth. It should take about 10 hours for the sample collection process. The rover will repeat transverse, science and data uplink for the duration of the mission since there is only enough power to go from one of the sites to the rim of the PSR and back. It will repeat the process for 2 other sites prior to ending the mission. The mission will take 24 earth days to complete.

Throughout the various phases of the mission, the thermal subsystem will regulate the temperature of the rover to ensure that all components remain within functional range.

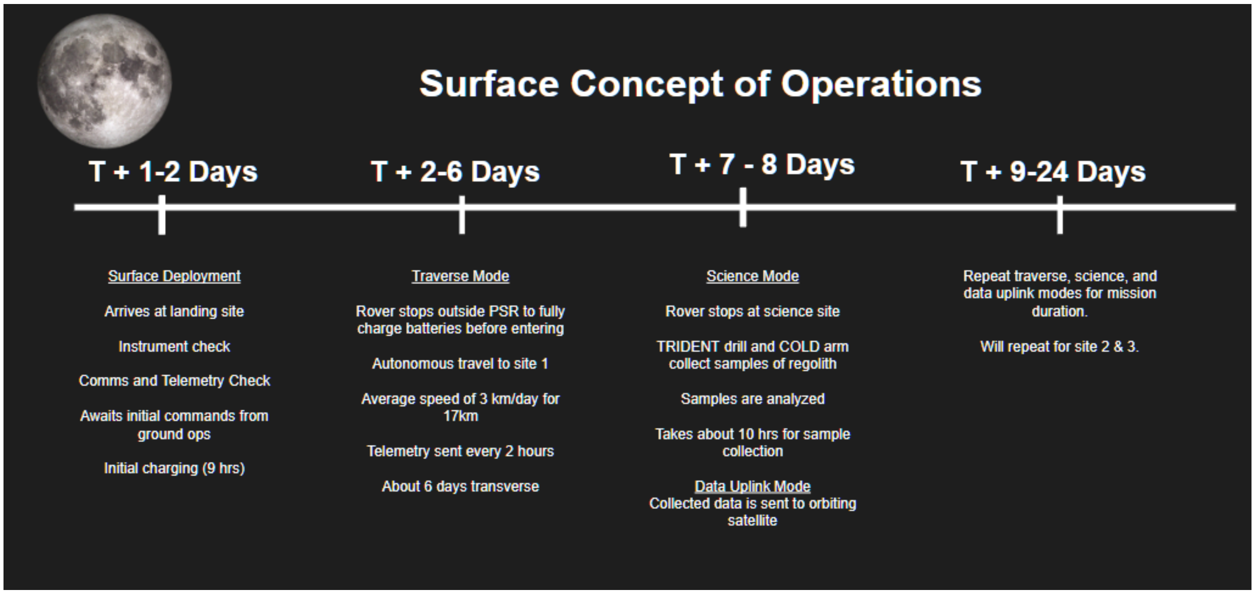
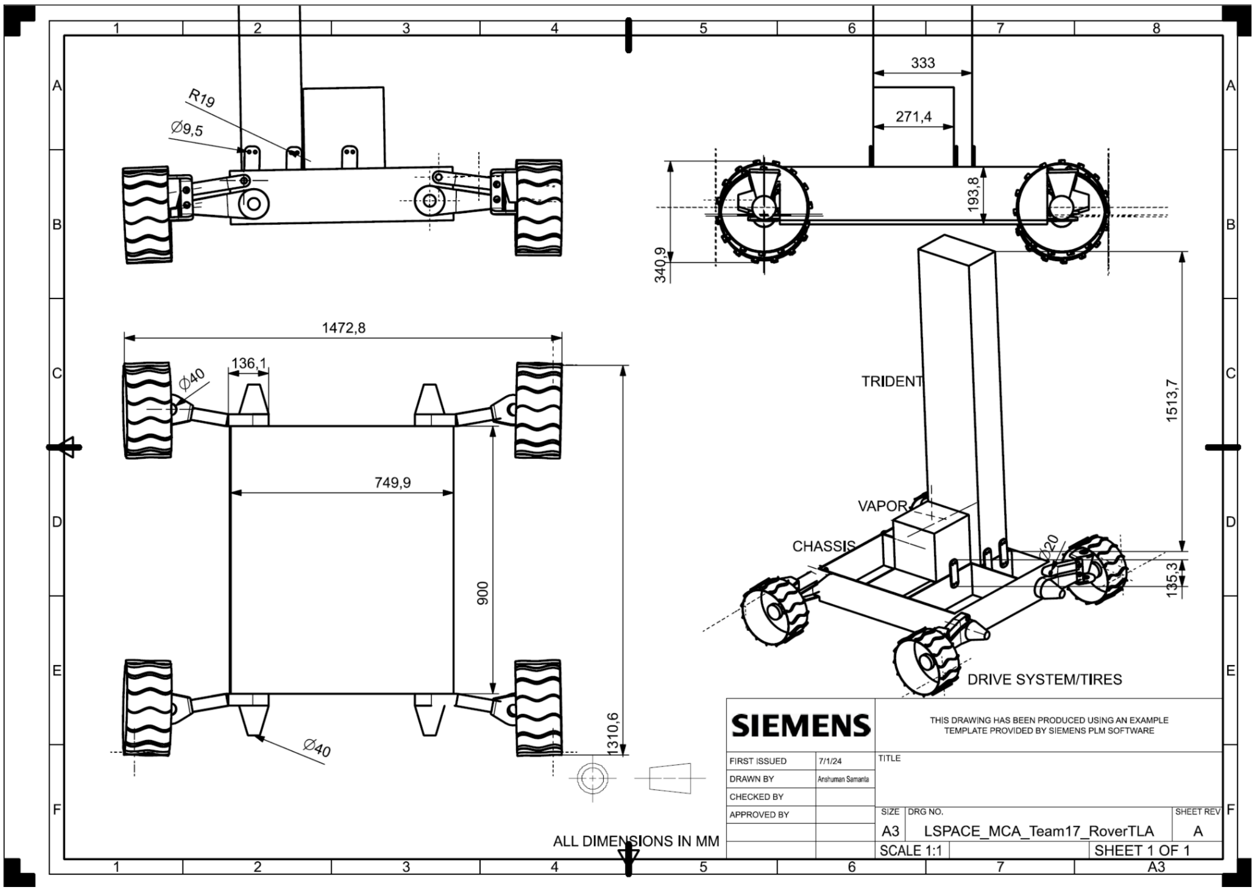


Figure 1.5.1 Mission ConOps Graphic showcasing the life cycle of the mission on the surface on the Moon

1.6 Vehicle Design Summary



Subsystem	Mass	Volume	Max Power Draw
Mechanical Subsystem	38.928 kg	1.472 x 1.310 x 0.341 m	50W
Power Subsystem	151.16 kg	0.0254 m^3	2383.78W
CDH Subsystem	1,860.5g	0.12m^2	230 W
Thermal Subsystem	1,703.6 g	1443 in^3	11.3 W
Payload Subsystem	35 kg	VAPoR: 200 cm^3 TRIDENT: 20.6cm x 33.3cm x 168cm	160W

1.7 Science Instrumentation Summary

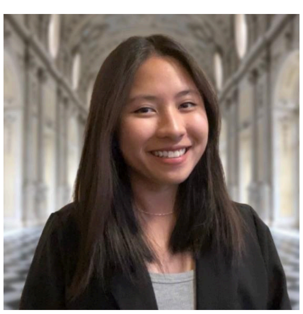
The spacecraft will be equipped with the VAPoR flight system, or the Volatile Analysis by Pyrolysis of Regolith in situ instrument. The purpose of the VAPoR system is to detect water and noble gasses in lunar regolith. As such, the VAPoR system simultaneously addresses both science goals; determining the water ice abundance in lunar regolith within and around Permanently Shadowed Regions, and investigating isotopic variations in lunar regolith to understand ancient cosmic and solar ray activity. VAPoR is a modified version of the Sample Analysis at Mars (SAM) instrument. While the SAM instrument weighs 40 kilograms and requires between 100-200 Watts of power, the VAPoR flight unit will weigh between 10 and 15 kilograms, and only require 50 to 60 Watts of power to complete testing. It is also much smaller, at about 20 dm^3. It is important to note that the VAPor flight unit is still being developed and the current breadboard has similar function to the SAM instrument. However, the VAPoR system makes lunar volatile sampling very effective. VAPoR uses six pyrolysis crucible ovens to heat samples up to 1400 degrees Celsius, allowing for the analysis of noble gasses. Noble gasses can only be released at temperatures above 1200 degrees Celsius. The primary sample collection focus of vapor is to detect and analyze Carbon, Hydrogen, Oxygen, Nitrogen, and Sulfur. This aligns with the physical parameters within the scientific measurement requirements of identifying deposits of Carbon 13, 14, 15, Nitrogen 14 and 15, and Sulfur 32 and 34.

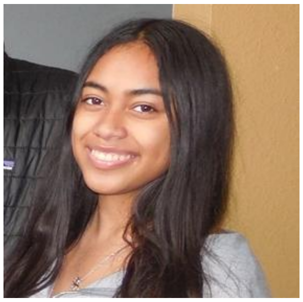
VAPoR is also capable of measuring H_2O released from lunar regolith, which fulfills the scientific measurement requirement of identifying water ice molecules. By using drilling sample collection methods, the depth of water ice will be able to be measured up to one meter, which will deliver insights about the abundance of water ice in Permanently Shadowed Regions. VAPoR is also capable of testing Helium-3 and Helium-4 isotopes. The analysis of Helium-3 is important because it is indicative of solar activity on the moon, and poses an interesting opportunity to develop energy on the moon through nuclear fusion. Additionally, the Residual Gas Analyzer is able to measure the pressure of different glasses, and categorize them accordingly. The payload subsystem will also be equipped with a COLDArm scoop to transfer samples to the VAPoR system's intake tube, as well as a modified TRIDENT drill that will unearth samples from the lunar regolith. It is ultimately the best choice of instrumentation for the scientific goals of determining water ice content in PSRs and understanding solar ray activity.

1.8 Programmatic Summary

1.8.1 Team Introduction

Team #17 is a team with diverse backgrounds in different industries and hands-on experiences. The Project Manager, a senior year Mechanical Engineering undergraduate student has prior work experience with risk management, finance and scheduling in the finance field. Ella, the chief scientist of the team, currently attends University of Washington. She has prior experience with team management, mechanical engineering and CAD design. Leeanna currently attending Cornell University has prior experience with risk management and budgeting for large-scale projects. Catherine is currently attending University of Texas and has experience with team management and robotics. This makes up the leadership for team #17 just to name a few. The below table goes into further detail for the rest of the team who went out of their way to collaborate on this mission proposal. Everyone took initiative and personal accountability throughout the making of the PDR.

Team Member Photo	Name	University	Location	Relevant Experience
	Ruth Laboy	ECPI University	Remote	Ruth has prior work experience with risk management, finance, scheduling, Microsoft and supervising a team.
	Ella Davis	University of Washington	Seattle, WA	Ella has experience with team management, scientific research, mechanical engineering, and CAD design software.
	Leeanna Chen	Cornell University	Ithaca, NY	Leeanna has experience with risk and budget management for large-scale projects.

	Catherine Franco	University of Texas	Austin, TX	Catherine has prior experience with team management in robotics/systems engineering and software development.
	Kishan Dalal	Rutgers University	New Brunswick, NJ	Kishan has prior experience conducting research projects in various engineering fields.
	Tasnim Goni	St. John's University	New York, NY	Tasnim has prior experience in data analysis and scientific research.
	Patrick Zhang	University of Maryland, College Park	College Park, MD	Patrick has prior experience in software development.

	Yvette Courchane	Western Governors University	Remote	Yvette has prior experience in software development.
	Anshuman Samanta	Purdue University	West Lafayette, IN	Anshuman has engineering design, analysis, and test experience for aerospace applications.
	Rene Jarquin-Le	University of Michigan	Ann Arbor, MI	Rene has engineering design, technical writing, and risk and cost management experience for climate and space applications.

Table 1.8.1.1 Team Introductions

1.8.2 Team Management Overview

The team currently has a clear hierarchy with each member having two roles, which include a primary role and a secondary role. As the Project Manager, Ruth Laboy delegates, oversees, and coordinates all tasks, meetings, and resources. As the Deputy Project Manager of Resources (DPMR), Leeanna Chen ensures that costs are allocated appropriately, timelines for mission phases are realistic, and risks are being addressed. In addition to working closely with the Project Manager, the DPMR is responsible for all operations within the programmatic subteam. As the Lead Systems Engineer, Catherine Franco approves all technical decisions and delegates tasks to her Mechanical Engineering, Electrical Engineering, Thermal Engineering, and Computer Hardware Engineering teams. The Lead Systems Engineer works closely with Ella Davis, the Chief Scientist, to select instruments and landing sites that satisfy the mission objectives. The Chief Scientist identifies satisfactory landing sites and appropriate instruments for the mission.

The team is equipped to address the mission given the members' diverse experiences, knowledge, and skill sets in engineering, science, and logistics. Everyone collaborates to deliver their tasks by coordinating with their sub teams and team leaders. Decision-making and coordination are crucial across all subteams. The team's decision-making process has become more structured and clear. For example, the team's onboarding and organizational decisions are made by the team leaders during their weekly meetings. All team leaders finalize the decisions before coordinating with their respective subteams.

Some issues that arose in the team coordination in completing the SRR document included communication and time management. While tasks were delegated to each subteam, there was, at times, little conversation between team members on each task's progress and completion. As a result, some sections in the submitted document lacked sufficient or crucial information. Learning from these weak points, Project Manager Ruth and Lead Systems Engineer Catherine decided to utilize a project management application, Asana, to assign due dates for future tasks, assign specific team members to each section of future documents, and track the overall progress of tasks. Through Asana, each member's involvement has been held more accountable, and the successful completion of mission documents has been ensured.

Additionally, team member Summer Mclure decided to leave the academy following the submission of the SSR document due to personal reasons. They were previously assigned to both the mechanical and thermal subteams. To address the lack of members working on the thermal subsystem, engineers from other subteams have been assigned to assist the main thermal engineers in their related tasks.

MCA Team #17

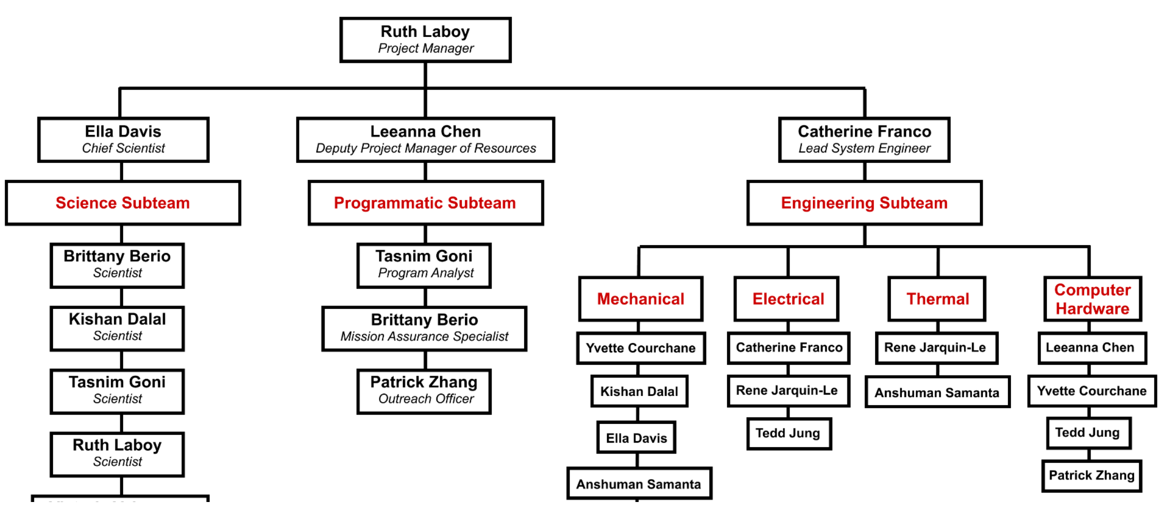


Figure 1.8.2.1 Team Organizational Graphic of Team Hierarchy Structure

1.8.3 Major Milestones Schedule

The team has broken down the major milestones for the mission. The below table has listed the start and end date for only the major milestones from phases C-F. These are the milestones that would help the team determine if we are behind or on schedule. The major timeline indicators for phase C would be the System Integration Review (SIR)(end of phase C), the Post-Launch Assessment Review (PLAR) (end of phase D), the Decommissioning Review(DR)(end of phase E) and the Final Archival of Data (end of phase F). The table below also contains the start and end date of those phases with the number of days that phase would last. Below in Figure 1.9.2.3 there is a more in depth breakdown of the tasks from phases C-F. The team referred to NASA's Systems Engineering Handbook to get more detail on the tasks and some of the major milestones that would significantly impact the mission. The Nasa's Systems Engineering Handbook also helped the team know the order of events for the schedule planning and Gantt chart. Some challenges that were encountered during the draw up of the Gantt chart were in regards to the conditional formatting of the template provided. Once rows were altered the template would know longer add the conditional formatting rules to the pertaining cells. This will be corrected prior to the PDR by recreating the Excel template and adding conditional formatting rules that better suit this specific gantt chart. The way the team selected dates for the schedule based on the sub-system lead times for supplies, materials, assembly as well as the usual review time needed for admin to review submitted deliverables in the past (about 2 weeks).

High Level View of Mission Schedule (Phase C-F)

Task	Start Date	End Date	Days
System Integration Review (SIR)	8/29/2024	5/30/2026	640
Post-Launch Assessment Review (PLAR)	5/17/2026	09/23/2028	861
Decommissioning Review (DR)	9/24/2028	10/25/2028	32
Final Archival of Data	9/25/2028	12/10/2028	77

Figure 1.8.3.1 High Level View of Mission Schedule (Phase C-F)

1.8.4 Budget Overview

The total budget for the entire mission is capped at $175 million. A decision made by the government reduced the total budget by $50 million from the previous $225 million. This budget includes costs for all personnel related fees, the manufacturing of and assembly of each subsystem, testing and facility costs, and outreach events to the public. The team's current budget estimate for the mission is $155 million, which includes a margin for each area and an overall mission margin to accommodate any difficulties that arise throughout the mission.

2. Overall Vehicle and System Design

2.1 Spacecraft Overview

To follow the above mission requirements, all subsystems have been designed to optimize reliability, cost, strength, and mission parameters. The chosen design is a four-wheeled rover with independent suspension and steering angle mechanisms. Mounted on the chassis are two payload tools to aid our instrument, VAPoR, in analyzing regolith samples for water ice and solar accretion isotopes. The TRIDENT drill will collect samples through a deployable opening in the bottom of the chassis while the COLDarm robotic device will take those samples output from the drill from the lunar surface to VAPoR's crucibles and sample analysis spectrometers. To ensure proper functioning of these instruments, an appropriately sized shell covered with an MLI blanket will protect against radiation and manage extreme temperature variations.

The CDH subsystem is composed of a RAD750 On Board Computer (OBS), which has been used in many successful missions and has a high TRL. The other components include C-RAM 4M Radiation-hardened non-volatile RAM, Mercury RH304T SSDR, XANT X-band Patch Antenna, and Iris V2.2 SmallSat Deep Space Transponder. The rover will be running on Robot Operating System 2 (ROS2). This is the software that will be used in the VIPER mission. ROS2 is open source, making it very affordable and customizable to the missions needs.

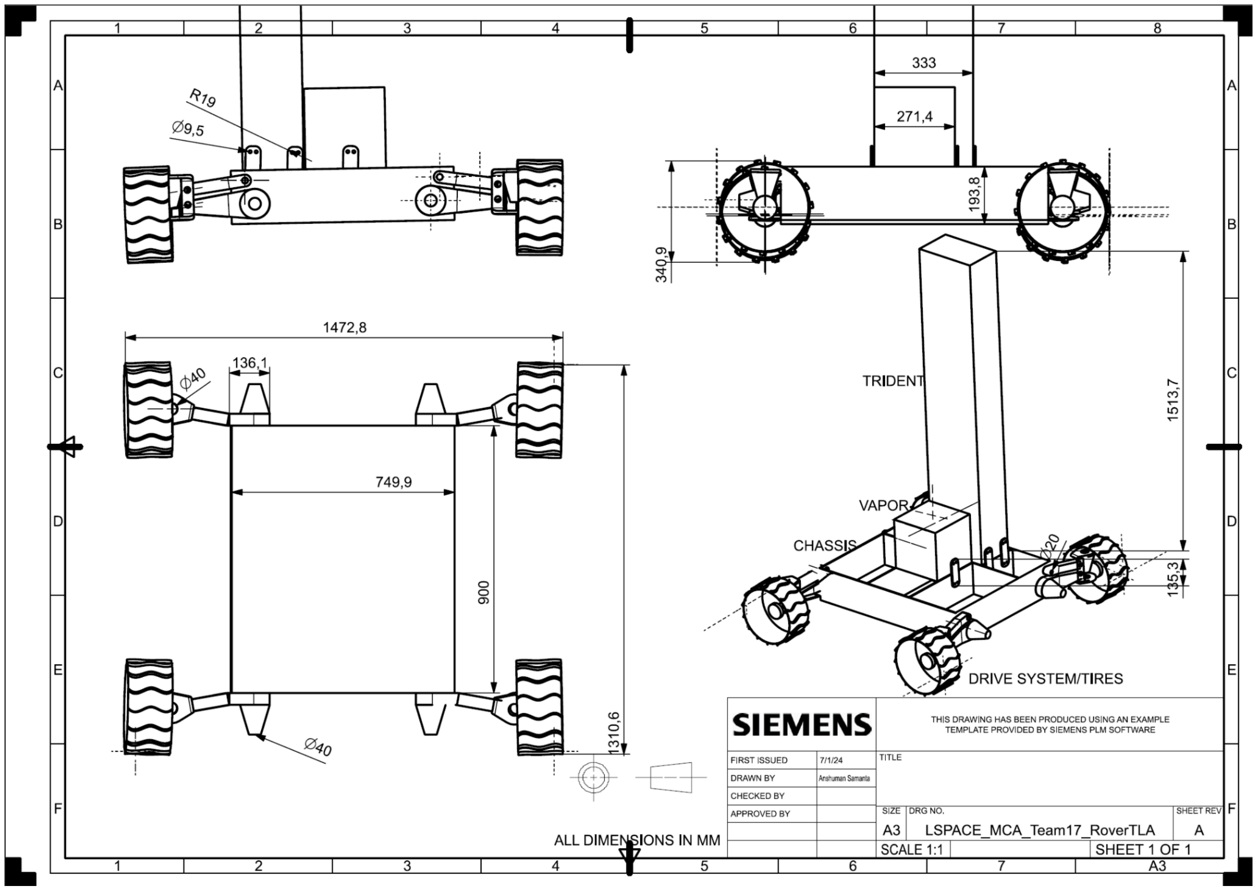


Figure 2.1.1: Rover Chassis and Wheels Drawing with Instrument Mounts and Thermal Modifications

Rover chassis and wheels drawing. Instruments will be mounted on top and covered by an appropriately sized shell with a thermal blanket and other necessary modifications.

Subsystem	Mass	Volume	Max Power Draw
Mechanical Subsystem	38.928 kg	1.472 x 1.310 x 0.341 m	50W
Power Subsystem	151.16 kg	0.0254 m³	2383.78W
CDH Subsystem	1,860.5g	$0.12m^2$	230 W
Thermal Subsystem	1,703.6 g	$1443\ in^3$	11.3 W

Payload Subsystem	35 kg	VAPoR: 200 cm^3 TRIDENT: 20.6cm x 33.3cm x 168cm	160W

Table 2.1.1: Mass, Volume, and Power Specifications of Various Subsystems

2.1.1 Mechanical Subsystem Overview

The mechanical subsystem works together in different ways to achieve the overall requirements of the mission. The mechanical subsystem must function to the best of its ability to provide a basis of support for all other subsystems and scientific components. The overarching goal of the mechanical subsystem is to support components of the thermal, power, CDH, and payload subsystems, while ensuring that the spacecraft is able to articulate. The mechanical subsystem is responsible for ensuring the spacecraft has components that enable it to move across the lunar surface. Some challenges when selecting components for the mechanical subsystem include considerations of cost, size, weight, risk, and success criteria. The spacecraft must also be able to respond to variations in lunar regolith when traveling, and must be able to drive on slopes of up to fifteen degrees. Risks associated with the mechanical subsystem include disruptions due to vibrations, power loss, and obstruction of components by fine pieces of lunar regolith. The mechanical subsystem was designed with these risks in mind to ensure optimal mission performance. The major components of the mechanical subsystem are the chassis and tires of the rover. The chassis provides the base of the rover and allows for connections to many other important features of this vessel, components relating to other subsystems. The chassis must be lightweight enough to ensure that the weight requirements for the mission are met, but it also must be sturdy enough to support all other subsystem components, such as the motor, instrumentation devices, and power sources. Additionally, the chassis supports the tires and allows them to maneuver in an efficient way to put the rover in motion. The tires allow the rover to navigate across the surface of the moon in order to reach the permanently shadowed region as well as other target sites. The tires were selected with maneuverability in mind, and will allow the spacecraft to seamlessly transverse the lunar environment. The wheels have multi-directional functionality, allowing them to avoid large obstacles that would otherwise pose a significant mission risk. The chassis also features a suspension system that will allow the spacecraft to lift its wheels in cases of entrapment, further decreasing risk. The mechanical subsystem is designed to withstand the terrain of the moon and the movements required for this trip. This consideration has been extended to the material selection for the mechanical subsystem. The use of Aluminum ensures that the spacecraft remains lightweight, and is capable of adapting to a range of temperatures, which is ideal for navigating the extreme cold of the permanently shadowed regions. The chassis and tires work together to allow the rover to be mobile in an efficient way, thus allowing the mission to be completed as expected. The design of the mechanical subsystem is a key factor in achieving overall mission success.

2.1.1.1 Mechanical Subsystem Requirements

These requirements are derived from the top level mission requirements and the subsystem requirements ensure the proper support and operation of all mission requirements and instrumentation, based on lunar surface research and possible risks to mitigate for when designing.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mechanical Reqs							
MEC-1	The system shall be confined to a volume of 0.139 cubic meters before deployment.	Provided by the Mission Document	Customer	TBD	Inspection	All	Met
MEC-2	The system shall not exceed a total mass of 85kg.	Provided by the Mission Document	Customer	TBD	Inspection	All	Met
MEC-3	The system shall not contain more than 5g of radioactive material.	Provided by the mission Document	Customer	TBD	Inspection	All	Met
MEC-4	The subsystem shall maintain, protect, and effectively integrate all components and	Overall need of mechanical subsystem	MEC-1, MEC-2, MEC-3	MEC-4.1, MEC-4.2, MEC-4.3	Demonstration	Mechanical	Not Met

	motion-related requirements.						
MEC-4.1	The subsystem shall protect components from abrasive wear from lunar regolith.	The sharp and erosive properties of regolith pose a risk to mechanical components	MEC-4		Analysis/Test	Mechanical	Not Met
MEC-4.2	The subsystem shall maintain stability while traversing crater slopes.	Tipover is a danger when going up and down crater slopes to reach PSRs	MEC-4		Analysis	Mechanical	Not Met
MEC-4.3	The subsystem shall protect core components from motion-related damage during operation.	Uneven craters of many sizes and regolith can cause turbulent driving conditions	MEC-4, MEC-4.1	MEC-4.3.1	Analysis/Test	Mechanical	Not Met
MEC-4.3.1	The subsystem shall keep instrumentation within +-0.05 inches of motion relative to the chassis during motion.	Sets vibrational tolerance for components during motion	MEC-4.3		Analysis/Test	Mechanical	Not Met

Table 2.1.1.1.1: Mechanical Subsystem Requirements Overview and Verification Status for Lunar Exploration Project

2.1.1.2 Mechanical Sub-Assembly Overview

The mechanical subsystem on this lunar rover provides the structural and mechanical connections and strength necessary to transport the rover from the landing site to the necessary sample collection sites both outside Shackleton crater in the sunlit regions to the PSRs. It integrates all other subsystems necessary for successfully completing mission requirements, including mounts for power, thermal devices, data storage, communication networks, and instrumentation integration into the chassis and into other instruments. For this rover, hereditary design was preferred to increase TRL levels and provide a reliable and tested design. Following this, trade studies were conducted for the chassis to endure the strength and motion requirements for navigating abrasive and slippery lunar regolith as well as uneven crater terrain. Wheel and tread design was also taken under consideration in order to minimize weight and cost and maximize movement efficiency through regolith displacement. The chosen design is based on a scaled-down version of the VIPER rover, a NASA rover created at Ames Research Center towards a similar mission goal of investigating polar volatiles in PSRs (NASA 2020). While the rover was designed for a much larger class mission in terms of mass, the team scaled it down by 75% and designed a much simpler and lighter chassis as well as simplified drive system to save on weight. With a TRL level of 7 after undergoing extensive prototype development in mission conditions and nearing certification as of writing, its relatively simple but strong and versatile mobility with independent steering and active suspension able to lift wheels out of regolith if necessary will make a capable rover transportation system. The drive system works on three main motors, one to turn the suspension bars up or down to lift the wheels, another motor to spin the main drive motor and change the angle of the wheel relative to the chassis, and one to turn the wheel directly. With these three, the rover will have excellent control and adaptability in uncertain regolith depths, conditions, and slopes. All drive components are covered in housings to prevent regolith abrasion and ensure electronic and mechanical operation as required by MEC-4.1. The chassis itself is currently very versatile, including ribs for strength and a strong aluminum build. Aluminum was chosen for its moderate strength, lightweight build, and ability to withstand thermal contraction and expansion in the large range of temperature experienced in the lunar polar regions, traversing both permanently lit and shadowed regions while collecting samples. [Insert structural description/choice here]. A small opening on the base of the chassis permits two doors, mechanically linked to TRIDENT, to open whenever the drill moves downwards and prevents regolith from eroding/damaging the payload when the drill is not in use. Dust covers will be placed on TRIDENT surface-side as well to prevent regolith abrasion while in use. There is a lack of information on the specific motors used on VIPER and thus an estimated power usage was derived based on motors of that scale. The specific motor needs enough torque to be able to lift that side of the chassis relative to the tire, as well as turn the entire tire and tire assembly under high torque itself.

To supplement this, the wheels should have good tread depth for excavating and displacing regolith as well as lightweight but strong spoke and rim construction. The chosen wheel design comes from the Oak Ridge National Laboratory, where scientists supplemented the original VIPER wheel design with added curved tread profiles for extra grip and displacement that were not possible in the original VIPER rover due to manufacturing constraints (Oak Ridge 2023). The wheel is additively manufactured using metal 3D printing, and adds onto the rover's wheel design with increased structural and efficiency modifications with a much lower cost due to increased manufacturing and labor speed and a similar weight.

The subsystem also needs to provide protection from abrasive lunar regolith particles as well as integrate thermal systems for regulating temperatures and protect electronic components from cosmic rays and radiation that an earth-like atmosphere usually provide. To this end, the mechanical structure will include a shell/rib structure over all critical components, covered by a multi-layer insulation blanket. This will create an enclosed system for instrumentation and maintain system integrity during mission operations as required by MEC-4.1 and MEC-4.3.

In addition to transport, the chassis will securely mount the payload through custom-designed panels and fasteners attached to the chassis, and support mission operations through deployable openings to the lunar surface for drill sample operation and collection.

Subsystem Component	Mass	Volume	Max Power Draw	TRL
Chassis	38.928 kg	1.472 x 1.310 x 0.341 m	50W	3
Tires	3.1488 kg	0.0004021 m^3	0W	6

Table 2.1.1.2.1 Mechanical Subsystem Characteristics

2.1.1.3 Mechanical Subsystem Recovery and Redundancy Plans

Mechanical Redundancy:

The chassis is a core part of the rover, so it is being designed well as a redundant chassis is not possible for cost, weight, or volume. The tires however are all independently driven and steered so the failure of one tire drive does not necessarily affect all other tires; effectively there are 4 redundant tires, although an increasing amount of motor failures would result in the rover stopping motion. The motors used for mobility will also be carefully chosen and validated through extensive simulation and environment testing to prevent failures.

Mechanical Recovery:

The computer and guidance system in charge of rover drive and navigation, in our case ROS2, should have procedures to test and identify malfunctioning motors and increase drive amounts on the working motors to compensate, up to a certain operational limit.

2.1.1.4 Mechanical Subsystem Manufacturing and Procurement Plans

Mechanical Suppliers and lead times:

NASA Johnson Space Center will be used for the VIPER rover chassis. They were selected as we are using the chassis from the rover, with appropriate sizing modifications for instrument mounting. They are the original designers of the rover hardware specifically and have all the appropriate design, analysis, and test information on its chassis, capabilities, and manufacturing methods, thus they are the most appropriate supplier. They also have all the information on its drive/mobility system capabilities, which are perhaps the most critical part we will be using from the VIPER design. The chassis itself is simply a structurally capable box, but the independent suspension bars and wheel orientation mechanisms are what will enable our rover to navigate the tricky lunar regolith. Due to its design having both scientists and engineers on the team as well as experience raising its TRL level, NASA resources are the best option for this chassis and private entities would not be able to acquire the design specific to the drive system for manufacture. Backup suppliers would include NASA Ames Research Center or Honeybee Robotics, which are currently VIPER partners/mission facilitators and either would have the relevant staff, software, skills, and access to Johnson’s mobility designs and research. Partner agencies are the ideal choice for high TRL components as original design and analysis are key to maintaining TRL level throughout development. Lead times would range from several months up to a year; at worst two years.

Oak Ridge National Laboratory will be used for the wheels. Researchers at this laboratory were able to design and improve upon the VIPER mission’s specified tires by adding previously non manufacturable components like curved tread profiles through additive metal manufacturing. Their specialities include additive manufacturing which is not all that common of a manufacturing resource yet. While private contractors exist for metal 3D printing, getting access to and redesigning the wheel that Oak Ridge already created would severely decrease the TRL level based on redoing the analysis and validation already performed. Backup suppliers would include other US commercial 3D printing contractors, like GE Additive or 3D Systems, for example. Lead times would be about a month or two to get in queue to print, print it, post process, and repeat four times; assume 6 months in a worst case scenario.

2.1.1.5 Mechanical Subsystem Verification Plans

For each of the subsystem's requirements, a verification method has been selected. The rationale for the method varies for each requirement based on what can most accurately reflect the subsystems performance in the lunar environment. The preliminary verification plans detail how the verification method of each requirement will be carried out. Requirements MEC-1, MEC-2, and MEC-3 can be verified by inspecting the rover. MEC-4 will be verified by demonstrating that the subsystem meets the requirement. The child requirements of MEC-4 will be verified with tests and analysis that can reflect the subsystem's ability to meet those requirements.

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
MEC-1	The system shall be confined to a volume of 0.139 cubic meters before deployment.	Inspection	The system can be measured to ensure that it fits within the volume requirements.	The system will be measured to ensure it fits within the required volume.
MEC-2	The system shall not exceed a total mass of 85kg.	Inspection	The system weighed to ensure it does not exceed the mass requirement.	The system will be weighed to ensure it does not exceed the mass requirement.
MEC-3	The system shall not contain more than 5g of radioactive material.	Inspection	The system can be inspected to ensure it does not contain more than 5g of radioactive material.	The system and documentation regarding its assembly will be inspected to ensure no more than 5g of radioactive material was added to the system.
MEC-4	The subsystem shall maintain, protect, and effectively integrate all components and motion-related requirements.	Demonstration	A demonstration of the subsystem's ability to maintain, protect, and integrate all components will most accurately ensure that the subsystem will meet this requirement in the lunar environment.	A demonstration will be performed simulating lunar environmental concerns and navigation to confirm the subsystem maintains, protects, and integrates all components and motion-related requirements.
MEC-4.1	The subsystem shall protect components	Test	Testing the effectiveness of the subsystem will most accurately reflect its performance in	The component will be tested using simulation techniques mimicking the abrasive material of

	from abrasive wear from lunar regolith.		the lunar environment.	the lunar regolith.
MEC-4.2	The subsystem shall maintain stability while traversing crater slopes.	Analysis	Analysis of the vehicle's mobility can accurately reflect how the subsystem will perform in traversal of crater slopes.	The designs and structure will be analyzed to ensure it will maintain its stability while traversing crater slopes.
MEC-4.3	The subsystem shall protect core components from motion-related damage during operation.	Test	Testing the effectiveness of the subsystem will most accurately reflect its performance in the lunar environment.	The subsystem will be tested by simulating traversal environments to ensure that the motion of the vehicle's traversal and operation will not cause damage to the core components.
MEC-4.3.1	The subsystem shall keep instrumentation within +-0.05 inches of motion relative to the chassis during motion.	Test	Testing the effectiveness of the subsystem will most accurately reflect its performance in the lunar environment.	The subsystem will be tested by simulating traversal environments to ensure the instrumentation does not move more than +-0.05 inches of motion relative to the chassis while the vehicle is in motion.

Table 2.1.1.5.1 Mechanical Sub-system Verification Method

2.1.2 Power Subsystem Overview

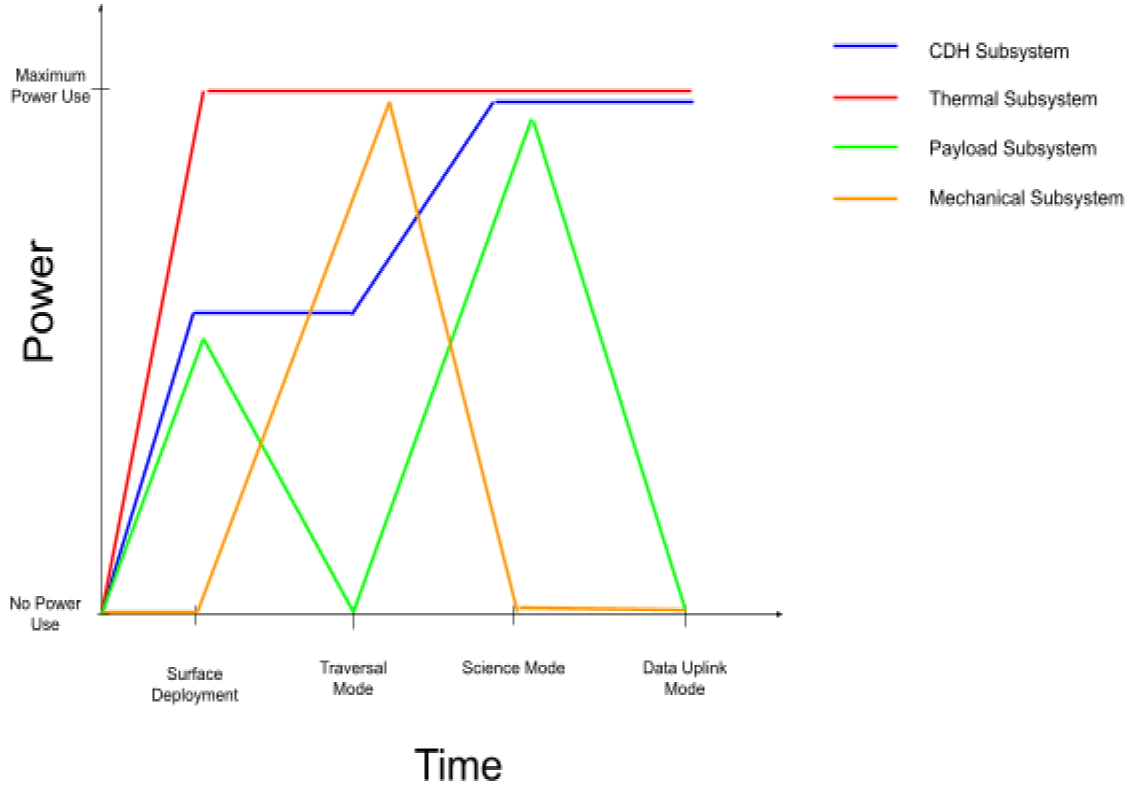
The power subsystem of the lunar rover is designed to ensure reliable and efficient energy distribution across the various phases of the concept of operation. The overall power needed for the rover's subsystems comes to a total of 452 Watts. Through the robust and efficient architecture of the system, the power needs of the rover are able to be met.

The solar cells are responsible for generating the power that will be used by the rest of the rover. The power generated is stored in the batteries. The DC-DC converter is used to ensure that an appropriate amount of power is provided to the various components of the rover, while the PCDU is responsible for distributing the power to the components. The regulator will maintain a constant DC voltage.

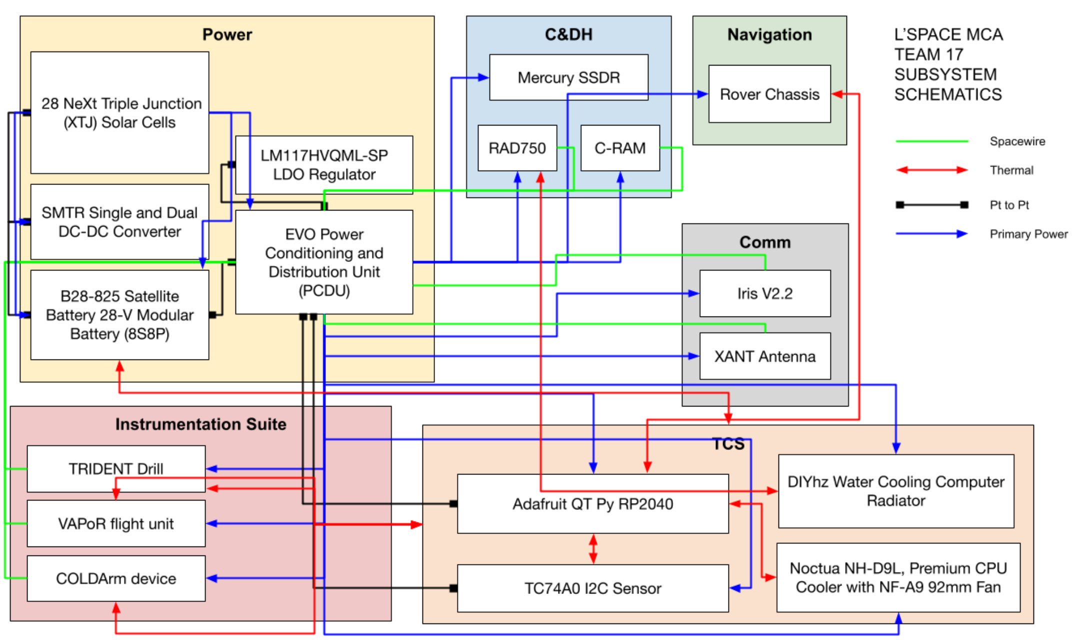
During the initial surface deployment, the rover will need a period to charge in order for operations such as telemetry and instrumentation checks to be performed. After these are completed, the rover will have lower power needs for the next few hours as it awaits commands from ground control. This time will be used for the rover to finish charging.

During traversal mode, the power system will need to power the thermal, CDH, and mechanical subsystems as the rover traverses to the outside of the PSR. The thermal subsystem will need to be powered for the duration of the mission. The mechanical system will need power for mobility, and the CDH subsystem will need power for telemetry operations and collecting and processing data from the other subsystems. Throughout the traversal process, the rover will be able to continue charging during the day time.

Once the rover arrives at the edge of the PSR, it will stop to power fully. This will be another period of reduced power usage, as the mechanical subsystem will be stationary. Once the batteries are charged, the rover will travel to the first science site. Once the rover has reached the science site, the power needs will change from powering the mechanical subsystem to powering the payload subsystem as it completes science tasks. The CDH subsystem will also have higher power needs as there will be more data to process and transmit. It will also need more power in data uplink mode, where it sends more data to the orbiting satellite.



The power subsystem provides primary power to all electrical components within the rover. Spacewire connections run between components from subsystems such as CDH, communications, power, and instrumentation. Pt to Pt components connect the thermal and power subsystem.



2.1.2.1 Power Subsystem Requirements

The power subsystem will be responsible for ensuring consistent and reliable power distribution to all rover components throughout the mission. Requirements include maintaining power within specific ranges, managing energy distribution to various subsystems, and accommodating the challenges that are presented by the harsh space environment. The system must handle extreme temperatures, varying power demands during operational phases, and efficient storage and recharging capabilities.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
EPS-1	The system shall not contain a Radioisotope Thermoelectric Generator (RTG) or derivative of such.	Provided by the Mission Document	Customer	TBD	Inspection	Payload	Met
EPS-2	The system shall power all necessary components for mission completion.	The system will require power to complete mission requirements	MR-1, MR-2, MR-3, MR-4	EPS-2.1, EPS-2.2, EPS-2.3, EPS 2.4	Demonstration	All	Met
EPS-2.1	The system shall provide continuous power to the payload instruments.	Instruments require constant power to operate	EPS-2	TBD	Test	Payload	Met
EPS-2.2	The system shall have a battery capacity sufficient for at least 14 days of continuous operation.	Ensure mission duration without power loss	EPS-2	TBD	Analysis	Payload	Met
EPS-2.3	The system shall have a solar array capable of recharging the batteries within 10 hours of lunar daylight.	Utilize lunar daylight efficiently	EPS-2	TBD	Analysis	Payload	Met
EPS-2.4	The system shall include a power management and distribution unit(PMAD) to regulate power usage.	Ensure efficient power distribution and management	EPS-2	TBD	Test	All	Not Met

EPS-3	The power subsystem shall operate within the temperature range of 88-100K.	Provided by the Mission Document	MR-4, TCS-1	TBD	Analysis	Payload	Not Met

Table 2.1.2.1.1 Power Sub-system Requirements

2.1.2.2 Power Sub-Assembly Overview

The power sub-assembly utilizes 28 NeXt Triple Junction (XTJ) Solar Cells for solar power generation. These solar cells were selected for a high efficiency of 29.5% (Spectrolab, 2010). The availability of smaller sizes enables the subsystem to stay within the overall rover size requirements, and prior use in space environments provides a higher TRL of 6, as this product has been used in a relevant environment (Spectrolab, 2010). The use of a Customizable Off the Shelf (COTS) product will enable shorter lead times and reduce risk.

The radiation-tolerant B28.825 Satellite Battery is both radiation and fault tolerant, making it a suitable option for space applications (Satsearch2024). The selected configuration will allow for 825 Watt-hour capacity. While information regarding prior component usage in space applications cannot be located, the product is intended to be used in spacecraft applications (ibeos, 2024), indicating that testing was done by the manufacturing company to ensure product quality. Based on this information, the TRL can be assumed to be a minimum of 5.

The converter selected is the SMTR DC-DC Converter. This product has a 84% efficiency rate (Crane Aerospace & Electronics Power Solutions, 2015), operates at a wide range of temperatures, and is radiation tolerant. Thorough testing of the component has been conducted by the manufacturer, and the product has an assumed TRL of 5.

The PCDU selected is the EVO Power Conditioning and Distribution Unit(PCDU). This product is intended for interplanetary missions and has a long design lifetime (Satnow, 2024), lowering the risk of the component. Given the testing necessary to confirm the product’s functionality in its intended environment, the TRL for this product can be assumed to be a minimum of 5.

The regulator selected is a LM117HVQML-SP LDO Regulator. This regulator has a high radiation tolerance and an adjustable output. This product is flight proven (Texas Instruments, 2024) Giving it a higher TRL of 6. The part contains thermal overload protection and a current limit.

The overall TRL of the sub-assembly is 5, as the lowest TRL components such as the battery, converter, and PCDU have a TRL of 5. The combination of components provides a robust architecture that will be able to meet the power needs of the whole system.

Subsystem Component	Mass	Volume	Power Draw	TRL
(28) 29.5% NeXt Triple Junction (XTJ) Solar Cells	84 mg/ cm^2 per cell	0.37268 cm m^3 per cell	29.78W	6
B28-825 Satellite Battery 28-V Modular Battery (8S8P)	7.8 kg	147 x 90 x 460 mm	2300W	5
SMTR Single and Dual DC-DC Converter	50 g	9.91 cm^3	30W	5
EVO Power Conditioning and Distribution Unit (PCDU)	143 kg	262 x 350 x 210 mm	10W	5
LM117HVQML-SP LDO Regulator	0.467 g	6.35 mm × 9.91 mm	14W	6

Table 2.1.2.2.1 Power Sub-system Overview

2.1.2.3 Power Subsystem Recovery and Redundancy Plans

Redundancy

The power components are essential parts of the mission as they provide the rover the ability to move, take measurements, relay information, and collect/store data. For this reason, it is crucial that there are backup options for some of the more important components. The 28 NeXt Triple Junction (XTJ) Solar Cells generate the electrical power needed for many of the rovers' applications. Due to the light weight of the individual solar cells, the rover can be equipped with 6 extra solar cells to provide more energy than the minimum required. Similarly, a backup B28-825 Satellite Batteries will be on the rover just in case the first battery does not function properly. For similar reasons, the rover will have a backup SMTR DC-DC Converter and LM117HVQML-SP LDO Regulator. Due to the large weight of the PDCU, there will be nop backup on the vessel. However, incase of failure of the PDCU, there will be a method in place for the power to be distributed directly to locations of need.

Recovery

As mentioned earlier, the power components functioning properly are very important for the mission to fulfill its requirements. If the system fails, there needs to be a way for the rover to continue on the mission as expected. A software will be in place to adjust where the power is being used. This software will base its decisions on the amount of energy being obtained for solar cells. It will then make sure to give priority to the most important subsystem components, depending on how far along the mission has progressed. It will also be important to manage the amount of power being sent to various components during the rover's journey. For instance, if a subsystem is not really required to be powered, then there will be no power sent to that subsystem. This will assist in keeping the batteries longer lasting, rather than depleting power and overusing. For the SMTR DC-DC converter, it will be important to monitor the voltage and check for deviations via software. If a deviation is seen, the software will prompt the use of the backup converter. Similarly, a software will monitor the voltage of the LM117HVQML-SP LDO Regulator and will prompt the use of a backup if the first one stops working. The PDCU will also be monitored through software making sure it is running smoothly. If an unexpected result is noticed, the software will prompt a reset of the PDCU to try and resolve the issue.

2.1.2.4 Power Subsystem Manufacturing and Procurement Plans

The solar panels used for the subsystem will be the 28 NeXt Triple Junction Solar Cells manufactured by Spectrolab. Spectrolab is a company specialized in manufacturing solar panels for space use. Their products have been used in NASA missions before and found to be reliable and high quality (Spectrolab, 2024). The estimated lead time for this product is 6-12 months.

The batteries used for the subsystem will be the B28-825 Satellite Battery 28-V (8S8P) manufactured by Ibeos. Ibeos specializes in manufacturing electronics for space missions, which are tolerant to radiation. NASA has used electronics from this manufacturer before and even mentioned them on the annual State of the Art of Small Spacecraft report. The estimated lead time varies but is about 3-4 months.

The subsystem will also use the SMRT DC-DC Converter manufactured by Crane Aerospace and Electronics Power Solutions. Crane Aerospace and Electronics Solutions is a company that manufactures Interpoint DC-DC power converters that are reliable and can withstand high levels of radiation. Crane Aerospace and Electronics Solutions have provided NASA with numerous electronics for previous missions, including electronics for Apollo 11, Apollo 13, and the Hubble Telescope. The lead time for this component varies but is around 3-5 months.

Another power subsystem component is the EVO Power Conditioning and Distribution Unit (PCDU) manufactured by AIRBUS. AIRBUS is a company that has a lot of experience working in the aerospace fielding, in particular in space exploration.

They have built and designed satellites for the European Space Agency and will be working with NASA on the new Artemis mission. The lead time for this product will be about 8-9 months.

This subsystem will also include a LM117HVQML-SP LDO Regulator manufactured by Texas Instruments. This regulator performs well when enduring high radiation and is flight-proven. Texas Instruments manufactures reliable power systems for space applications. They have worked on projects with NASA in the past on areas regarding radiation in space. The lead time for this regulator will be about 4-5 months.

2.1.2.3 Power Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
EPS-1	The system shall not contain a Radioisotope Thermoelectric Generator (RTG) or derivative of such.	Inspection	Provided by the Mission Document	Verify through inspection of system design and component list.
EPS-2	The system shall power all necessary components for mission completion.	Demonstration	The system will require power to complete mission requirements	Perform an end-to-end power-up of the system with all components.
EPS-2.1	The system shall provide continuous power to the payload instruments.	Test	Instruments require constant power to operate	Conduct a continuous power test over the operational phase cycle.
EPS-2.2	The system shall have a battery capacity sufficient for at least 14 days of continuous operation.	Analysis	Ensure mission duration without power loss	Simulate power consumption over 14 days with the specified load.
EPS-2.3	The system shall have a solar array capable of recharging the batteries within 10 hours of lunar daylight.	Analysis	Utilize lunar daylight efficiently	Perform a simulation of solar charging under daylight conditions.

EPS-2.4	The system shall include a power management and distribution unit(PMAD) to regulate power usage.	Test	Ensure efficient power distribution and management	Test the PMAD with various loads and operational scenarios.
EPS-3	The power subsystem shall operate within the temperature range of 88-100K.	Analysis	Provided by the Mission Document	Conduct thermal analysis and testing to ensure system performance within the specified range.

Table 2.1.2.3.1 Power Sub-system Verification Plans

2.1.3 CDH Subsystem Overview

Each of the subassemblies in the CDH subsystem work together to meet the CDH requirements of the mission and enable mission success. The RAM, OBC, and storage work together to run necessary software and process data received from other instruments. These enable commands to be processed and sent. These elements send telemetry to the transponder, which allows for data to be sent to the orbiting spacecraft, and the antenna allows for telemetry to be received from ground control.

The power subsystem's data needs include tracking the amount of charge remaining in the batteries, as well as information such as when the vehicle will be able to charge again. The payload subsystem requires that science data that has been collected can be stored as well as transmitted to the orbiting satellite and relayed to the DSN. Commands must also be given to the science instruments to begin sample collection at the correct locations. The mechanical subsystem data needs include tracking the distance of the vehicle to monitor how long the vehicle can be expected to be operational. Data regarding navigational instructions and where the vehicle has previously traveled must also be processed and stored. The thermal subsystem is the only one on the rover that does not have any data needs, as this subsystem is only composed of multi-layer insulation.

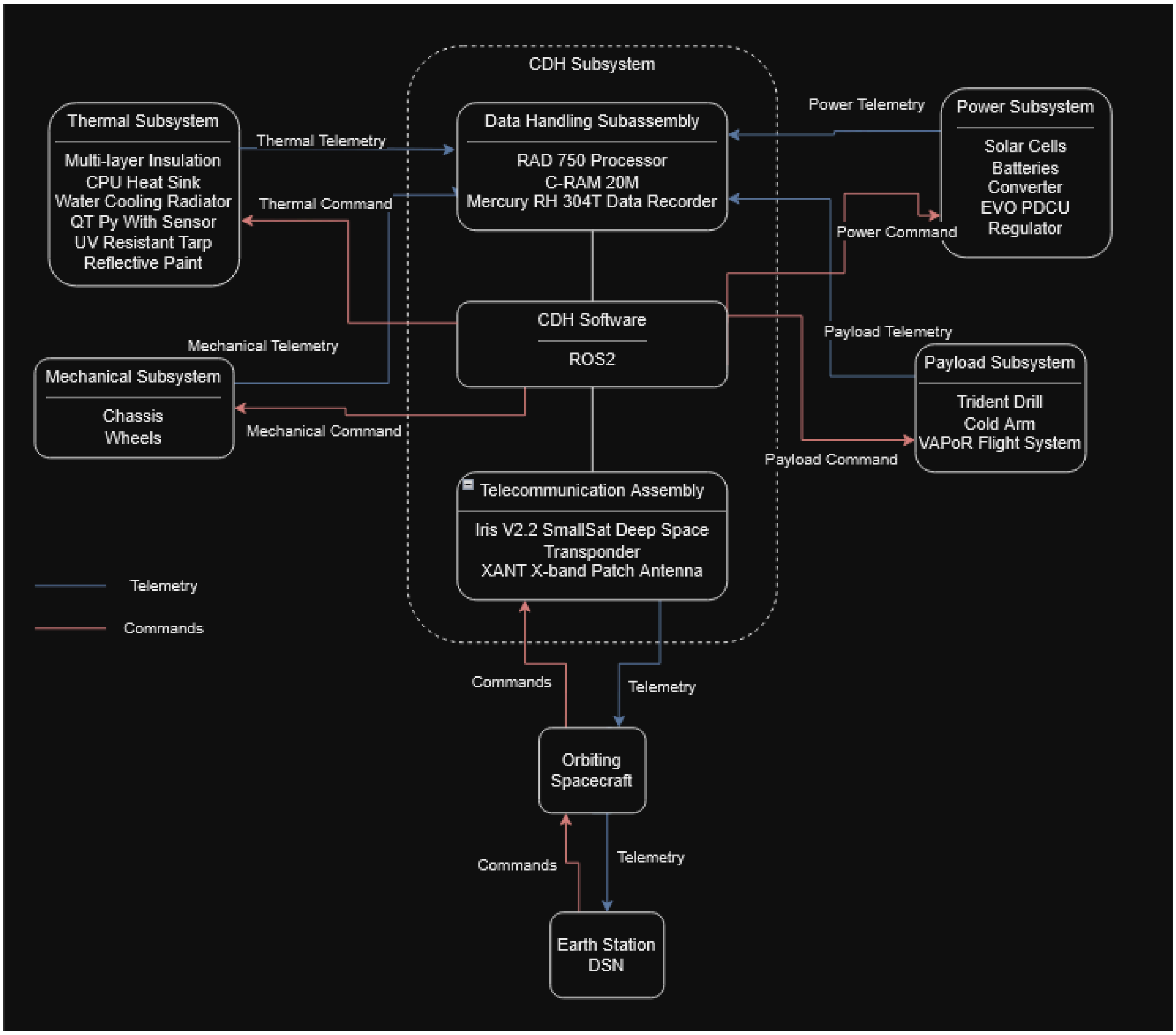


Figure 2.1.3.1 CDH Flow Chart

The software architecture flowchart details the communication between all of the subsystems of the rover, as well as how communication is sent back to the Deep Space Network (DSN).

The CDH subsystem uses data from the Power subsystem to monitor charging times of the batteries as well as the current charge. This data can be used to determine if the rover needs to leave the PSR to recharge in order to complete the science goals. Commands relevant to this subsystem include those to limit power usage if necessary. The CDH subsystem will require that all hardware components be powered by the power subsystem. The CDH subsystem will require an estimated 230W from this subsystem.

The payload subsystem passes data collected by the science instruments to the CDH subsystem to be stored and relayed to the DSN. Commands from the rover’s installed software will control when the equipment begins sample collection.

The CDH subsystem will need to record data from the mechanical subsystem such as how far the rover has traveled. This will be important for navigating the lifespan of the vehicle. The mechanical subsystem will require commands from the CDH subsystem relating to navigation and traversing to the science sites. Navigational instructions passed from ground control will need to be relayed to this subsystem once received from the telecommunication subassembly.

The QT Py with an attached sensor will be used to monitor the heat of the system. This data is passed to the CDH subsystem as telemetry. This data will be used to generate commands regarding cooling of the rover.

The software to be used by the rover is Robot Operating System 2. This is a customizable open source software written using C++. Using the Visual Studio Code integrated development environment, changes and customizations to the software can be made to meet the missions needs. Software development work will be done using Agile methodology, which will minimize cost increase for changes that may need to be made to the development plans.

The vehicle will have different data handling needs throughout the rover’s operational cycle. During surface deployment, instrumentation as well as communication and telemetry systems will need to be checked to ensure functionality. This information will need to be relayed to the orbiting satellite. The progress of the battery charging will be tracked to ensure the rover has full power before beginning traversal mode, and the vehicle will await initial instructions from ground operations.

During traversal mode, the battery charge will once again need to be monitored. The vehicle will stop and fully charge its batteries again before entering the PSR. The vehicle will autonomously travel to science site , so the location of the site as well as navigational instructions will need to be saved. The rover will send telemetry information to the orbiting satellite every 2 hours.

Once the vehicle has reached the first science site, the rover will enter science mode. Commands will be given to the science instruments to begin sample collection, and science data from the collected samples will be analyzed and stored. During data uplink mode, the rover will transmit the collected information to the satellite to be relayed to the DSN. These modes will repeat for the remaining two science sites.

2.1.3.1 CDH Subsystem Requirements

The CDH system will be responsible for interfacing with the orbiting spacecraft to relay communication to Earth. The requirements include ensuring that the subsystem can tolerate the hazards of the lunar environment, including radiation, extreme cold, and lunar dust. The subsystem must also have the necessary hardware and capacity to send communication to the orbiting spacecraft.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH-1	The subsystem communicates directly with the designated orbiting spacecraft.	Provided by the mission document	Customer	CDH-1.1	Analysis	Communications	Met
CDH-1.1	The subsystem must transmit to the distance of the orbiting spacecraft in a circular polar orbit at 100km.	Allows communication with orbiting spacecraft	CDH-1		Analysis	Communications	Met
CDH-2	Subsystem functions in environmental hazards present in the lunar environment.	Necessary for achievement of mission goals	MR-1, MR-2, MR-3, MR-4	CDH-2.1, CDH-2.2	Analysis	Hardware, Communications	Met
CDH-2.1	Subsystem tolerates radiation levels of up to 1.14 rad	Radiation may interfere with the function of hardware	CDH-2		Inspection	Hardware, Communications	Met
CDH-2.2	Subsystem is protected from lunar dust containing fine, sharp, sedimentary particles.	Dust particles may cause damage to hardware components	CDH-2		Inspection	Hardware	Met
CDH-3	Subsystem relays telemetry and	The CDH subsystem			Demonstration	Communications	Met

	commands to other subsystems	receives all data					
CDH-4	The subsystem can receive data and telemetry from the other subsystems	Data must be collected to be sent to the orbiting spacecraft			Demonstration	Communications	Met

Table 2.1.3.1.1 CDH Sub-system Requirements

2.1.3.2 CDH Sub-Assembly Overview

The CDH subsystem is responsible for handling the internal and external communication between all the subsystems, allowing them to receive the necessary commands, as well as processing, storing, retrieving, and sending data collected. The trade studies completed factored in temperature tolerance, TRL score, power usage, cost, mass, radiation tolerance, and other factors specific to each component's functionality. Temperature and radiation tolerance were considered to ensure the subsystem would be able to endure the harsh environmental conditions on the moon, meeting the CDH-2 requirement and its child requirements. The other factors contributed to the component's adequacy at its required functionality and overall mission constraints such as cost and mass.

For the onboard computer, the rover will use the RAD 750 processor by BAE Systems. It has a TRL level of 8 and has been utilized in several NASA missions previously, regarding both the moon and mars, including the Lunar Reconnaissance Orbiter, Curiosity Rover, and Perseverance Rover (Artisan Technology Group n.d.). It is well protected against radiation, being able to take up to 200 krad. The processor works at a speed of up to 200 Mhz, allowing for all commands to run smoothly and efficiently (BAE Systems 2008).

The rover will also include the C-RAM 20M radiation-hardened non-volatile RAM by BAE Systems for its memory. The RAM is designed for high radiation environments and contains 256k x 8 bits. It also has the feature of single-bit error correction, allowing it to fix data incorrectly transmitted (BAE Systems 2017). This component has an estimated TRL of 6, as data relating to any space flight use was unavailable. However, according to BAE Systems, all radiation-hardened products are "...specifically designed for space applications" (BAE Systems, 2024). In order to ensure that the product will be functional in the space environment, testing must have been conducted with the component to ensure it would function in its intended environment, indicating a TRL level of 6.

To communicate data, the rover will utilize the Iris V2.2 SmallSat Deep Space Transponder designed by NASA's Jet Propulsion Laboratory (JPL) and the XANT X-band Patch Antenna produced by Cubecom. The transponder is compatible with NASA's Deep Space Network, Near Earth Network, and Space Network (NASA JPL n.d.). The antenna contains built-in protection against the environment with an integrated radome that prevents corrosion and safeguards from radiation in the atmosphere. The antenna also has a band of 8-8.4 GHZ with a maximum gain of 8 dbi to ensure that the rover will be able to communicate with the orbiting satellite and meets requirements CDH-1 and CDH-1.1 (Cubecome n.d.). The Iris V2.2 Smallsat Deep Space Transponder has an estimated TRL of 8, given its prior use in space missions such as the Lunar Flashlight (Lunar Flashlight: Mapping Lunar Surface Volatiles Using a Cubesat, 2013). Information regarding space use of the XANT Patch antenna was not available, but given that it was created and is currently marketed for space use, testing in a relevant environment has been completed, indicating a TRL of 6.

The main software being used is the Robot Operating System 2 (ROS 2), which has been used in robot related applications. ROS 2 is open source, meaning it is free to use and will allow for more cost effective development by building off of technologies already available rather than having to invent from scratch. ROS 2 is also easily customizable and integrable, meaning that it will be able to be adjusted to fit mission criteria and software needs (ROS n.d.). ROS 2 is also being used on the VIPER mission and being integrated into NASA’s Open Mission Control Technologies (Open MCT), a software used for data visualization. Although not much is known about Open MCT at the moment, NASA plans to release more information proceeding the VIPER mission, allowing for any future missions to incorporate the existing technology (NASA 2023). Based on ROS2’s planned usage in the VIPER mission, it is assumed testing or demonstration was conducted in a relevant environment, giving a TRL of 6.

The overall TRL of the subsystem is 6, as the two lowest TRL components (the RAM and the antenna) have a TRL of 6. The overall subsystem provides a high radiation tolerance and a large amount of space flight proven technology.

Subsystem Component	Mass	Volume	Max Power Draw	TRL
RAD 750	9 g	120 mm^2	10 W	8
C-RAM 20M radiation-hardened non-volatile RAM	181.5	16.256 x 25.55 x 2.5 mm	155 mW	6
Mercury RH304T SSDR	750 g	160 x 100 x 133.1 mm	25 W	8
XANT X-band Patch Antenna	26.5 g	51 x 51 x 5 mm	5 W	6
Iris V2.2 SmallSat Deep Space Transponder	1075 g	100.5 x 101.0 x 56.0 mm	35 W	8

Table 2.1.3.2.1 CDH Component Overview

2.1.3.3 CDH Subsystem Recovery and Redundancy Plans

All major components of the CDH system except for the data recorder and transponder will have a duplicate system on board for redundancy. Due to the weight of the transponder, including a duplicate would infringe on the weight limits of other critical systems. The transponder will be a Single Point Failure (SFP). The Mercury RH304T SSDR contains built-in reliability and integrity features, providing a measure of redundancy with one device (Mercury, 2024). The data recorder will also be a SFP, but due to its built-in redundancy, the risk of failure is minimal.

As a part of the CDH system's recovery, all components will have associated errors for common malfunctions or issues that may arise. This will save time in identifying complications and provide a path forward for resolving the issue. Any automated processes to resolve complications will be programmed to execute autonomously without input from mission control. If any component other than the transponder or data recorder fails, the system will be programmed to automatically switch functionality to the redundant device.

2.1.3.4 CDH Subsystem Manufacturing and Procurement Plans

The CDH subsystem relies on COTS components, making many of the selected components vendor specific. ROS2 is offered by ROS, and has a lead time of 0 days, as it is available for download immediately. The RAD750 OBC is manufactured by BAE systems, as is the C-RAM 20M radiation-hardened non-volatile RAM. The RAD750 has an estimated lead time of 4 months, based on the lead times available for similar products (CubeSatShop, 2024). The lead time for the RAM is 5 months, based on the estimated lead times for other space-grade components. The Mercury RH304T SSDR is manufactured by and will be procured from Mercury Systems. Based on the time this product was announced to be in testing (Mercury, 2021) and the time it was used in a system launch (Mercury, 2022), the estimated lead time for this product is 6 months. The XANT X-band Patch Antenna is manufactured by Cubecom and has an estimated lead time of 4 months, based on the lead times for similar products (CubeSatShop, 2024). The Iris V2.2 SmallSat Deep Space Transponder Vendor is manufactured by NASA's Jet Propulsion Laboratory and has an estimated lead time of 6 months based on the time difference from when the product was in testing (Digital Commons, 2017) and when it was used in a launched system (eoPortal, 2024).

Because of the CDH subsystem's reliance on COTS components, many of the components are only available through their manufacturer. As a result, many of the backup supplier products require selecting a different but similar component. The operating system that will be used if ROS is not available is the VxWorks operating system, which will be purchased from its manufacturer Wind River. If BAE Systems is unavailable, the replacement for the RAD750 will be the Sirius Quadcore OBC from AAC Clyde Space, and the memory replacement will be the SRAM Space Grade Radiation Tolerant Memory Stacks from MSA Components. For data storage, the subsystem will use the On Board Recorder from ST Engineering Satellite Systems. The antenna will be replaced with Space-Rated SATCOM Panel Antenna from Southwest Antennas and the transponder will be replaced with the General Dynamics Deep Space Transponder. The use of backup suppliers is not expected to impact lead times, as those are created from averages of those products.

2.1.3.5 CDH System Verification Plans

A variety of verification methods have been selected to verify that the CDH subsystem meets the subsystem requirements. CDH-1 and its child requirement will be verified through analysis, as these two cannot be tested or demonstrated. For these two requirements, analysis will also provide more accurate results than inspection. CDH-2 will be verified by analysis of the data produced by the verification of its two child requirements CDH-2.1 and CDH-2.2. CDH-3 and CDH-4 can be verified by demonstration once the rover has been fully assembled.

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
CDH-1	The subsystem communicates directly with the designated orbiting spacecraft.	Analysis	The orbiting spacecraft cannot be reached by the rover from earth, making analysis the most accurate option.	Analysis of component capabilities will be completed to ensure the subsystem will be able to communicate at the appropriate range and has relevant compatibility.
CDH-1.1	The subsystem must transmit to the distance of the orbiting spacecraft in a circular polar orbit at 100km.	Analysis	The orbiting spacecraft cannot be reached by the rover from earth, making analysis the most accurate option.	Analysis of component capabilities will be completed to ensure the subsystem will be able to communicate at the appropriate range.
CDH-2	Subsystem functions in environmental hazards present in the lunar environment.	Analysis	Accurate analysis can be conducted with the data from child requirement verification.	Analysis will be conducted based on the verification of requirements CDH-2.1 and CDH 2.2 to ensure the subsystem will function in the lunar environment.
CDH-2.1	Subsystem tolerates radiation levels of up to 1.14 rad	Inspection	COTS components have been tested by their manufacturers to determine their radiation tolerance, so inspection of product documentation can provide accurate information.	The documentation of each component will be reviewed to confirm the radiation tolerance of all subsystem components.
CDH-2.2	Subsystem is protected from lunar dust containing fine, sharp, sedimentary particles.	Inspection	The subsystem can be inspected to see if there are any exposed components that could be damaged by sedimentary particles.	The subsystem will be inspected to see if there are any exposed components that could be damaged by sedimentary particles.

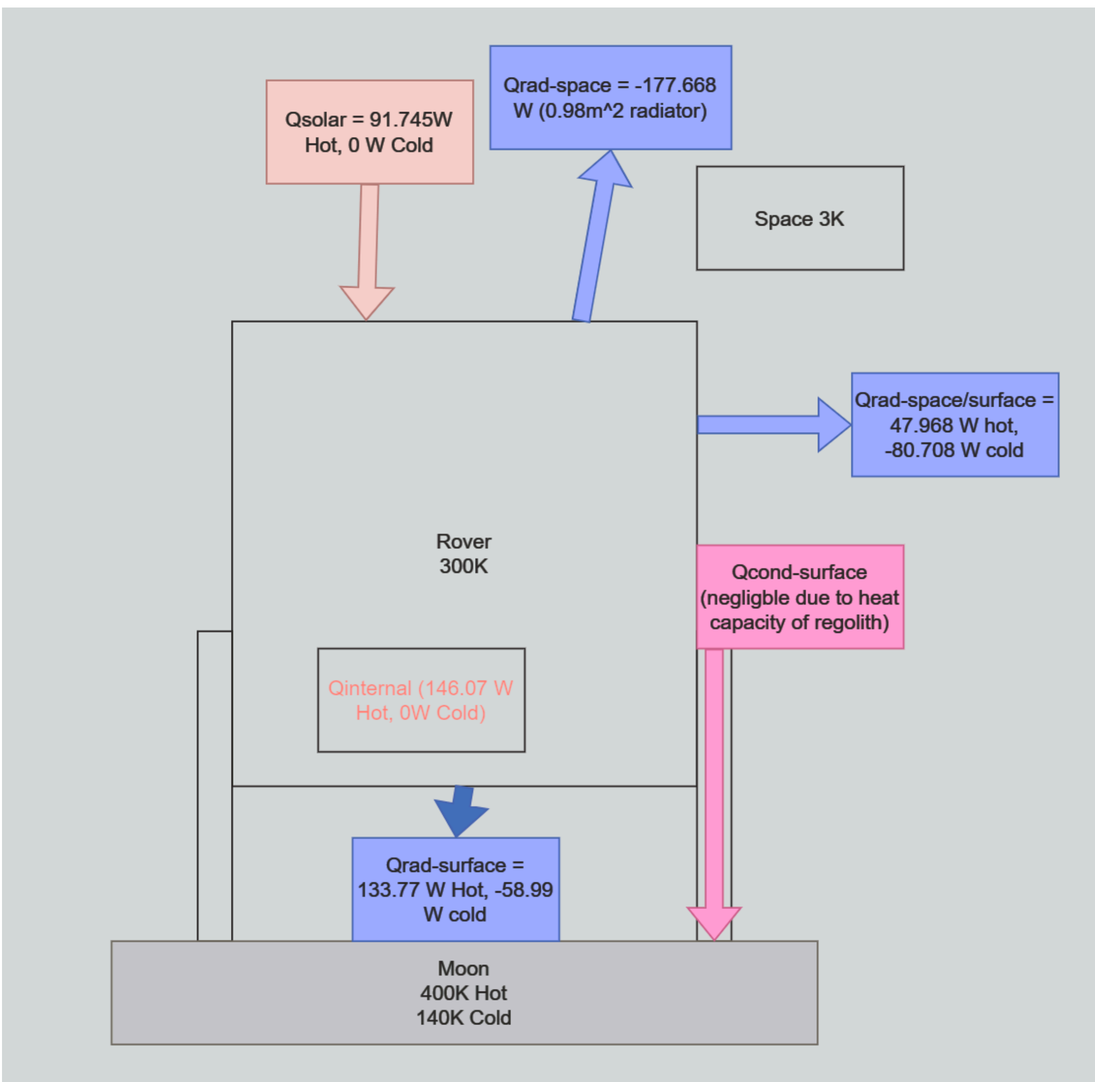
CDH-3	Subsystem relays telemetry and commands to other subsystems	Demonstration	After assembly of the rover, the ability for the CDH subsystem to send commands and telemetry can be demonstrated.	After assembly of the rover, a demonstration will be conducted confirming the CDH subsystem can send commands and telemetry to the other subsystems.
CDH-4	The subsystem can receive data and telemetry from the other subsystems	Demonstration	After assembly of the rover, the ability of the CDH subsystem to receive data and telemetry from the other subsystems can be demonstrated.	After assembly of the rover, a demonstration will be conducted confirming the CDH subsystem can receive data and telemetry from the other subsystems.

Table 2.1.3.5 CDH Sub-system Verification Methods

2.1.4 Thermal Control Subsystem Overview (2 pages recommended)

*This section should include an **overall description of how the thermal sub-assemblies work together**. What are the operating temperatures for each payload (i.e. Batteries, sensors, etc)? **Include heat flow maps describing heat transfer in and out of the system**. When calculating the heat transfer, it's helpful to state assumptions and show governing equations so that the reader can understand how the final values were derived. No need to show the calculations in this section, those should be included in the appendix, just the general governing equations here.*

This diagram shows the steady-state (no heat flow in or out) of the lunar surface thermal system. Space is assumed to be 3K with the moon in the sunlit phase at 400K and in shadow at 130K. Regolith is assumed to have a near infinite heat capacity and thus conduction heat transfer is irrelevant.



$$Qrad = \varepsilon\sigma FA(T_1^4 - T_2^4)$$

Figure 2.1.4.1 Heat Transfer Flow Map

2.1.4.1 Thermal Control Subsystem Requirements

These requirements are derived from the goal of having a thermally managed system, which is one that can achieve a steady-state temperature over the course of the mission duration; that is, heat flow in is the same as heat flow out. This is achieved through radiators, MLIs, temperature sensors, and heat generation units.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Thermal Control System Reqs (TCS)							
TCS-1	System shall regulate itself to an appropriate temperature range for functionality of all components.	Temperatures in shadowed regions of the moon can range from 88-100K	MR-4	TCS-1.1, TCS-1.2, TCS-1.3	Analysis	Thermal Control System	Not Met
TCS-1.1	System shall not go below 138 K and above 358 K to ensure the proper functionality of all components	Allows specified management to a temperature range for operability	TCS-1	TCS-1.1.1	Analysis	All subsystems	Not Met

TCS-1.1.1	System shall generate 50 W of heat to support temperature control	Provides source of heat for instruments in extremely cold PSRs	TCS-1.1	None	Analysis/Test	Thermal Control System	Not Met
TCS-1.2	System shall prevent both overheating and excessive heat loss	Solar radiation can cause thermal runaway while in PSRs the temperature can go below operable limits	TCS-1	TCS-1.2.1, TCS-1.2.2	Analysis	All subsystems	Not Met
TCS-1.2.1	System shall utilize a Multi-Layer Insulation to mitigate temperatures passively	Can prevent both overheating and heat loss through conductive barrier	TCS-1.2, TCS 1.1	None	Analysis/Test	Thermal Control System	Not Met
TCS-1.2.2	System shall use a radiator to expel any excess heat passively	Prevents possible overheating through waste heat dumping via IR	TCS 1.2, TCS 1.1	None	Analysis/Test	Thermal Control System	Not Met

TCS-1.3	System shall have protective barriers on critical parts	Pieces exposed directly to lunar regolith can be adversely affected by erosion, especially thermal control surfaces	TCS-1	None	Analysis	Thermal Control System	Not Met

Table 2.1.4.1 Thermal Subsystem Requirements

2.1.4.2 Thermal Control Sub-Assembly Overview

The thermal subsystem is responsible for regulating the internal temperature of the rover, and protecting it from solar radiation under the light of the sun. The entire subsystem consists of multilayer insulation (MLI), a CPU heat sink, a water cooling radiator using liquid ammonium coolant, a UV resistant tarp, highly reflective white paint, and a QT Py with an attached sensor to read temperature within the rover. These parts were chosen after evaluating their effectiveness in either protection, thermal regulation, or practicality on the lunar surface depending on the various parts' purposes as we split the subsystem into protection, and regulation.

The protection side of the thermal subsystem is upheld by the MLI, tarp, and paint which allow the rover to both absorb and reflect the incoming solar radiation. The MLI's high UV resistance is able to cover the whole rover, while the tarp and paint covers the radiator and acts to reflect light. The MLI is also able to regulate heat well, not letting the internal heat of other components get too low.

The regulating side of the subsystem is governed by the heat sink, radiator, and mini computer which work together to monitor and control the temperature within the rover. The heat sink will aid in temperature of the CDH subsystem's core processor, while the radiator uses liquid coolant (ammonium) to regulate the rest of the rover's systems. Additionally, the QT Py mini computer will be measuring internal temperature which can be acted upon by the radiator and heat sink to work faster.

2.1.4.3 Thermal Control Subsystem Recovery and Redundancy Plans

Thermal Recovery: In the case that the heatsink on the core processor fails, the radiator would draw more power up to

Thermal Redundancy: The MLI would serve to insulate and protect all thermal, electrical, and CDH systems from solar radiation, and the painted tarp would act to reflect sunlight away from the radiator as it works to pump coolant throughout the rover.

2.1.4.4 Thermal Control Subsystem Manufacturing and Procurement Plans

Thermal Suppliers and Lead Times:

The thermal subsystem is reliant mainly upon the insulation, radiator, heat sink, and QT Py to capture and dissipate heat from the electrical and CDH subsystems. The

AC Outlet sells multi layer insulation, Amazon sells heatsinks and radiators fit for computer systems as an alternative to fans on the central processing unit (Amazon, 2024), and Adafruit sells mini processors and extensions that can measure their environments like Arduinos do. Each component has standard shipping within the United States, so a standard within 10 day shipping can be expected. When ordering the heatsink on Newegg, the website itself states delivery within 4 days for the Noctua NH-P1. This paired with the insulation roll, will be able to effectively regulate the temperature of the rover; keeping the necessary heat within the system, protecting the system from solar radiation, and regulating internal heat through the heatsink. Even though it states lead time, the team has a time margin of 2 months for all thermal components/materials. Given that many companies have not yet fully recovered from the COVID-19 pandemic chaotic schedules.

In the case that one or both of the primary suppliers for the thermal subsystem components are unavailable or unreliable, there are a number of alternative vendors with the setback of tendency toward higher pricing. An example for another multi layer insulation provider is Insulation4Less which promises UV resistance, prevents 97% of heat transfer, and is resistant to tear while also being able to do next business day delivery. For an alternative heatsink, one Noctua NH-D9L off of Amazon should be similar enough to the Noctua NH-P1 from Newegg and has a lead time of around 3 days.

Since the thermal subsystem relies entirely on outsourced components, there are many similar components that can substitute in for damaged or unavailable thermal components.

2.1.4.5 Thermal Control Subsystem Verification Plans

The below table helps dive deeper into the verification plans needed for the thermal subsystem of the rover. This subsystem will have a thermal sensor that will regulate itself based on the surrounding temperature to an appropriate range for optimal function. The below table goes more in depth on the rest of the verification methods listed for this subsystem.

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
TCS-1	System shall regulate itself to an appropriate temperature range	Analysis	Temperatures in shadowed regions of the moon can range from 88-100K	Conduct thermal analysis simulations under expected lunar temperature conditions to ensure the system can

	for functionality of all components.			regulate within required temperature ranges.
TCS-1.1	System shall not go below 138 K and above 358 K to ensure the proper functionality of all components	Analysis	Allows specified management to a temperature range for operability	Validate through thermal modeling and simulation, taking into account worst-case lunar environmental conditions and component operational temperature limits.
TCS-1.1.1	System shall generate 50 W of heat to support temperature control	Test	Provides source of heat for instruments in extremely cold PSRs	Perform thermal vacuum testing with integrated heating elements to ensure the system generates and maintains 50W of heat in simulated PSR conditions.
TCS-1.2	System shall prevent both overheating and excessive heat loss	Test	Solar radiation can cause thermal runaway while in PSRs the temperature can go below operable limits	Conduct thermal balance testing to simulate lunar day/night cycles, ensuring the system can manage both heat gain and loss effectively.
TCS-1.2.1	System shall utilize a Multi-Layer Insulation to mitigate temperatures passively	Inspection	Can prevent both overheating and heat loss through conductive barrier	Inspect and verify the installation and material properties of the MLI on all critical surfaces during assembly.
TCS-1.2.2	System shall use a radiator to expel any excess heat passively	Demonstration	Prevents possible overheating through waste heat dumping via IR	Demonstrate the radiator's capability to expel excess heat in a thermal vacuum test, monitoring the system's ability to maintain temperature within limits.
TCS-1.3	System shall have protective barriers on critical parts	Inspection	Pieces exposed directly to lunar regolith can be adversely affected by erosion, especially thermal control surfaces	Inspect the protective barriers on thermal control surfaces during assembly and perform post-deployment inspections.

Table 2.1.4.5.1 Thermal Subsystem Verification Methods

2.1.5 Payload Subsystem Overview

The spacecraft will be equipped with the VAPoR flight system, or the Volatile Analysis by Pyrolysis of Regolith in situ instrument. The purpose of the VAPoR system is to detect water and noble gasses in lunar regolith. As such, the VAPoR system simultaneously addresses both science goals; determining the water ice abundance in lunar regolith within and around Permanently Shadowed Regions, and investigating isotopic variations in lunar regolith to understand ancient cosmic and solar ray activity. This provides a sleeker and more cost efficient solution to instrumentation, as VAPoR will be able to comprehensively collect and test samples in lunar regolith.

VAPoR is a modified version of the Sample Analysis at Mars (SAM) instrument. While the SAM instrument weighs 40 kilograms and requires between 100-200 Watts of power, the VAPoR flight unit will weigh between 10 and 15 kilograms, and only require 50 to 60 Watts of power to complete testing. It is also much smaller, at about 20 dm^3. It is important to note that the VAPor flight unit is still being developed and the current breadboard has similar function to the SAM instrument. However, the VAPoR system makes lunar volatile sampling very effective. VAPoR uses six pyrolysis crucible ovens to heat samples up to 1400 degrees Celsius, allowing for the analysis of noble gasses. Noble gasses can only be released at temperatures above 1200 degrees Celsius. Crushed lunar regolith is poured into VAPoR's Solid Sample Intake Tube (SSIT) via a robotic scooping arm. The samples enter a vacuum sealed pyrolysis oven, where the six crucibles and samples are heated. Samples are then analyzed by a quadrupole mass spectrometer, which has a sensitivity of about 10^{-4} (counts/second)/(particle/cc). Currently, a miniature TOF-MS quadrupole mass spectrometer is being tested, with the objective of being more lightweight and sensitive to measurement. The mass resolution range and resolution for the miniature TOF-MS is about 500 m/Δm. This sensitivity will allow the spectrometer to identify the appearance of isotopes of Helium like He-3, which is integral to fulfilling scientific goals of determining the presence of different isotopes in lunar regolith.

The VAPoR system also contains an atmospheric inlet that allows samples to be collected directly around the spacecraft, which feeds directly into the mass spectrometer. There is also a getter and an atmospheric outlet that enable samples of noble gasses to be enriched, this also directly feeds into the mass spectrometer. VAPoR includes a residual gas analyzer, and is also equipped with multiple pressure sensors to ensure that the vacuum in the oven is functioning properly to ensure optimal heating is reached. The vacuum seal allows temperatures to reach up to 1400 degrees Celsius, which allows for the release of noble gasses and noble gas isotopes. The Residual Gas Analyzer (RGA) has a sensitivity of 2 x 10^{-4} A/torr, which enables it to make fine tuned measurements. The primary sample collection focus of vapor is to detect and analyze Carbon, Hydrogen, Oxygen, Nitrogen, and Sulfur. This aligns with the physical parameters within the scientific measurement requirements of identifying deposits of Carbon 13, 14, 15, Nitrogen 14 and 15, and Sulfur 32 and 34. VAPoR is also capable of measuring H_2O released from lunar regolith, which fulfills the scientific measurement requirement of identifying water ice molecules. By using drilling sample collection methods, the depth of water ice will be able to be measured up to one meter, which will deliver insights about the abundance of water ice in Permanently Shadowed Regions. VAPoR is also capable of testing Helium-3 and Helium-4 isotopes. The analysis of Helium-3 is important because it is indicative of solar activity on the moon, and poses an interesting opportunity to develop energy on the moon through nuclear fusion. The TOF-MS mass spectrometer analyzer has a carbon nanotube, focusing lens, field emission electric gun, steering/focusing lenses, a field reflectron, microchannel plate, and NiCr ion extraction. Electron ionization allows the spectrometer to pulse ion lens voltages, which allows the ion species to be accurately sorted by mass at the detector. Additionally, the Residual Gas Analyzer is able to measure the pressure of different glasses, and categorize them accordingly. H_2O had the greatest abundance at temperatures between 100-200 degrees Celsius, and between 1.0 x 10^{-6} and 1.5 x 10^{-6} torr. Helium isotopes were most present between 1.2 x 10^{-8} and 1.6 x 10^{-8} in the 300 to 1400 degree Celsius range (Kate et al 2010).

Currently, the VAPoR system has been tested on both a breadboard and system-wide level. This gives it, and the instrumentation payload, an overall TRL of six, where the system itself has been tested in a relevant environment. The function of the breadboard and sample analysis has been tested using a sample obtained from the Apollo 16 mission. Testing samples from Permanently Shadowed Regions on the Moon with VAPoR are promising based on test sample results. Due to colder temperatures, it is widely believed that there is a greater concentration of water ice and volatiles deposited by solar ray activity. VAPoR's test of the Apollo 16 lunar regolith sample was successfully able to measure volatiles released from lunar regolith, such as H2O+, CO2+, and N2+. It is critical to take steps to increase the overall TRL of the instrument to ensure the systems safety and efficacy. In 2011, the VAPoR field instrument was tested in a DRATS field test inside the DRATs Geolab (Glavin et al 2012). The TRL could be increased to a seven through testing the entire prototype in a lab that simulates the lunar environment. While VAPoR has a lower TRL than other considered systems, its unique advancements and capabilities for measuring noble gasses ultimately makes it key in understanding cosmic solar ray activity and aligns to the predetermined science objectives. It is a smaller, lighter, and more effective alternative to the SAM instrument, which has already been used on the Mars Curiosity Rover. VAPoR's foundation in a mission validated design enables its selection despite its lower TRL, as it is an active improvement of a system that has been proven to work effectively. This reduces some of the risk associated with using a newer system, and testing has shown that VAPoR's more sensitive mass spectrometer offers promising advancements in scientific measurements. VAPoR's comprehensive range of measurement also ensures that only one scientific instrument is needed on the mission, which reduces overall costs. As such, more time, effort, and budget are available to develop VAPoR and increase its TRL level. Therefore, it is ultimately the best choice of instrumentation for the scientific goals of determining water ice content in PSRs and understanding solar ray activity.

The additional science payloads will be the TRIDENT Drill and the Cold Operable Lunar Deployable (COLD) arm. The TRIDENT drill can take samples of lunar regolith up to a depth of one meter, and is a rotary percussive drill capable of cutting through ice in PSRs. It has a weight of 20 Kg, volume of 20.6 cm x 33.3 cm x 168 cm, and a maximum power draw of 100 Watts. TRIDENT has been used in missions before, and is at a TRL level eight. TRIDENT drills ten centimeters at a time, which enables the drill to continue to take samples without getting stuck. The drill then deposits samples onto the lunar surface using a passive brush, forming a pile (Zackny et al 2021). Normally, samples would be able to be analyzed directly on the surface, but VAPoR requires all samples be put into the Solid Sample Intake Tube, requiring the use of a robotic arm. The COLD arm is a robotic arm that is ideal for navigating extreme cold temperatures in PSRs. The COLD arm is specifically designed with gears and motors that don't require heating components to allow the arm to articulate, which helps save power in the spacecraft, enabling more effective sample collection. The COLD arm is 6.5 feet long, and has a small scoop that moves in four directions and is capable of transmitting samples to the SSIT. It has been tested in relevant extreme cold environments, granting it a TRL level of six, and is being developed by NASA's Jet Propulsion Laboratory (NASA 2024). With an overall TRL of six, the VAPoR flight instrument, TRIDENT drill, and COLD arm will be capable of fulfilling all outlined mission goals, and will ultimately advance understanding of lunar ice abundance and isotopic variations in lunar regolith.

The table below demonstrates the parameters of the instrument, which include mass, volume, and max power draw:

Instrument	Mass	Volume	Max Power Draw
VAPoR flight system	15 kilograms	20 dm^3	60 Watts

Table 2.1.5.1: VAPor Flight System Specifications

2.1.5.1 Science Instrumentation Requirements

The payload subsystem requirements have been derived from the mission requirements as a guideline for the spacecraft's payload and scientific instruments. These requirements must be met to satisfy customer requirements, and ensure that the mission meets all of its science goals. The design of the payload subsystem must be modeled based on the subsystem's ability to meet the science goals.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
PAY-1	The system shall not contain more than 2 science instruments.	Provided by the Mission Document	Customer	TBD	Inspection	Payload	Met
MR-1	The system shall determine water ice abundance in the lunar regolith.	Provided by the Mission Document	Customer	ESP-2, CDH-2	Demonstration	Payload	Met
MR-2	The system shall determine the isotopic variation of lunar regolith.	Provided by the Mission Document	Customer	ESP-2, CDH-2	Demonstration	Payload	Met
MR-3	The system shall gather water ice compounds and formations in the lunar regolith.	Provided by the Mission Document	Customer	ESP-2, CDH-2	Demonstration	Payload	Met
MR-4	The system shall determine volatile components in and around lunar permanently shadowed regions(PSRs).	Provided by the Mission Document	Customer	TCS-1, ESP-2, CDH-2	Demonstration	Payload	Met

Table 2.1.5.1.1: Payload Subsystem Requirements

2.1.5.2 Payload Subsystem Recovery and Redundancy Plans

The payload subsystem will use a software that will monitor certain parameters allowing for the smooth collection of samples and data. This software will be autonomous, thus it will not require any decisions from mission control. The software will monitor the amount of power the instruments use and the amount of power needed to measure data from the samples. If there are any irregularities monitored by the software, the system will perform a reboot inorder to ensure the accurate measurements of samples with minimal delay. The computer software will also use a compression data technique to allow for more measurements to be collected and prevent the data storage from maxing out too early. The software controls will allow for the elimination of error in the measurements from the VAPoR system and the TRIDENT drill.

The payload subsystem will not have a redundant subassembly due to the payload cost and large components. The VAPoR flight system, which includes its breadboard, spectrometer, and pyrolysis oven, is expensive and requires extensive testing. As such, the VAPoR flight system will be a Single Point Failure (SFP). The TRIDENT drill is also an expensive payload with a larger size, with dimensions of 20.6 cm x 33.3 cm x 168 cm. Therefore, it isn't realistic to have a redundant component of a drill subassembly, making TRIDENT another SFP. However, the VAPoR system collects samples through both a Solid Sample Intake Tube and an atmospheric inlet that takes samples from the environment around it. In a case where either the COLDArm or the drill fail, it would still be possible for VAPoR to complete sample analysis if compounds became airborne as the spacecraft navigates the lunar surface. Finally, the COLD arm is a larger component of the spacecraft, and is 6.5 feet long. While it is hypothetically possible to include a second COLD arm, this might interfere with the COLD arm's range of motion and articulation. Ultimately, the COLD arm will be another SFP. Due to the unique nature of the payload subsystem, it consists of Single Point Failures that are ultimately unable to have redundant subassemblies.

2.1.5.3 Payload Subsystem Manufacturing and Procurement Plans

The instrumentation subsystem is reliant on the VAPoR testing system to analyze lunar volatiles, and the COLD arm to transport samples to the VAPoR system's catalysis oven. Vapor is currently being developed at the Goddard Space center in Maryland (Kate et al 2010). The VAPoR system has been previously tested, but needs additional testing to increase its TRL level and achieve mission readiness. In 2011, the VAPoR field instrument was tested in a DRATS field test inside the DRATs Geolab Navarro-González et al 2010). Given that further refining is needed to fully develop VAPoR, including further testing to ensure the pyrolysis ovens function at optimal temperatures and ensuring accurate material analysis, lead times of six months to a year should be expected, at worst, two years of lead times. The COLD Arm is currently being developed at NASA's jet propulsion laboratory as part of the Lunar Surface Innovation Initiative (LSII). It is primarily made out of 3D printed titanium, and is still being evaluated for potential arm attachments (NASA 2024). It is already slated to be used on a commercial mission within the next five years. Given the COLD Arm's availability within NASA and that many parts are 3D printed, lead times between six months to a year can be expected.

2.1.5.4 Payload Subsystem Verification Plans

The verification matrix below demonstrates the payload subsystem's requirements, and the steps that will be taken to verify that all customer constraints and requirements for the subsystem are being met. Testing these functions will be completed through inspection and demonstration. The payload subsystem should be able to demonstrate that it is capable of recording and storing data from the required science goals as it completes its mission. This will result in accurate data and lead to overall mission success.

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PAY-1	The system shall not contain more than 2 science instruments.	Inspection	Visually recognize that the spacecraft meets customer constraints and outlines.	Review CAD models and spacecraft once built to ensure that only the VAPoR instrument has been added.
MR-1	The system shall determine water ice abundance in the lunar regolith.	Demonstration	The spacecraft must be able to detect water ice within the lunar regolith in permanently shadowed regions.	The spacecraft will demonstrate that it can store repeated and quantified data regarding the abundance of water ice in PSRs.
MR-2	The system shall determine the isotopic variation of lunar regolith.	Demonstration	The spacecraft should demonstrate the presence of different isotopes in the lunar regolith.	The spacecraft will demonstrate its ability to detect isotopic variations of Carbon, Nitrogen, Sulfur, and Helium, and will be able to store data for analysis.
MR-3	The system shall gather water ice compounds and formations in the lunar regolith.	Demonstration	The spacecraft must be able to demonstrate that it is capable of quantifying lunar ice deposits.	The spacecraft's modified TRIDENT will demonstrate its ability to effectively collect water ice samples from lunar regolith.
MR-4	The system shall determine volatile components in and around lunar permanently shadowed regions(PSRs).	Demonstration	The spacecraft must be capable of detecting lunar volatiles, such as water ice and isotopic variation, in the permanently shadowed regions.	The spacecraft's VAPoR system will demonstrate that it can accurately detect, categorize, and store data about volatile components in lunar PSRs.

Table 2.1.5.4.1 Payload Subsystem Verification Methods

2.2 Interface Control

Instrumentation is mounted to the chassis through conventional brackets and fasteners attached to ribs that span the entire chassis dimensions for maximum strength. Since the thermal management system services the entire interior, components do not need to be thermally isolated. Components are also not in use in motion, so no stabilization/gimballing is necessary for payload. Some shock absorption material, like rubber or foam, will be used to reduce violent dips and rises during motion.

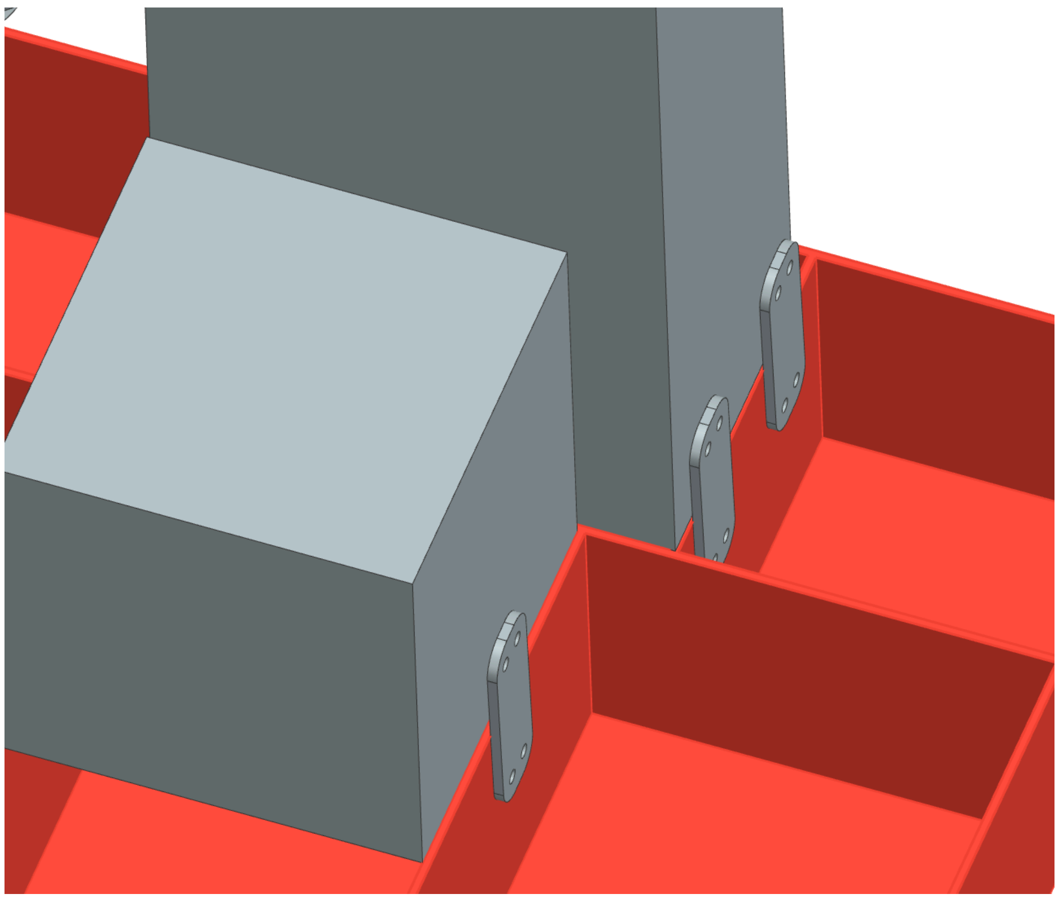


Figure 2.2.1. Mounting brackets between the ribs on the chassis (red) with TRIDENT (top) and VAPoR (bottom left).

Two 3/8in bolt holes provide stability for each payload mounting attachment point. The wall thickness of the ribs (5mm) will provide a space for shock-absorbent foam to be sandwiched between the bracket, and this provides slight mechanical/thermal isolation.

3. Science Mission Plan

3.1 Science Objectives

The first Mission Goal is determining the water ice abundance in lunar regolith within and around Permanently Shadowed Regions (PSRs). The Scientific Objectives of this Mission Goal are to determine concentration of water ice present in the lunar regolith and to determine the depth of water ice present in the lunar regolith to determine feasibility of use of water ice. Addressing these two goals will determine both the presence and amount of water ice in PSRs, to determine feasibility for use in deriving oxygen. Finding water ice within the lunar regolith will be both informative scientifically, and will be useful for future lunar settlements. The second Mission Goal is to investigate isotopic variations in lunar regolith to understand ancient solar and cosmic ray activity, which will be framed through the science objectives of determining whether solar activity has affected isotope variation in the lunar regolith and determining the extent of helium deposits in the lunar regolith. Finding whether deposits of isotopes Carbon 13, 14, 15, Nitrogen 14, 15, and Sulfur 32, 24 are present in the lunar regolith will be helpful for understanding ancient solar and cosmic ray activity. The presence of Helium-3 is not only indicative of solar activity on the Moon, but also poses an interesting opportunity to develop energy on the moon through nuclear fusion. PSRs may be particularly rich in the isotope Helium-3 due to extremely low temperatures.] The VAPoR analysis system will be able to take measurements of both water ice and isotopes in lunar regolith. Particularly, the VAPoR system is capable of detecting the presence of Helium-3, which is a distinct advantage to its use as a scientific instrument. The VAPoR system comprehensively addresses all science goals. The mission objectives are key to guiding the mission direction and Scientific Objectives, while adhering to stakeholder goals of determining water ice and isotopic deposits in PSRs on the Moon.

3.2 Experimental Logic, Approach, and Method of Investigation

The distinct goals of this mission are to determine the abundance of water ice in permanently shadowed regions on the lunar surface, and the presence of different isotopes in lunar regolith. As such the payload subsystem must be capable of recording accurate data to meet mission goals. The other spacecraft subsystems must seamlessly work to assist the payload subsystem in data collection. The mechanical subsystem was designed with instrumentation in mind. The wheels have a tread depth that will allow the spacecraft to seamlessly traverse the landing site and allow for sample collection. With this, the lightweight and strong chassis has independent steering and an active suspension system that allows the wheels to lift themselves. This allows the spacecraft to navigate lunar regolith more effectively, and will make it possible to lift important components, such as the VAPoR system, over potential obstacles. This will protect important components of the payload subsystem. Additionally, the mechanical subsystem has been designed to allow for the smoothest possible sample collection. A metal shell protects data analysis components of the payload subsystem, to prevent dust from damaging the function of scientific devices. This shell is also covered by a multi-layer insulation blanket, to ensure that the scientific instruments function at optimal temperatures. Multi Layer Insulation was determined to be most effective at regulating the spacecraft throughout both extremely hot and cold temperatures. Protections from the thermal subsystem allow the instrumentation to function effectively at a range of temperatures to ensure sample collection is completed. As outlined in the mechanical subsystems NX Cad sketches, instruments will be mounted to the spacecraft's chassis. This will allow for ideal sample collection, as the modified TRIDENT drill will have optimal placement to drill up samples. The COLDArm is placed in a position where it is able to fully articulate, and will transport samples from where TRIDENT has drilled them to the VAPoR system's Solid Sample Intake Tube.

The power subsystem provides the payload subsystem with power, which allows it to collect and analyze samples. The power subsystem will use solar panels to collect energy from the sun before entering the permanently shadowed regions. These panels can be spread across the spacecraft for optimal energy collection, and will be stored in Lithium Ion Batteries, to ensure that the spacecraft can continue to function in permanently shadowed regions. The batteries will be able to reach full charge after nine hours, and will allow the payload subsystem to collect data through the drill and scoop, then allow the VAPoR system to analyze samples for data. The rover may have to stop occasionally to recharge. The CDH subsystem works to meet the mission's science goals by recording data collected by VAPoR. The onboard computer, a RAD 750 processor, will provide the spacecraft with commands that will enable it to navigate between sample sites, will allow data to be collected, and samples to be analyzed. This computer has been used in NASA missions on the Moon and Mars, and its processing speed of 200 Mhz will allow it to quickly and effectively carry out commands. The CDH system uses a C-RAM 20M radiation-hardened non-volatile RAM by BAE Systems to record its memory, and can fix incorrectly transmitted data through the C-RAM's single-bit error correction feature. The CDH system completes the important task of storing data collected by VAPoR on a Mercury RH 304T Solid-State Data Recorder. This recorder has 4.5 TB of memory, and is capable of withstanding solar radiation. The recorder has failsafes in place for inaccurately recorded data, and will retire failed blocks if the spacecraft's power supply is interrupted. A key way the CDH subsystem allows scientific goals to be met is by communicating data back to Earth. The rover will utilize the Iris V2.2 SmallSat Deep Space Transponder designed by NASA's Jet Propulsion Laboratory (JPL) and the XANT X-band Patch Antenna produced by Cubecom. The transponder is compatible with NASA's Deep Space Network, Near Earth Network, and Space Network (NASA JPL n.d.). The CDH completes the important task of storing and transmitting data collected by scientific instruments, which is needed for mission completion.

Experimental collection is heavily reliant on the overall mission timeline. Samples must be collected from a variety of sites to prevent skewed data in sample collection. The spacecraft must also be able to verify its functionality after it lands, but before it enters the permanently shadowed regions. This involves completing a preliminary instrumentation check to ensure that the COLDArm, drill, and VAPoR system are all functioning optimally. The solar panels will be charged before entering the PSR to ensure that there is enough power to support all spacecraft subsystems. The rover would travel to site 1 at an average speed of 3 km/day for about 17 km. Taking about 6 days for the transverse process. It will send a telemetry signal every 2 hours to the orbiting satellite to actively communicate with the ground ops.

This plan was developed based on the location of the landing site. The distance to the edge of the permanently shadowed region from the landing site is about 3.4 kilometers as seen in Figure 3.2.1. Thus, the rover can stop at the edge of the permanently shadowed region in order to charge sufficiently. In order to ensure accurate measurements of the site, the rover will travel deep into the permanently shadowed region. Figure 3.2.2 shows the entire area covered by the permanently shadowed region. These JMARS images were used to determine the path of the rover, as well as the data collection sites, in order to ensure the data is obtained from accurate locations.
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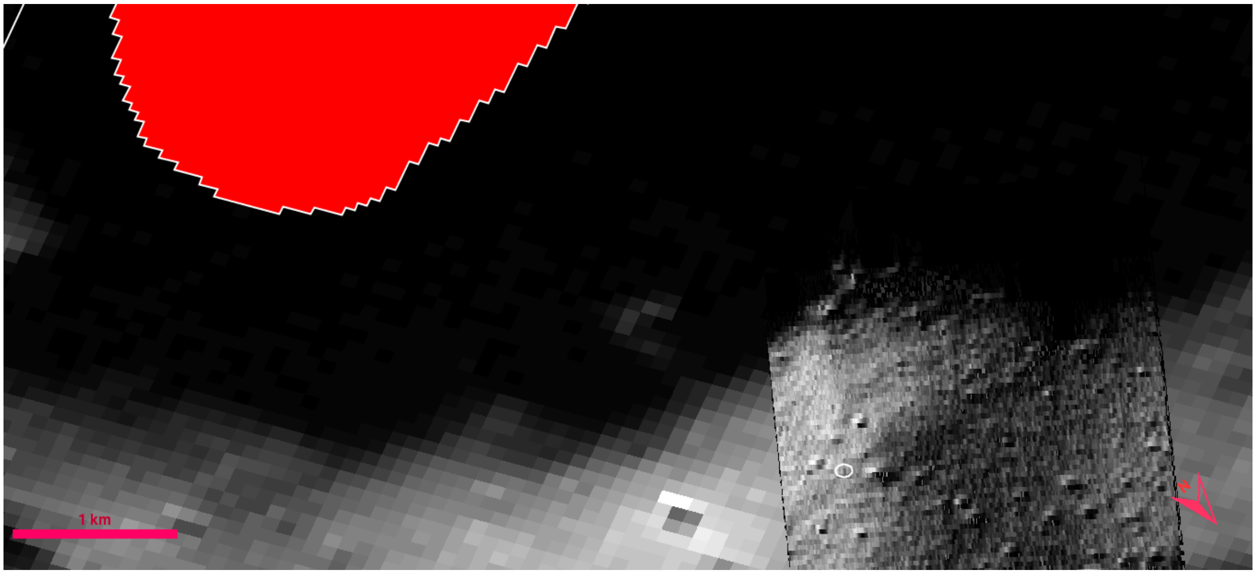


Figure 3.2.1 JMARS Image of site location

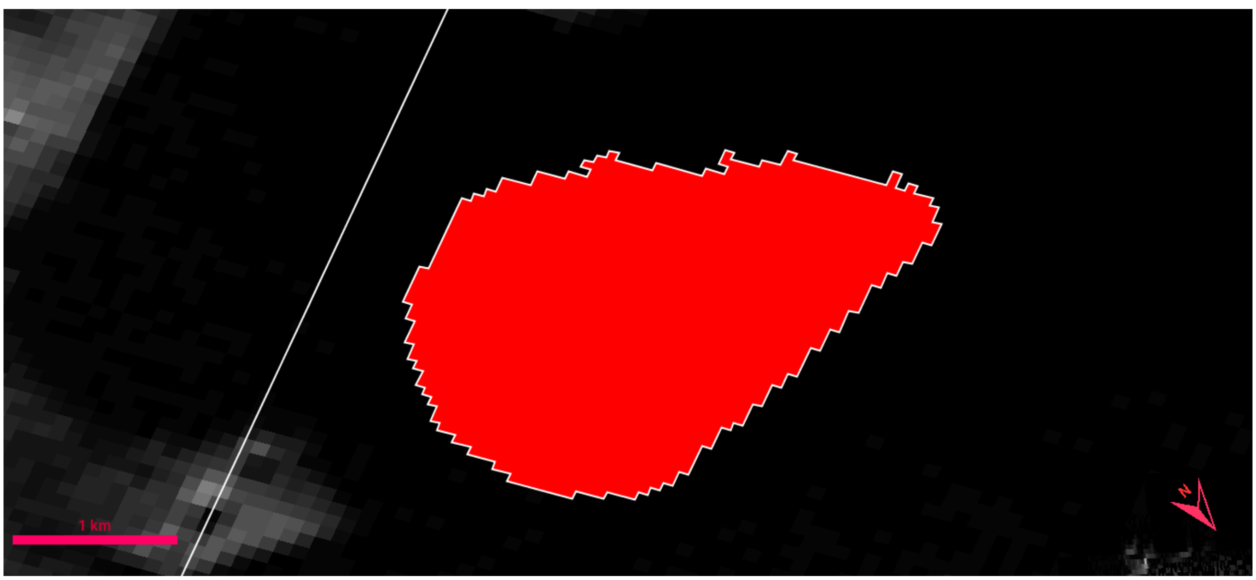


Figure 3.2.2 Site location JMARS Visual

Once the spacecraft arrives at the testing site, it will prepare itself to complete sample collection operations. The modified TRIDENT rotary percussive drill will take samples of lunar regolith every ten centimeters, until a depth of one meter is reached. This will allow the drill to complete sample collection without getting stuck in the frozen regolith. The drill will then use its passive brush to transfer samples from within the drill to a pile onto the lunar surface (Zackny et al 2021). Then, the COLDArm, which is capable of navigating the extreme cold temperatures within the PSR, will move samples from the pile deposited by the drill into VAPoR's Solid sample intake tube. The

COLDArm can articulate in four directions, granting it with ideal functionality for scooping and pouring samples. After entering the Solid Sample Intake Tube, the samples are then transferred to six crucibles within VAPoR's vacuum sealed pyrolysis oven, which is capable of heating samples up to 1400 degrees Celsius in the lunar environment. This is crucial for analyzing isotopes of noble gasses, such as Helium-3, which can only be released at temperatures above 1200 degrees Celsius. Samples are then analyzed by a quadrupole mass spectrometer, which has a sensitivity of about 10^{-4} (counts/second)/(particle/cc). Currently, a miniature TOF-MS quadrupole mass spectrometer is being tested, with the objective of being more lightweight and sensitive to measurement. The mass resolution range and resolution for the miniature TOF-MS is about 500 m/Δm. This sensitivity will allow the spectrometer to identify the appearance of isotopes of Helium like He-3, which is integral to fulfilling scientific goals of determining the presence of different isotopes in lunar regolith. To enrich noble gas samples, VAPoR's getter and atmospheric inlet transfers noble gasses to the mass spectrometer. Additionally, the VAPoR system has an atmospheric inlet that allows samples to be collected from around the spacecraft, which is helpful if gasses and other isotopes escape while being drilled. VAPoR's Residual Gas Analyzer, has a sensitivity of 2×10^{-4} A/torr, and it will ensure that VAPoR is functioning at optimal pressure, while measuring fine turned data. The TOF-MS mass spectrometer analyzer has a carbon nanotube, focusing lens, field emission electric gun, steering/focusing lenses, a field reflectron, microchannel plate, and NiCr ion extraction. Electron ionization allows the spectrometer to pulse ion lens voltages, which allows the ion species to be accurately sorted by mass at the detector. Additionally, the Residual Gas Analyzer is able to measure the pressure of different glasses, and categorize them accordingly. H_2O had the greatest abundance at temperatures between 100-200 degrees Celsius, and between 1.0×10^{-6} and 1.5×10^{-6} torr. Helium isotopes were most present between 1.2×10^{-8} and 1.6×10^{-8} in the 300 to 1400 degree Celsius range (Kate et al 2010). After completing necessary sample collection, the spacecraft will travel out of the PSR to recharge the solar panels, then repeat the sample collection process within the PSR as is needed.

Once the samples have been collected, the CDH subsystem will transmit the collected data to the orbiting satellite, which will then send the collected data back to Earth. It should take about 10 hours for the sample collection process. The rover will repeat transverse, science and data uplink for the duration of the mission, as there is only enough power to go from one of the sites to the rim of the PSR and back. It will repeat the process for 2 other sites prior to ending the mission. The mission would take 24 earth days to complete. Throughout the various phases of the mission, the thermal subsystem will regulate the temperature of the rover to ensure that all components remain within functional range. If all aspects of the engineering subsystems, site navigation, mission timeline, and data collection components function smoothly together, the mission will be capable of meeting all scientific goals. This will allow the mission to provide valuable information about the abundance of water ice and different isotopes in permanently shadowed regions on the lunar surface.

3.3 Payload Success Criteria

Failure modes for the instrumentation subsystem include factors that would stop instruments from functioning properly or could result in a loss of data. The main point of risk centers around the payload subsystem's ability to complete sample collection. If there was a loss in power, or samples were collected improperly, there would be an increased likelihood that the data the VAPoR system collects would not be accurate. The system itself does not have redundant subassemblies, and therefore carries a significant amount of risk because it is a single point failure. It is important to ensure that samples are collected and transferred to the VAPoR system without failure, so mission data can be collected. Given that there is only one copy of each instrumentation payload and scientific instrument, there is a possibility one may spontaneously fail, resulting in an inability to collect, transmit, or analyze samples, ultimately leading to a lack of data. Other failures include inaccurate sample collection - if particles are too large to be properly analyzed, or if the sample collection zone has lower than average deposits of various isotopes, data could be skewed inaccurately. The VAPoR system itself could break or malfunction, such as if the vacuum on the pyrolysis oven wasn't able to be sealed correctly, which would result in the oven not reaching temperatures suitable for sample analysis. As the VAPoR system is a single point failure, and is also responsible for the mission's data collection, it is imperative to understand its potential failures, in order to better recognize mission success.

There are also potential failure points from the modified TRIDENT drill and the COLDArm scoop. The biggest point of failure centers around the power subsystem's ability to provide power to all parts of the payload subsystem. If the spacecraft suddenly lost power, or the power subsystem stopped responding, it would negatively affect all aspects of the payload subsystem. The TRIDENT drill could stop running, and the COLDArm would lose its articulation abilities. This would result in a loss of viable sample collections. While drilling in frozen regolith, the TRIDENT could slow down or get stuck, which would limit sample collection. Finally, vibrations during travel could disrupt instruments, potentially dislodging them or breaking them entirely. This would inhibit the functionality of the payload subsystem, and limit its ability to collect samples.

Successful data collection is considered to be when sample analysis by the spacecraft comprehensively addressed the outlined science objectives. The mission aims to discover both the existence and abundance of water ice in Permanently

Shadowed Regions on the lunar surface. As such, successful data analysis should be able to quantify the abundance of water ice. This will occur by measuring samples of lunar regolith of up to one meter of depth. This will allow VAPoR to collect data on the presence of water ice in a repeated manner that will allow it to determine how much water ice is present in the testing sites within the PSR. The second goal of the mission is to determine the presence of different isotopes in lunar regolith to understand ancient cosmic and solar ray activity. As such, this objective will be considered successful as long as VAPoR is able to detect different isotopes of lunar volatiles, such as Carbon, Nitrogen, Sulfur, and Helium-3. Ideally, VAPoR would be able to quantify the amount of lunar volatiles within the testing site, to inform viability for different purposes like nuclear fusion of volatiles. However, if problems were to occur that prevented the VAPoR system from taking samples to the best of its ability, successful mission criteria dictate it must be able to primarily determine whether or not there are deposits of different isotopes in lunar regolith. Defining what comprises successful sample collection is necessary to parameterize overall mission success.

3.4 Testing and Calibration Measurements

Once the rover has arrived at the target body, the VAPoR system will begin to run some tests to ensure that any experiments conducted provide accurate data. It will run basic tests to guarantee there were no damages to the machine during the trip. After this, the focus will shift on confirming the abilities of the pyrolysis system. The system will be calibrated by heating up samples of the regolith, ensuring it can detect the gasses that are being released. The thermal sensors part of this system will also be tested. As the samples are heated up, the thermal sensor will be monitored to make sure the temperature readings are accurate. The spectrometer will also have to be calibrated. It will begin by running tests on samples to confirm its functionality. In order to confirm accurate measurements, a reference material must be used. Previous studies with the VAPoR system used Apollo 16 regolith samples to test functionality. A measurement can be compared to previous tests to authenticate the data being received. By monitoring these tests and ensuring the data received is as expected, the measurements received from the experiments will be accurate. If the tests provide data that do not align with the expected values, adjustments to the system will have to be made to account for the change.

Some tests will be conducted on the TRIDENT drill to ensure accurate measurements of the collected samples. Upon arrival of the target body, the instrument will perform basic tests to make sure the moving mechanisms are working. It will also perform simple drilling into the surface to make sure the system is working and that there was no damage to the drill or drill bit during the journey. During this process, the drill bit will be monitored to see the wear it undergoes when in contact with the surface. Based on this analysis, the system can judge the proper rotation speed of the bit to avoid damage that can alter the data. Similarly, monitoring these drill tests will provide answers to the optimal parameters for data collection. These parameters will include drill depth, torque of the drill, and temperature (avoid overheating). This information will allow the TRIDENT drill to operate efficiently in collecting the necessary samples for the mission.

After arriving at the target body, the COLDArm will run some basic tests to make sure it functions properly when transferring the samples. It will initially perform basic tests to ensure there was no damage during the transport. The COLDArm will also be tested to see if there is proper communication with the system as well as sufficient power. It will then perform simple movements to make sure it can move around as needed, as well as get samples to the desired locations of the VAPor system. If the COLDArm is moving as expected, then the experiments can continue as normal. If there is an issue with the movement, then adjustments will be made regarding the communication between systems.

https://ntrs.nasa.gov/citations/20240000585
https://www.nasa.gov/centers-and-facilities/kennedy/apollo-to-artemis-drilling-on-the-moon/

3.5 Precision and Accuracy of Instrumentation

The payload subsystem consists of the VAPoR system, or Volatile Analysis by Pyrolysis of the Regolith system. The VAPoR system includes a pyrolysis oven and a residual gas analyzer, which utilize a vacuum seal to ensure samples are heated to optimal temperatures for data collection. The Residual Gas Analyzer (RGA) has a sensitivity of 2 x 10^{-4} A/torr, allowing it to collect a range of fine-tuned measurements. This allows the RGA to detect differences between isotopes discovered in the lunar regolith (Kate et al 2010). In previous experiments, the VAPoR system has been tested to determine its functionality and measurement accuracy. The VAPoR system is capable of heating up to 1400 degrees Celsius, which allows it to record data pertaining to the release of noble gasses. Researchers found that the sample temperature of the VAPoR system has an acceptable range of accuracy of ± 5 degrees Celsius throughout the entire temperature range (Glavin et al 2012). Similarly, it is important for the VAPoR system's pyrolysis oven to provide a vacuum seal to maintain oven temperature and ensure sample collection is successful. Loss of the vacuum seal would contaminate samples and would prevent the oven from reaching temperatures capable of measuring noble gasses. Researchers found an acceptable range of accuracy for the vacuum seal force of ± 10 percent (Glavin et al 2012). The temperature range of the VAPoR system is 0 - 1400 degrees Celsuis, to allow for complete sample analysis. Water ice and lunar volatiles can be observed at a range of pressures by the VAPoR system, but demonstrate greater abundance around certain peaks. Any data that has been collected while the VAPoR system is functioning outside of its accurate range of measurement would be considered inaccurate, and would have to be discarded. Determining the acceptable range of precision and accuracy for scientific instrumentation ensures that all experimentation goals will be met, and that the returned results are scientifically acceptable.

en Kate, Inge, et al. 2010. "Characterization of Volatiles by Pyrolysis and Mass Spectrometry." https://science.gsfc.nasa.gov/691/analytical/PDF/tenKateetal2010.pdf.

Glavin et al: https://www.researchgate.net/publication/234006851_Volatile_Analysis_by_Pyrolysis_of_Regolith_for_Planetary_Resource_Exploration.

3.6 Expected Data & Analysis

The VAPoR system will be the instrument responsible for scientific analysis on the spacecraft. The primary sample collection focus of vapor is to detect and analyze Carbon, Hydrogen, Oxygen, Nitrogen, and Sulfur. This aligns with the physical parameters within the scientific measurement requirements of identifying deposits of Carbon 13, 14, 15, Nitrogen 14 and 15, and Sulfur 32 and 34. VAPoR is also capable of measuring H_2O released from lunar regolith, which fulfills the scientific measurement requirement of identifying water ice molecules. By using drilling sample collection methods, the depth of water ice will be able to be measured up to one meter, which will deliver insights about the abundance of water ice in Permanently Shadowed Regions. VAPoR is also capable of testing Helium-3 and Helium-4 isotopes. The analysis of Helium-3 is important because it is indicative of solar activity on the moon, and poses an interesting opportunity to develop energy on the moon through nuclear fusion. The TOF-MS mass spectrometer analyzer has a carbon nanotube, focusing lens, field emission electric gun, steering/focusing lenses, a field reflectron, microchannel plate, and NiCr ion extraction. Electron ionization allows the spectrometer to pulse ion lens voltages, which allows the ion species to be accurately sorted by mass at the detector. Additionally, the Residual Gas Analyzer is able to measure the pressure of different glasses, and categorize them accordingly. H_2O had the greatest abundance at temperatures between 100-200 degrees Celsius, and between 1.0×10^{-6} and 1.5×10^{-6} torr. Helium isotopes were most present between 1.2×10^{-8} and 1.6×10^{-8} in the 300 to 1400 degree Celsius range (Kate et al 2010).

Table 1. Release temperatures of gases targeted by the VAPoR pyrolysis mass spectrometer instrument for compound identification and isotopic analyses.[17]

	VAPoR target gases	Temperature range (°C)
CHONS-Inorganics	Atmospheric volatiles	Not applicable
	H_2O, H_2, CO_2, CO, N_2, SO_2	0-1400[6, 7, 18]
	$^{13}C/^{12}C$ ratio of CO_2	100-1400[18]
	$^{15}N/^{14}N$ ratio in N_2	600-1400[18]
	HDO/H_2O ratio	0-1400
Noble Gases	He, Ne, Ar	300-1400[18, 19]
	Isotope ratios ($^3He/^4He$, $^{36}Ar/^{40}Ar$)	He: 200-500[5] Ar: 300-1400[18, 20]
Organics	$^{13}C/^{12}C$ ratio in CO_2 from organics combustion	400-500[19]
	Volatile hydrocarbons: methane, ethane, benzene, amines, alcohols, formaldehyde	300-1000[18]
Other Resources	Water-ice in regolith	0-100
	O_2	1100-1400[5]
	Reduced inorganic gases such as HCN, NH_3, and H_2S	HCN/NH_3: 100-900[18] H_2S: 700-1300[6]
	^3He relative abundance	He: 200-500[5]
	^3He relative abundance	He: 200-500[5]

Figure 3.6.1 The image above depicts a table that states the ideal release temperatures of different gasses and organics that the VAPoR system is capable of analyzing. https://www.researchgate.net/publication/234006851_Volatile_Analysis_by_Pyrolysis_of_Regolith_for_Planetary_Resource_Exploration.

In 2010, researchers tested the VAPoR system to discover its analysis capabilities (Kate et al 2010). One major issue in testing is that there are no lunar samples from permanently shadowed regions. To remedy this, researchers selected two samples: sample 64801,53, a sub-sample from the Apollo 16 mission, and a sample from the Murchison meteorite. These samples were then grinded if needed, and fed into the VAPoR oven through the Solid Sample Intake Tube. The oven started at a temperature of 25 degrees Celsius and was increased incrementally until temperatures reached 1200 degrees. Then, the partial pressures released from the samples were tested and observed, to see what compounds the samples contained. VAPoR was capable of detecting H20, as well as Helium-4, demonstrating promising results for mission sampling. Results from the testing, which plot temperature and partial pressure, are demonstrated in the images below:

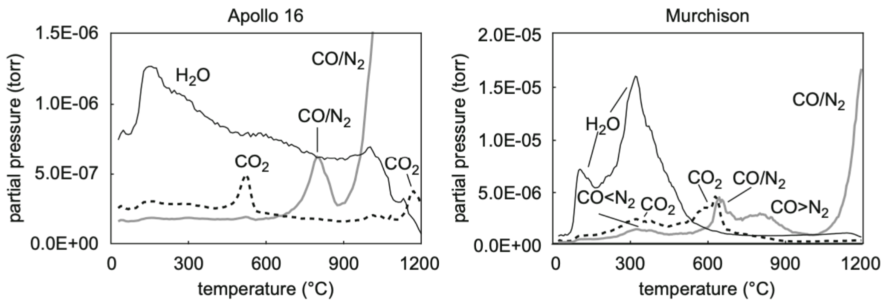


Fig. 5. Water, CO/N_2, and CO_2 evolved gas profiles as function of temperature for Apollo 16 and Murchison. Please note different scales on *y*-axis.

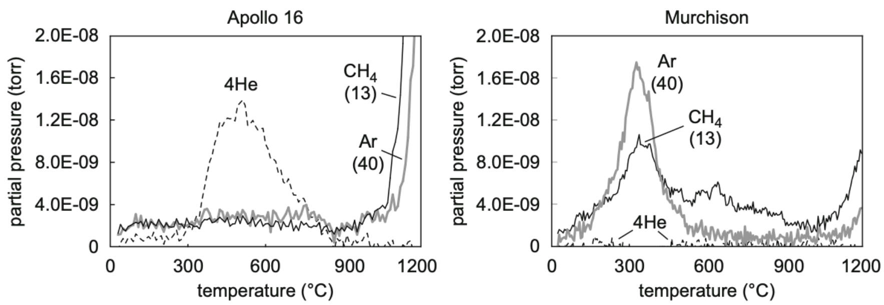


Fig. 6. Noble gases helium and argon, and methane (represented by m/z 13) evolved gas profiles as function of temperature for Apollo 16 and Murchison. The CH-fragment, m/z 13, of methane is shown because the methane contribution in its other fragments (12, 14, 15, 16, and 17) is too small to be distinguishable from other fragments at these m/zs. Please note different scales on *y*-axis.

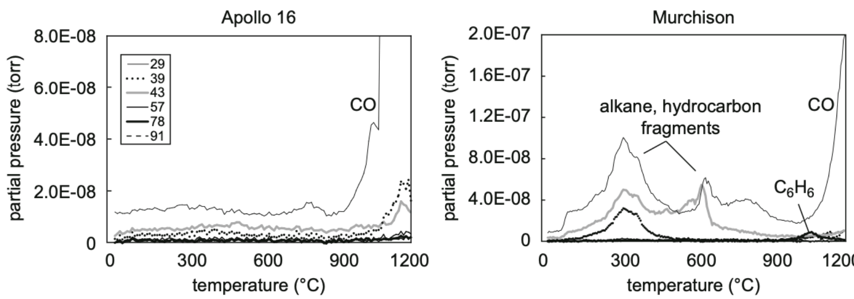


Fig. 7. Evolved gas profiles of hydrocarbon and alkane fragments as function of temperature for Apollo 16 and Murchison. Please note different scales on *y*-axis.

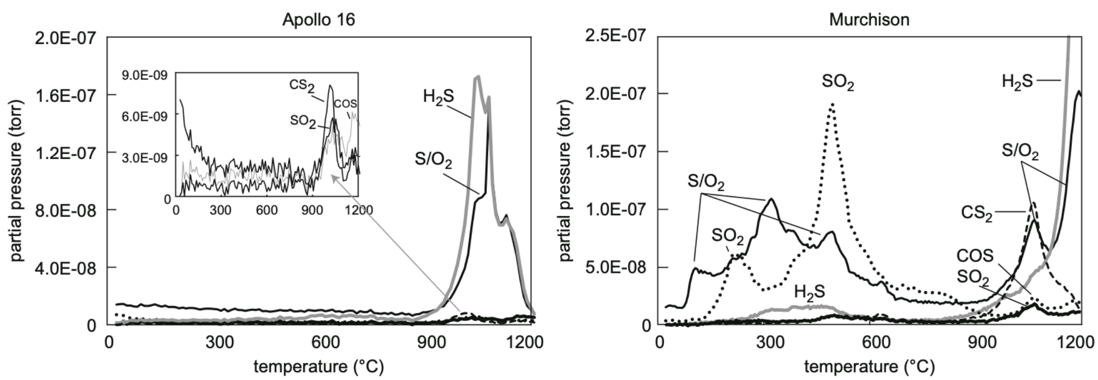


Fig. 8. Evolved gas profiles of the sulfur-bearing species SO_2, H_2S, COS and CS_2, and S/O_2 as function of temperature for Apollo 16 and Murchison. The inset in the Apollo 16 plot shows SO_2, COS, and CS_2 traces on a different scale as well to highlight their profiles at higher temperatures. Please note different scales on *y*-axis.

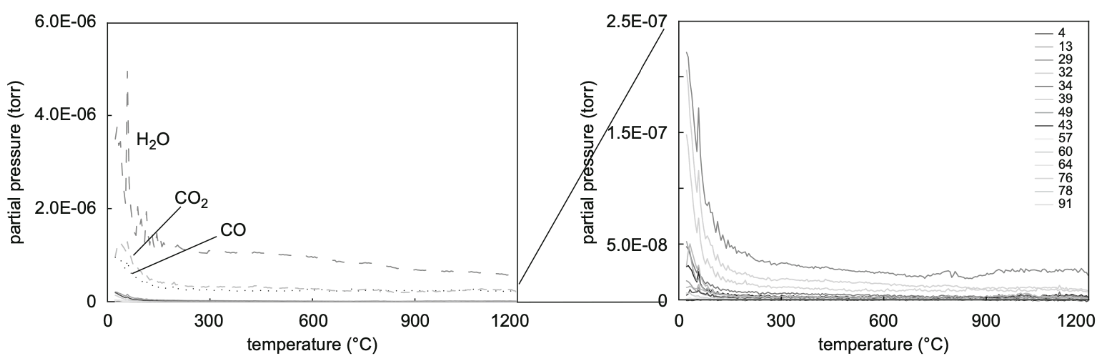


Fig. 9. Background evolved gas profiles of the VAPoR breadboard with an empty quartz sample holder. The left-hand plot shows all the fragments analyzed in this study. In the right-hand plot all fragments except H_2O, CO/N_2, and CO_2 are shown on a smaller scale.

Similar testing was completed in 2011 at the DRATs Geolab (Glavin et al 2012). Samples were collected from the Geolab field, and various rocks were analyzed to test how well VAPoR could function. In this test, samples from Earth were used. This test, whose results are shown below, was successfully able to characterize H20 from the collected sample. This demonstrates promising results for the spacecrafts test of lunar regolith within the PSR.
https://www.researchgate.net/publication/234006851_Volatile_Analysis_by_Pyrolysis_of_Regolith_for_Planetary_Resource_Exploration.

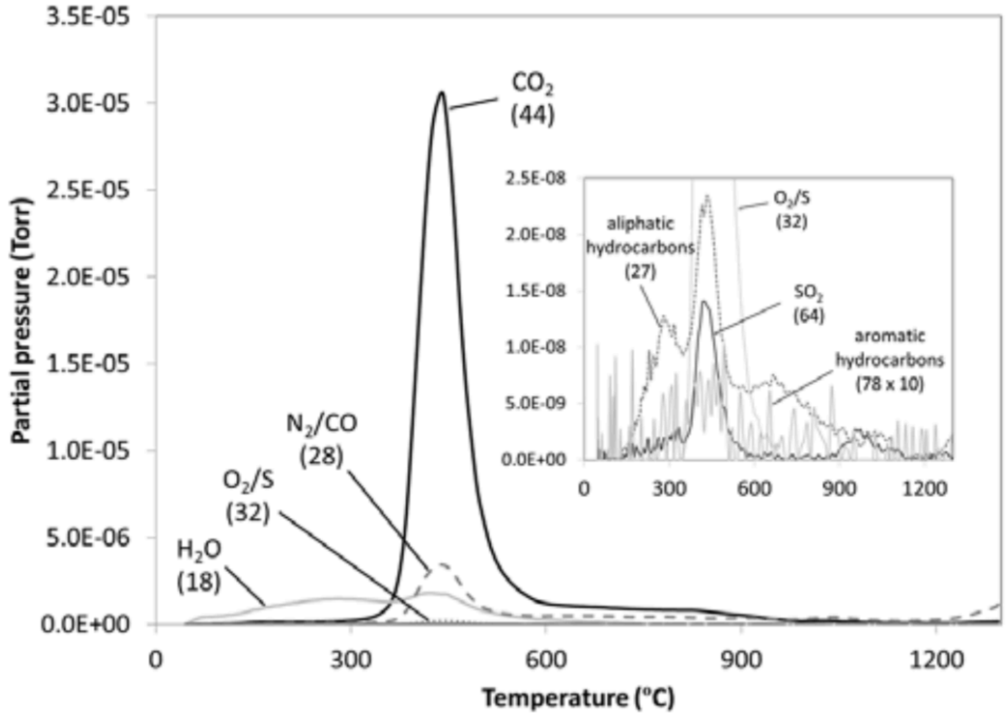


Fig. 9. VAPoR evolved gas analysis of DRATS sample 0212, a vesicular basalt collected at Black Point Lava Flow in Arizona, showing selected inorganic and organic volatiles released from the sample as a function of sample temperature.

While the tests were not able to analyze all desired compounds due to their lack of abundance on Earth or in samples, similar results should be expected during the mission. Many data points are already present through testing, and should be observed in regolith analysis. Once results are transmitted back to Earth, the data would then be interpreted to determine what volatiles are present within the lunar regolith. Repeated trials via testing in new sample locations will provide information about the abundance of different lunar volatiles. Data can be accepted as long as VAPoR functions within the boundaries of its accuracy and precision for the oven temperature, seal strength, and maintained pressure. Successful sample analysis will lead to results that help inform about the lunar environment in permanently shaded regions, and will advance scientific knowledge for future lunar missions.

4. Mission Risk Management

4.1 Safety and Hazard Overview

One of the methods of risk identification includes analyzing the unique constraints and challenges of the lunar environment. The harsh environmental hazards on the Moon introduces a wide variety of risks to various components included within the rover. The amount of testing conducted with specific components can also be used to estimate the amount of risks that will be discovered or are possible when using said components. Risks from past missions and projects can also be used to predict possible risks in this mission.

Identifying possible risks can be used to maintain good risk posture by enabling the mitigation and reduction of various risks, as well as introducing the opportunity to develop recovery, redundancy, and backup plans related to those risks.

A majority of the subsystems carry risks associated with lunar environmental hazards. These are often able to be mitigated through selecting products with higher TRL for that environment. The thermal subsystem reduces the risk for other subsystems to be damaged due to the extreme cold, while the mechanical subsystem reduces risk of damage from abrasive regolith. Some risks will need to be researched further in order to be mitigated. Risks with either low probability or low impact may be accepted.

Planetary protection and environmental concerns include damage that may be done to the lunar environment as a result of sample collection or damage to the rover. One risk is that materials could leak from the rover and cause environmental damage. Other risks include contamination of samples.

4.1.1 Risk Analysis

The risks of the mechanical subsystem come from either a lack of power or interference from environmental conditions on the lunar surface. Power risks could prevent the spacecraft from functioning properly, primarily if the spacecraft lost its ability to maneuver across the lunar surface. Failure to store energy could result in a sudden and complete loss of function of the mechanical subsystem. Furthermore, unforeseen variations in the lunar environment could obscure mechanical function by causing different aspects of the subsystem to break, become blocked, or move more slowly. While certain risks are unavoidable, ensuring there are redundant power subassemblies, accurate material selection, and informed manufacturing processes would mitigate the risks associated with the mechanical subsystem.

The main risks with the thermal subsystem itself that don't depend on the risks of the subsystems supplying it like power or mechanical, are the stresses put on the material and the contamination via lunar regolith. Thermal stresses can degrade material quality and thermal management effectiveness while lunar regolith contamination could seriously impact radiative emissivity and radiation cooling techniques on the MLI and radiator. Barriers or placing components high above the distribution of regolith during lunar movement would greatly reduce this risk, and using appropriate materials and doing thermal analysis would help sustain material integrity.

The primary sources of risk to the CDH subsystem are the extreme cold and radiation of the lunar environment. If components of the CDH subsystem are exposed to temperatures outside of their operating range or too much radiation, those components could become damaged and impair communications or data handling. There are two Single Point Failures within the subsystem that also pose risks. Due to the weight of the transponder, there is no redundant component included in the rover. There is also no duplicate data recorder, however, this component has built in redundancy reducing that risk. Errors in software also pose a risk to impairing the function of the rover.

Risks for the instrumentation subsystem include factors that would stop instruments from functioning properly or could result in a loss of data. The main point of risk centers around the payload subsystem's ability to complete sample collection. If there was a loss in power, or samples were collected improperly, there would be an increased likelihood that the data the VAPoR system collects would not be accurate. The system itself does not have redundant subassemblies, and therefore carries a significant amount of risk because it is a single point failure. It is important to ensure that samples are collected and transferred to the VAPoR system without failure, so mission data can be collected.

The main risks associated with programmatic are the limited budget and personnel. Given that there is a limited budget, issues can arise from underestimating the costs of development resulting in the need to make unexpected budget cuts lowering the budget to some or all departments within the team. The mission also has a high reliance for cutting edge technology for key mission components, budget cuts would result in needing to utilize sub-par systems or designs than what was intended for top-of-the-line technology and components. This can further lead to cost-overruns, late deliverables and compromised mission capabilities. A limited budget or even a blown budget could also result in cutting of personnel in key areas that are paramount to mission success.

Planetary Protection and Environmental risks are focused on ensuring the lunar environment remains stable and viable for future missions. As such, the spacecraft should aim to reduce disruption to the lunar environment and surface as much as possible. The main risks associated with planetary protection and the environment center around contamination of the Moon and the samples that the spacecraft aims to collect. Environmental risks include permanently damaging the Moon’s environment in a manner that is severely disruptive for future missions. The spacecraft won’t be bringing samples back to Earth, which reduces risks immensely. Ultimately, these risks are important to note to ensure that the Moon’s environment is respected, and can be utilized for scientific development in the future.

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Mechanical	4	2	➡	Accept	Given that the lunar surface contains abrasive particles and dust, exposure to the lunar environment may cause abrasion to exposed components, creating small wear and damage.	Active

2	Mechanical	1	4	⬇	Mitigate	Due to the vehicle being close to the ground, debris could reach and damage the motor, causing motor failure and preventing function and mobility of the vehicle.	Active
3	Mechanical	2	3	⬇	Accept	Because of the variations in the lunar surface, the wheels of the rover could get stuck, disrupting the vehicle’s only method of transportation and causing a loss of vehicle mobility and function.	Active
4	Mechanical	1	3	⬇	Mitigate	Given that chassis balance is required for full mobility of the vehicle, uneven payload distribution may cause the chassis to be unevenly balanced, limiting the mobility of the vehicle.	Active
5	Mechanical	3	2	➡	Accept	Given that the rover will disturb the lunar regolith as it moves, it could develop a build up of regolith in the interacting mechanical parts, causing a loss of function.	Active
6	Mechanical	3	2	➡	Accept	Given that motion sensing devices will be necessary for accurately maneuvering the spacecraft, lunar regolith disturbed by vehicle motion may obscure motion sensing devices, creating difficulty in maneuvering the spacecraft.	Active
7	Mechanical	3	3	⬇	Research	Given that extreme cold can impair the function of mechanical components, The extreme cold could have an impact on the mechanical subsystem, causing a loss of function to the rover.	Active

8	Mechanical	4	4	⬇	Research	Given that traveling can cause vibrations, the vibrations from traveling could cause the mechanical subsystem to break during transit, causing a loss of movement and measurement capabilities.	Active
9	Power				Mitigate	Given that exposure to the sun is necessary to keep power flowing through the rover, all electronics apart from the power supply must be shielded by insulation in order to prevent disablement by solar electromagnetic pulses.	Active
10	Power				Accept	Due to the fact that the power subsystem cannot self repair in the event that even one section shorts or overheats, the rover may gain even more power-related issues which will affect every other subsystem.	Active
11	CDH	2	5	⬇	Mitigate	Given that there is a large amount of solar radiation in the lunar environment, there is a possibility of critical components becoming damaged by radiation, causing failure of hardware components, resulting in data received from science instruments not being sent to the orbiting spacecraft.	Active
12	CDH	1	5	➡	Accept	Due to the fact that the CDH subsystem only includes one data recorder, if the data recorder becomes damaged, there is no redundancy for that component, and the system will not have a method of storing data.	Active
13	CDH	2	4	⬇	Mitigate	Due to the extreme cold of the lunar environment, there is a possibility that critical components could be exposed to temperatures outside of their functioning range, causing the CDH subsystem to malfunction.	Active

14	CDH	2	5	➡	Accept	Due to the fact that the CDH subsystem only contains one transponder, if the transponder is damaged, there is no redundancy for that component, preventing communication.	Active
15	Thermal	4	4	➡	Mitigate	Given that the lunar regolith is an abrasive and infiltrating substance, there is a high chance that dust covers exposed thermal units like radiators, reducing their thermal management capacity and stopping the proper regulation of internal temperatures.	Active
16	Thermal	4	2	➡	Accept	Given that many thermal cycles can affect the integrity of materials, there is likelihood that thermal materials like radiators or blankets will suffer some structural integrity compromises, which may affect thermal regulation performance by small amounts.	Active
17	Instrumentation	2	5	➡	Accept	Given that there is only one copy of each instrumentation payload and scientific instrument, there is a possibility one may spontaneously fail, resulting in an inability to collect, transmit, or analyze samples, ultimately leading to a lack of data.	Active
18	Instrumentation	2	3	➡	Research	As the VAPoR system favors smaller particle size when sampling, it is possible that some samples of lunar regolith drilled by TRIDENT are slightly larger than preferred, leading to potentially inaccurate measurements about volatiles in lunar regolith, resulting in skewed data.	Active

19	Instrumentation	3	5	⬇	Mitigate	Given that connection to the CDH subsystem is necessary for science instruments to function, hazards such as vibrations from vehicle movement could disconnect the science instruments, reducing articulation abilities and sample collection efficacy.	Active
20	Instrumentation	1	5	➡	Research	Given that the vacuum seal in the oven is necessary for sample analysis, vibrations from motion could damage the vacuum seal, disrupting the collection and accuracy of data.	Active
21	Instrumentation	2	1	➡	Accept	Considering that the mission aims to create an understanding of the volatiles and water ice present on the moon, the rover could land in a location with a lower than average quantity of water ice and volatiles, causing the instrumentation to not be able to create an accurate data collection.	Active
22	Instrumentation	2	4	➡	Mitigate	Given that the drill is susceptible to damage when collecting samples, sample collection could cause the drill to get stuck, resulting in a loss of viable sample collection.	Active
23	Instrumentation	4	4	➡	Research	Given that traveling will create vibrations in the rover, traveling on the lunar surface could cause vibrations that could dislodge, break, disrupt, or impair the function of science instruments, preventing accurate sample collection.	Active

24	Programmatics	3	5	➡	Accept	Given that there is a limited budget for the mission control, there is a possibility of overestimating the costs of development, resulting in the need to make unexpected budget cuts to compensate, thus failing to mitigate financial risks associated with the project.	Active
25	Programmatics			➡	Accept	Given the reliance on cutting-edge technology for key mission components, there is a possibility of unforeseen technical challenges or delays, affecting the development and integration of critical systems, potentially leading to significant schedule slippage, cost overruns, or compromised mission capabilities .	Active
26	Planetary Protection	2	2	➡	Accept	Given that future missions may be conducted to confirm or elaborate on the findings of this mission, the sample collection done on the moon during this mission may disrupt the available samples, causing future missions to collect inaccurate data.	Active
27	Planetary Protection	3	2	⬇	Mitigate	Given that the samples could become damaged during collection, removing samples from the regolith could cause the samples to become contaminated.	Active
28	Planetary Protection	1	3	⬇	Mitigate	Given that there are materials on the rover that could be harmful to the lunar environment, chemicals and materials could leak onto the moon, changing the makeup and safety of the lunar surface.	Active

29	Environmental	2	2	⬇	Accept	Given that the rover will be conducting sample collection, The removal of samples could cause a disruption to the lunar environment, possibly releasing new volatiles into the environment.	Active
30	Environmental	3	1	⬇	Accept	Given that sample collection removes substances from the environment, the collection of samples could cause a change of composition to the lunar regolith.	Active
31	Environmental	5	1	⬇	Accept	Given that the rover is not from the lunar environment, if the rover is not returned to earth, the rover will become environmental debris on the moon’s surface.	Active

Table 4.1.1 Risk Analysis Table

LIKELIHOOD					
5	20	17	19		
4		22		8, 15	
3	28		7		
2		29		16	
1		21	30		31
	1	2	3	4	5
	CONSEQUENCES				

Table 4.1.2 Risk Analysis Graphic

4.1.2 Failure Mode and Effect Analysis (FMEA)

The FEMA risks, as outlined in the table below, track the highest priority risks from the risk matrix. These include mechanical, thermal, power, and instrumentation risks. The risks are given a risk priority number based on their likelihood of occurrence, their severity, and how easily they can be detected. In the FEMA table the highest priority risks were the derailment of Mission Scope and the power sub system failure when the sun's rays heats up the internals. We see that these two risks truly impact the rest of the sub-systems and therefore they tend to have a big risk factor score. The poor scope management risk impacts the rest of the sub-systems by utilizing resources such as budget and personnel for objectives that don't closely correlate with this mission's goals. This can be a drain of money and can even affect the policies and regulations placed by NASA. The team can mitigate such derailment by having experienced management personnel as well as management who has the company's best interest at play. By having management attend weekly meetings and updating upper management about the everyday tasks, there is a better chance that derailment of project scopes could be catched before it's too close to the launch date. Having management attend and actively engage in meetings, can also prevent many of the small mistakes that one can make from the lack of knowledge.

Changing gears to the power sub-system failure, we see that this failure also affects a majority of the other sub-systems and it's hard to mitigate. Since there is a lack of atmosphere on the moon and the rover requires solar rays to charge the internal batteries for operation we run the risk of the heat from the sun affecting internal components. The rover would be made from aluminum which also holds on to the heat from the sun. Without proper insulation or proper insulation installation we would run into the issue of harming the electrical components inside. With proper testing and Finite Element Analysis we can mitigate some of these potential concerns. We would have a temperature sensor to depict the internal temperatures at all times.

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Mechanical Subsystem - Motor	Debris could get into the motor from the lunar surface.	Motor gets clogged and fails to run properly.	9	Risk was accepted rather than mitigated.	5	Build protections or coverings around motor.	4	180	Reenforce coverings around motor.
	Motor is close to the ground and could scrape lunar surface.	Motor is scraped and damaged, or is entirely broken.	8	Testing was skipped to determine proper motor placement.	7	Determine a motor height that gives it appropritate clearance.	2	112	Redesign motor to be in a different location on the spacecraft.
	Electrical issues could stop the motor from recieving power.	Motor loses power and stops functioning.	10	Components could be manufactured or connected improperly.	6	Test to make sure electrcal and motor systems are wired properly and are responding promptly.	2	120	Add redundancies for power connections to the motor.
Mechanical Subsystem - Vibrations	Vibrations could cause different components of the spacecraft to break during the mission.	Spacecraft could have a limited range of motion due to damage.	7	Strength testing of mechanical subsystem was not completed.	6	Complete vibrational tests of the spacecraft to see how it responds to	2	84	Modify spacecraft design to become more resistant to vibration damage.
		Instrumentation subsystem could fail to measure and record scientific	10	Instrumentation subsystem was not tested for vibrations.	8	Secure and test components of instrumentation subsystem.	3	240	Further reenforce instrumentation components.
		Thermal protections could break or malfunction, exposing the spacecraft to extreme cold.	8	Vibrational tests were not completed and breaking points were not discovered.	7	Test temperatures to see how components function when exposed to extreme cold.	4	224	Add extra thermal protections or reenforce existing thermal proections.

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
CDH Subsystem- Error Codes	There is a possibility that there will be one or more errors in the version of Robot Operating System 2 installed on the rover	Freezes system for rover	8	Broken Code	5	Code Break Down	4	160	Review code several times
		Can't process ground commands	8	Contengincies in the code have come to a halt	7	Peer Review Code	4	224	Test code
		Can't transmit data to orbiter	9						Simulate code in said enviroment
				Malfunction, Reboot	2	Shut rover off accidently	5		
Thermal Subsystem	There is a possibility that critical components could be exposed to temperatures outside of their functioning range.	The CDH subsystem to malfunction	9	Improper installation	5	Inspection of unit	1	45	Descope to insulation alternatives
		Mechanical Systems over work	8	Insulation is broken	6				
		Electrical Systems condensate	9			Simulated Enviroment Testing			Longer Verification process

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Thermal Sub-System	There is a high chance that dust covers exposed thermal units.	Reduces their thermal management capacity	9	Given that the lunar regolith is an abrasive and infiltrating substance	4	Model simulation	3	108	Further Testing
		Stops the proper regulation of internal temperatures.	8			Simulated Enviroment testing			Inspection of all seals
Power Sub-System- Solar	Solar Power heats up other components	Heats up internal components	9	Lack of solar ray deterants	8	Conduct proper research for components used	4	288	Simulation Testing
	Inefficient battery charge	Mission behind schedule	8	Improper electrical components	7		3	168	Material Science Specialist Involvement
	Solar panels are dusty, scratched	Can't absorb the suns rays to charge batteries	10	Incorrect material for solar panels	5		1	50	FEA model simulation

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Programmatic subsystem	Going over budget	Budget cuts for other departments	10	Unexpected errors, fines, penalties	6	Follow regulations and policies	1	60	Training for all Personnel
	Going over schedule	Less time to do other admin tasks	8	Short Staff due to illness, personal reasons	8	Have a back up plan and personnel	3	192	Reward system for coming to work
	Poor Scope Management	Budget and Timelines spents on the wrong objectives	8	Poor priority setting	6	Hire Management with similar company interests and experience	8	384	Training and meeting on the objectives of the company

Figure 4.1.2.1 FMEA Table outlining risks and mitigation plan

4.1.3 Personnel Hazards and Mitigations

1. Chemical exposure
    - ❖ From cleaning solvents, adhesives, and other materials used in manufacturing and testing
        - ➢ Mitigation: Proper ventilation, PPE, safety data sheets, chemical hygiene plans.

2. Electrical hazards
    - ❖ During component testing, wiring, and system integration
        - ➢ Mitigation: Insulated tools, proper grounding, lockout/tagout procedures.

3. Mechanical injuries
    - From manufacturing equipment, assembly processes
        - Mitigation: Machine guarding, safety interlocks, proper training.

4. Ergonomic strain
    - Due to repetitive tasks or awkward positions during assembly and testing
        - Mitigation: Ergonomic workstations, job rotation, proper lifting techniques.

5. Eye strain and vision hazards
    - From precision work, welding, or prolonged computer use
        - Mitigation: Proper lighting, protective eyewear, regular breaks.

6. Noise-induced hearing loss
    - From machining and testing equipment
        - Mitigation: Hearing protection, sound barriers, equipment maintenance.

7. Cuts and lacerations
    - Handling sharp tools or materials during fabrication and assembly
        - Mitigation: Cut-resistant gloves, proper tool handling training.

8. Burns
    - From soldering, welding, or handling recently machined parts
        - Mitigation: Heat-resistant gloves, cooling periods, awareness training.

9. Crushing or pinching injuries
    - During movement of large components or use of hydraulic equipment
        - Mitigation: Safety zones, proper equipment operation training.

10. Falls from height
    - While working on tall structures or elevated platforms
        - Mitigation: Fall protection equipment, proper scaffolding, safety harnesses.

11. Exposure to fumes
    - From soldering, welding, or composite material work
        - Mitigation: Local exhaust ventilation, respirators, proper ventilation.

12. Laser injuries
    - ❖ During alignment procedures or testing of optical systems
        - ➢ Mitigation: Laser safety goggles, beam enclosures, warning systems.

13. Compressed gas hazards
    - ❖ From use of gas cylinders in testing or manufacturing processes
        - ➢ Mitigation: Proper storage, handling procedures, pressure relief devices.

14. Repetitive strain injuries
    - ❖ Due to repeated motions in assembly or computer work
        - ➢ Mitigation: Ergonomic tools, work breaks, proper technique training.

15. Slip and trip hazards
    - ❖ From cables, equipment, or spills in work areas
        - ➢ Mitigation: Good housekeeping, cable management, non-slip flooring.

16. Psychological stress
    - ❖ Due to project deadlines, high-stakes work, or long hours
        - ➢ Mitigation: Stress management programs, clear communication, proper scheduling.

17. Fatigue-related errors
    - ❖ From extended work periods or night shifts
        - ➢ Mitigation: Work hour limits, fatigue management policies, adequate rest periods.

18. Radiation exposure
    - ❖ During testing of communication equipment or power systems
        - ➢ Mitigation: Shielding, limited exposure times, radiation monitoring.

19. Static electricity damage
    - ❖ To sensitive electronic components during handling
        - ➢ Mitigation: ESD-safe workstations, grounding straps, humidity control.

20. Confined space hazards
    - ❖ While working inside spacecraft modules or test chambers

        - ➢ Mitigation: Confined space entry procedures, air monitoring, buddy system.

21. Fire hazards
    - ❖ When working with flammable chemicals or high-oxygen atmospheres
        - ➢ Mitigation: thorough cleaning of test surfaces to prevent ignition, separation of fuels and oxidizers during testing

General mitigations:

- ❖ Comprehensive safety training specific to each phase of mission development.
- ❖ Regular safety inspections and audits of work areas and processes.
- ❖ Clear safety procedures and protocols for all tasks.
- ❖ Incident reporting and investigation systems.
- ❖ Emergency response plans and regular drills.
- ❖ Proper signage and labeling in all work areas.
- ❖ Regular maintenance and inspection of all equipment
- ❖ Appropriate personal protective equipment for each task
- ❖ Risk assessments before implementing new procedures or equipment

5. Activity Plan

5.1 Project Management Approach

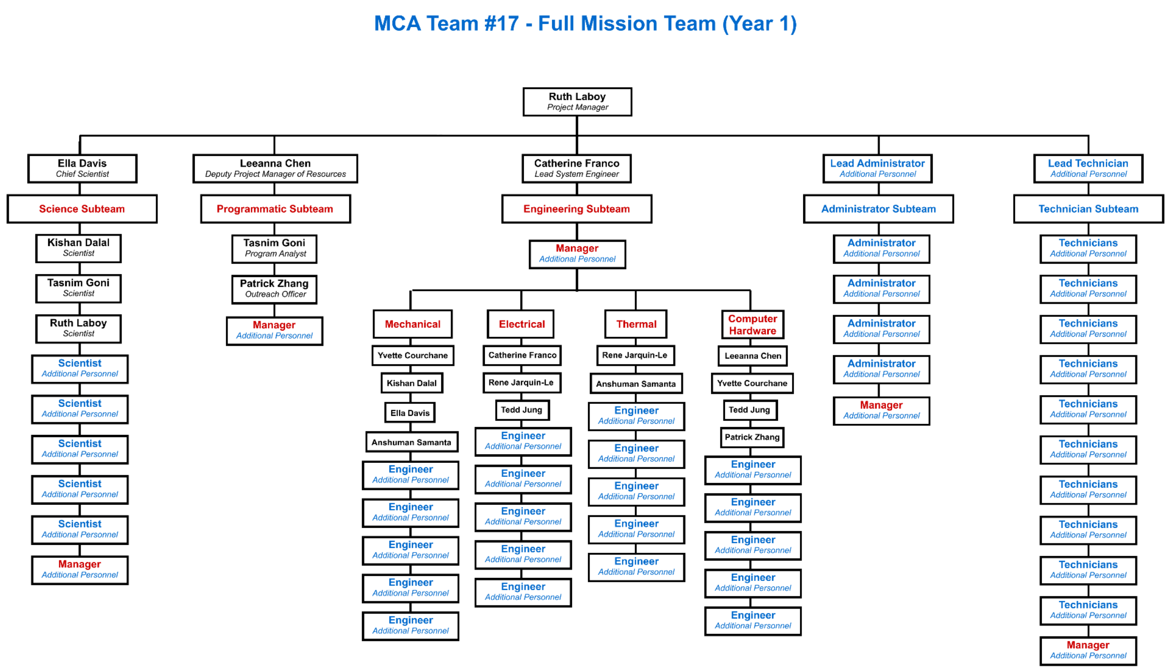


Figure 5.1.1: Organizational chart for full mission team including additional personnel

Personnel	Year 1 (C)	Year 2 (C)	Year 3 (C-D)	Year 4 (D)	Year 5 (E)	Year 6 (F)
Scientists	5	5	5	5	20	20
Engineers	20	15	15	15	15	15
Technicians	10	10	10	10	0	0
Administrators	4	4	4	4	4	4
Managers	5	5	5	5	5	5

Table 5.1.1: Additional personnel needed to accomplish mission Phases C-F

All subteams have their own hierarchy for smooth deliveries of tasks and to coordinate communications more closely. The engineers are responsible for crafting innovative, functional, and cost-effective systems that address the research findings of scientists. Engineers are skilled in designing prototypes that fit the needs of science instruments and the mission's success criteria, as well as reallocating personnel resources when needed. The scientists are skilled in gathering data to devise solutions that fulfill the mission's success criteria. The scientists are also responsible for keeping track of payload costs. The engineers and scientists work closely together across their subteams. The technicians are skilled in assisting the engineers with manufacturing, installing, repairing, and maintaining the electrical circuits and systems for the instrument. Technicians have the technical knowledge necessary to interpret the engineers' design specifications. The administrators and managers are responsible for overseeing the progress of subteams. Administrators and managers are skilled in adjusting the budget and schedule if the project scope changes. The proposed organizational structure for the rover mission project emphasizes a balance between specialized expertise and cross-functional collaboration. The science subteam, responsible for overseeing the VAPOR system and DRILL, forms the core of the scientific endeavor. To ensure mission qualifications are met, individual scientists may be assigned to other engineering systems as well. Engineers and technicians are distributed across various subsystems, with each subsystem having a designated lead engineer. The structure includes at least one administrator and manager per team, with an overall manager overseeing all subsystems to maintain cohesion and direction.

Subteams are granted significant autonomy in developing and optimizing their respective subsystems. This autonomy extends to budget authority, with each subteam allocated a specific amount for their rover subsystem development. It's important to note that this budget is separate from the personnel budget, which covers salaries, travel, insurance, and other related expenses.

The skill set required for this project is diverse and specialized. Engineers are expected to have deep knowledge of their assigned subsystem, as well as familiarity with at least one other area to facilitate resource reallocation when necessary. Managers and administrators play a crucial role in overseeing progress, adjusting timelines, and managing budgets to meet project goals. They also handle external communications, including outreach and contractor relations. Scientists are tasked with maintaining a clear understanding of the mission's objectives and ensuring that all subsystems meet the necessary qualifications through testing, working closely with engineers to achieve this.

This organizational structure aims to foster innovation and efficiency within individual teams while maintaining overall project cohesion and progress toward the mission's goals. By combining specialized expertise with cross-functional oversight, the project is well-positioned to address the complex challenges of rover mission development and execution.

5.2 Mission Schedule

5.2.1 Schedule Basis of Estimate

Key Drivers

The launch date of September 1st, 2028 was a critical driver in developing the mission schedule. This date was determined based on optimal planetary alignment for the mission trajectory, available launch windows, and NASA's overall mission portfolio and resource allocation. The expected annual funding allocations also influenced the pace of development across different mission phases.

Ground Rules

Following NASA guidelines, schedule margins were incorporated, including 1 month per year for Phases A-C, 2 months per year for Phase D, and 1 month per year for Phases E-F. Standard NASA review cycles were factored in, including the System Requirements Review (SRR), Preliminary Design Review (PDR), and Mission Definition Review (MDR). A standard 40-hour work week was assumed for all personnel, with provisions for overtime during critical periods.

Assumptions

Regarding personnel, a core team will be maintained throughout the mission lifecycle, with 10% additional schedule time included for onboarding and training new team members. A turnover rate of 5% per year was assumed. For the supply chain, a 3-month buffer was added to account for potential disruptions, and long-lead items were identified early with procurement scheduled accordingly. Testing and integration assumptions included 3 months for environmental testing and 6 months for system integration. External factors assumed no major budget cuts or policy changes affecting the mission, and standard regulatory approval timelines were factored into the schedule.

Budget Basis of Estimate

All cost estimates assume a projected inflation rate of 2.1% by 2028. The provided budget accounts for all phases after the PDR (Phase C-F), with pre-Phase A, Phase A, and Phase B considered sunk costs. Annual salary scales were provided including scientists, engineers, technicians, administration, and managers. Costs are broken down per mission phase and accounted for in USD with the assumed inflation rate applied.

Payments will be made in periodic installments, with 33% completion milestones for all suppliers/contractors and final payment contingent on successful product/service walk-through. The fiscal year will follow the calendar year for easier comparison with historical data.

A 15% reserve is included for known-unknowns, and a 10% contingency is allocated for unknowns. Operations costs are based on similar past missions, adjusted for mission duration and complexity, and include ground system operations, data processing, and science team support. This basis of estimate provides a foundation for understanding the schedule and budget development process and should be reviewed and updated regularly as the mission progresses.

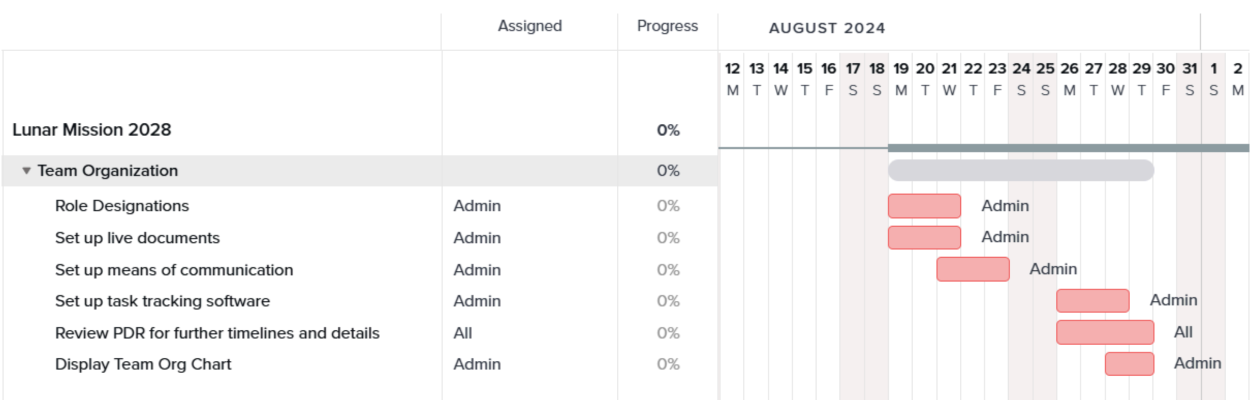
5.2.2 Mission Schedule

The team has broken down the major milestones for the mission. The below table has listed the start and end date for only the major milestones from phases C-F. These are the milestones that would help the team determine if we are behind or on schedule. The major timeline indicators for phase C would be the System Integration Review (SIR)(end of phase C), the Post-Launch Assessment Review (PLAR) (end of phase D), the Decommissioning Review(DR)(end of phase E) and the Final Archival of Data (end of phase F). The table below also contains the start and end date of those phases with the number of days that phase would last. Below in Figure 1.9.2.3 there is a more in depth breakdown of the tasks from phases C-F. The team referred to NASA's Systems Engineering Handbook to get more detail on the tasks and some of the major milestones that would significantly impact the mission. The Nasa's Systems Engineering Handbook also helped the team know the order of events for the schedule planning and Gantt chart. Some challenges that were encountered during the draw up of the Gantt chart were in regards to the conditional formatting of the template provided. Once rows were altered the template would no longer add the conditional formatting rules to the pertaining cells. This has been corrected prior to the submission of the PDR by using TeamGantt to ease the editing of the gantt chart. The way the team selected dates for the schedule based on the sub-system lead times for supplies, materials, assembly as well as the usual review time needed for admin to review submitted deliverables in the past (about 2 weeks).

High Level View of Mission Schedule

Task	Start Date	End Date	Days
Develop Final Design	8/29/2024	12/29/2024	123
Develop Final Procedures	12/30/2024	03/31/2025	92
Fabrication	4/1/2025	05/1/2026	396
Critical Design Review (CDR)	05/2/2026	5/16/2026	15
System Integration Review (SIR)	05/17/2026	5/30/2026	14
System Assembly	06/1/2026	6/1/2027	366
System Integration	6/2/2027	6/29/2028	394
System Test	7/01/2027	6/30/2028	365
Operational Readiness Review (ORR)	7/01/2028	7/31/2028	31
Mission Readiness Review (MRR)	8/01/2028	8/31/2028	31
Launch	09/01/2028	09/01/2028	1
Operation and Sustainment	09/01/2028	09/24/2028	24
Post-Launch Assessment Review (PLAR)	09/02/2028	09/23/2028	22
End of Mission	9/24/2028	9/24/2028	1
Decommissioning Review (DR)	09/25/2028	10/25/2028	31
Closeout	10/26/2028	10/26/2028	1
Disposal Readiness Review (DRR)	10/27/2028	11/9/2028	14
Final Archival of Data	11/10/2028	12/10/2028	31

Figure 5.2.2.2 Detailed High Level View of Mission Schedule (Phase C-F)



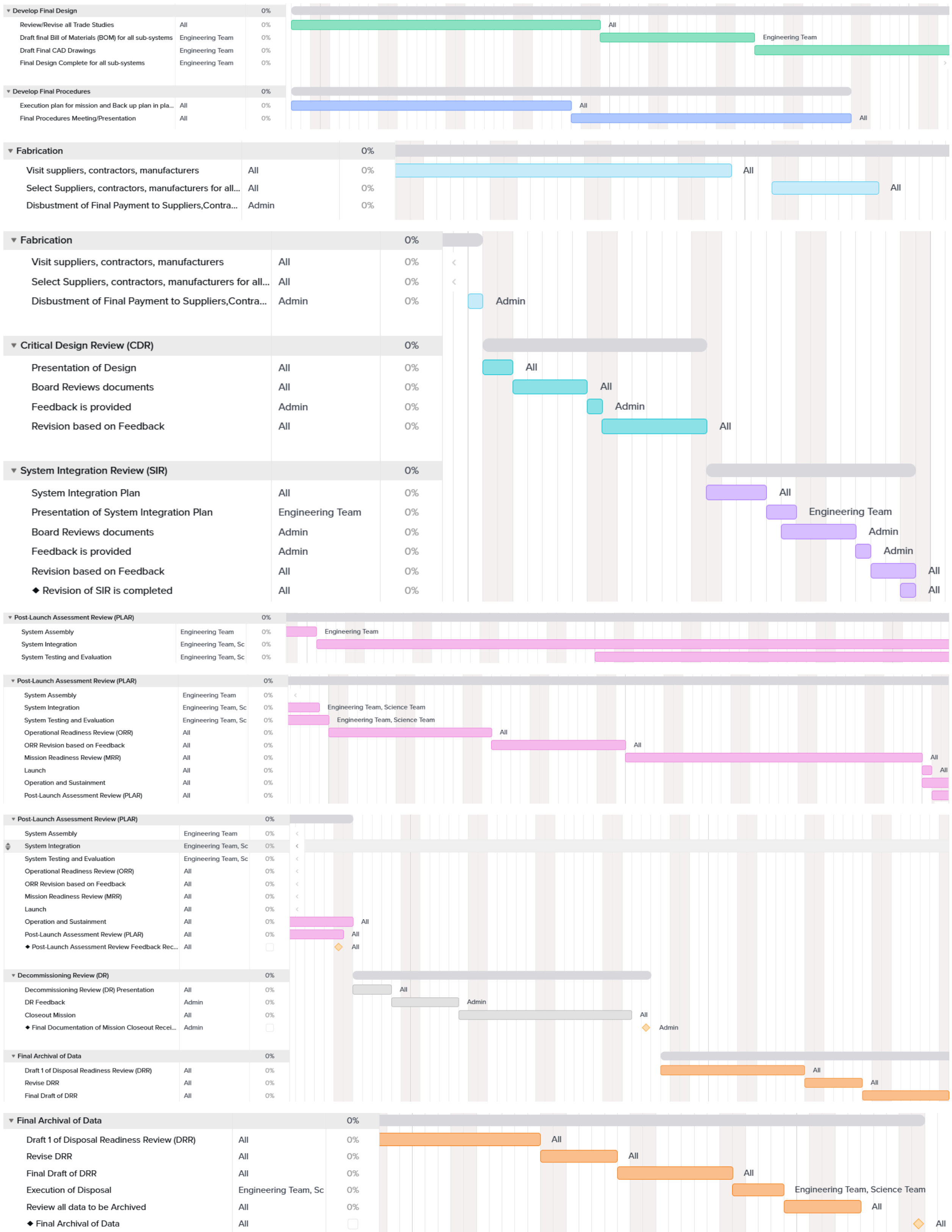


Figure 5.2.2.3 Gantt chart with break down of tasks from Phases C-F

5.3 Budget

5.3.1 Budget Basis of Estimate

When developing the budget and making estimates, constraints were included in the process to ensure that potential factors were accounted for and that all costs were calculated in a standard format. All trips, other than the launch, were calculated using the rates for Washington D.C, assuming all major meetings and check-ins are to be held at NASA headquarters.

A critical driver of the final budget was the descoping announcement. The team evaluated which areas of the mission were most critical to its successful completion and determined that the science objectives and rover functionality were the priority of the budget. Because of this, the personnel budget and associated costs such as travel and outreach had the highest constraints and suffered the most loss from the descope.

5.3.2 Total Mission Cost

The total mission cost is estimated to be around $175 million. Personnel takes up roughly $31 million. Total travel costs around $1 million. Outreach events require nearly $2 million. The rest of the budget goes to direct costs and resulting margin at around $135 million.

NASA L'SPACE Mission Concept Academy Budget

Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative Total**
PERSONNEL							
Science Personnel	$ 400,000	$ 410,400	$ 420,800	$ 431,200	$ 1,766,400	$ 1,808,000	$ 5,236,800
Engineering Personnel	$ 1,600,000	$ 1,231,200	$ 1,262,400	$ 1,293,600	$ 1,324,800	$ 1,356,000	$ 8,068,000
Technicians	$ 600,000	$ 615,600	$ 631,200	$ 646,800	$ -	$ -	$ 2,493,600
Administration Personnel	$ 240,000	$ 246,240	$ 252,480	$ 258,720	$ 264,960	$ 271,200	$ 1,533,600
Project Management	$ 600,000	$ 615,600	$ 631,200	$ 646,800	$ 662,400	$ 678,000	$ 3,834,000
Total Salaries	$ 3,440,000	$ 3,119,040	$ 3,198,080	$ 3,277,120	$ 4,018,560	$ 4,113,200	**$ 21,166,000**
Total ERE	$ 960,104	$ 870,524	$ 892,584	$ 914,644	$ 1,121,580	$ 1,147,994	**$ 5,907,431**
Personnel Margin	$ 340,000	$ 310,000	$ 320,000	$ 330,000	$ 400,000	$ 410,000	**$ 2,110,000**
TOTAL PERSONNEL	$ 4,740,104	$ 4,411,353	$ 4,640,019	$ 4,874,462	$ 6,116,315	$ 6,408,449	$ 31,190,701

TRAVEL							
Total Flights Cost	$ 27,200	$ 27,200	$ 23,200	$ 31,200	$ 35,200	$ 58,400	**$ 202,400**
Total Hotel Cost	$ 53,040	$ 53,040	$ 45,240	$ 93,955	$ 68,640	$ 113,880	**$ 427,795**
Total Transportation Cost	$ 1,000	$ 1,000	$ 1,000	$ 2,000	$ 2,000	$ 4,000	**$ 11,000**
Total Per Diem Cost	$ 17,510	$ 17,510	$ 14,935	$ 33,742	$ 22,660	$ 37,595	**$ 143,952**
Travel Margin	$ 10,000	$ 10,000	$ 9,000	$ 16,000	$ 13,000	$ 21,400	**$ 79,400**
Total Travel Costs	$ 108,750	$ 111,578	$ 98,231	$ 190,695	$ 156,216	$ 265,861	**$ 931,330**
OUTREACH							
Total Outreach Materials	$ 275,000	$ 275,000	$ 50,000	$ 50,000	$ 50,000	$ 50,000	**$ 750,000**
Total Outreach Venue Costs	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	**$ 120,000**
Total Outreach Travel Costs	$ 60,000	$ 60,000	$ 60,000	$ 60,000	$ 60,000	$ 60,000	**$ 360,000**
Total Outreach Services Costs	$ 30,000	$ 30,000	$ 30,000	$ 30,000	$ 30,000	$ 30,000	**$ 180,000**
Total Outreach Personnel Costs	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	**$ 120,000**
Outreach Margin	$ 40,000	$ 40,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	**$ 160,000**
Total Outreach Costs	$ 445,000	$ 456,570	$ 210,400	$ 215,600	$ 220,800	$ 226,000	**$ 1,774,370**
DIRECT COSTS							
Mechanical Subsystem	$ 5,000,000	$ 5,000,000	$ 3,000,000	$ -	$ -	$ -	**$ 13,000,000**
Power Subsystem	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ -	$ -	$ -	**$ 3,000,000**
Thermal Control Subsystem	$ 1,000	$ 1,000	$ 1,000	$ -	$ -	$ -	**$ 3,000**
Comms & Data Handling Subsystem	$ 2,000,000	$ 2,000,000	$ 1,500,000	$ -	$ -	$ -	**$ 5,500,000**
Guidance, Nav, & Control Subsystem	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ -	$ -	$ -	**$ 3,000,000**
Science Instrumentation	$ 20,000,000	$ 20,000,000	$ 8,700,000	$ -	$ -	$ -	**$ 48,700,000**
Spacecraft Cost Margin	$ 14,000,000	$ 14,000,000	$ 7,000,000	$ -	$ -	$ -	**$ 35,000,000**
Total Spacecraft Direct Costs	$ 43,001,000	$ 44,119,026	$ 23,355,452	$ -	$ -	$ -	**$ 110,475,478**
Manufacturing Facility Cost	$ 4,000,000	$ 4,000,000	$ 2,000,000	$ -	$ -	$ -	**$ 10,000,000**
Test Facility Cost	$ 4,000,000	$ 4,000,000	$ 2,000,000	$ -	$ -	$ -	**$ 10,000,000**
Facility Cost Margin	$ 1,000,000	$ 1,000,000	$ 500,000	$ -	$ -	$ -	**$ 2,500,000**
Total Facilities Costs	$ 9,000,000	$ 9,234,000	$ 4,734,000	$ -	$ -	$ -	**$ 22,968,000**
Total Direct Costs	$ 52,001,000	$ 53,353,026	$ 28,089,452	$ -	$ -	$ -	**$ 133,443,478**
Total MTDC	$ 43,001,000	$ 44,119,026	$ 23,355,452	$ -	$ -	$ -	**$ 110,475,478**
FINAL COST CALCULATIONS							
Total F&A	$ 2,900,100	$ 3,011,903	$ 1,635,545	$ -	$ -	$ -	**$ 7,547,548**
Total Projected Cost	$ 60,194,954	$ 61,344,429	$ 34,673,646	$ 5,280,757	$ 6,493,331	$ 6,900,310	**$ 174,887,427**
Total Cost Margin	$ 15,390,000 25.6%	$ 15,360,000 25.0%	$ 7,849,000 22.6%	$ 366,000 6.9%	$ 433,000 6.7%	$ 451,400 6.5%	**$ 39,849,400**
Total Project Cost	$ 60,194,954	$ 61,344,429	$ 34,673,646	$ 5,280,757	$ 6,493,331	$ 6,900,310	**$ 174,887,427**

Figure 5.3.2.1 Complete Budget Breakdown

5.3.3 Personnel Budget

The total budget allocated for personnel is around $31 million, which is about 17 percent of the total mission budget. The total personnel of the mission will change over its course according to the needs of each phase. All employees will be full-time and compensated as such. Personnel rates, inflation rates, and margins were all deduced from the academy's Project Management slides and Budget Template tool.

For phases C and D, there is a decrease in the number of scientists and an increase in the number of engineers and technicians. Phases C and D primarily focus on the design and assembly of the rover. Because of this, the necessity of scientists is low and is kept at a minimum to still assist the engineers in making sure the rover meets science requirements while keeping the budget cost low. Engineers and technicians are necessary in these phases to ensure manufacturing and testing goals are completed.

For phases E and F, there is an increase in the number of scientists and the removal of technicians. Phase E and F occur after the rover is launched. The primary focus at this time is the current operation and sustainment of the rover in achieving its science goals until the close of the mission. More scientists are required at this stage to study the data collected from the rover. Technicians are no longer needed as no more manufacturing or assembly is required. The number of engineers remains similar to previous phases to maintain the rover in its duration on the moon.

The amount of administrators and managers remains constant throughout the mission. The manager and administrators are responsible for ensuring all mission tasks are met promptly, as well as assisting with external business affairs. There is a necessity for both jobs in all phases, and there is only a little variance in the total staff, meaning that all related staff will stay on board until the completion of the mission.

There is also an ERE margin to ensure that the staff is properly accommodated and an overall personnel margin of 10% of each year's total salary, rounded to the closest ten thousand, set aside for any issues that may arise during the mission.

Personnel	**Year 1 (C)**	**Year 2 (C)**	**Year 3 (C-D)**	**Year 4 (D)**	**Year 5 (E)**	**Year 6 (F)**
Scientists	5	5	5	5	20	20
Engineers	20	15	15	15	15	15
Technicians	10	10	10	10	0	0
Administrators	4	4	4	4	4	4
Managers	5	5	5	5	5	5
Sum	44	39	39	39	44	44

Table 5.3.3.1 Number of personnel needed for Phases C-F

PERSONNEL							
Science Personnel	$ 400,000	$ 410,400	$ 420,800	$ 431,200	$ 1,766,400	$ 1,808,000	$ 5,236,800
Engineering Personnel	$ 1,600,000	$ 1,231,200	$ 1,262,400	$ 1,293,600	$ 1,324,800	$ 1,356,000	$ 8,068,000
Technicians	$ 600,000	$ 615,600	$ 631,200	$ 646,800	$ -	$ -	$ 2,493,600
Administration Personnel	$ 240,000	$ 246,240	$ 252,480	$ 258,720	$ 264,960	$ 271,200	$ 1,533,600
Project Management	$ 600,000	$ 615,600	$ 631,200	$ 646,800	$ 662,400	$ 678,000	$ 3,834,000
Total Salaries	$ 3,440,000	$ 3,119,040	$ 3,198,080	$ 3,277,120	$ 4,018,560	$ 4,113,200	**$ 21,166,000**
Total ERE	$ 960,104	$ 870,524	$ 892,584	$ 914,644	$ 1,121,580	$ 1,147,994	**$ 5,907,431**
Personnel Margin	$ 340,000	$ 310,000	$ 320,000	$ 330,000	$ 400,000	$ 410,000	**$ 2,110,000**
TOTAL PERSONNEL	$ 4,740,104	$ 4,411,353	$ 4,640,019	$ 4,874,462	$ 6,116,315	$ 6,408,449	$ 31,190,701

Figure 5.3.3.2 Break down of Personnel needed and Expenses associated with Personnel

5.3.4 Travel Budget

The total budget allocated for travel is around $820 thousand, which is about 0.4 percent of the total mission budget. There will be a total of six weeks of travel, with the fourth year having two consecutive weeks, and in the second week, more staff will join those that already traveled in the first week. There will be no travel in the second year, hence no associated travel costs. To calculate the lodging and per diem cost, the U.S. General Services Administration tool was used. For the lodging cost, the peak price of the 2024 FY was rounded up to the nearest five in all calculations. Flights were calculated using round-trip, economy class, and the ticket from Seattle because it is the furthest major city from both Washington D.C. and Cape Canaveral on the Google Flights tool. Estimates were done by looking at the median flight price of current (August 10-14) prices.

In the first year, the mission team, not including the ten technicians, will convene for a one week meeting. The per diem cost for meals on the first and last days are $60 and normally are $79. For one week of travel that is $60 for two days and $79 for five days. The team will only need lodging of six nights, assuming travel on the last day. The lodging per diem value is $260. Adding these values up and multiplying by 34 team members gives us roughly $17k for per diem fees and $53k for hotel fees.

While there is no designated week of travel in the second year, the budget includes fees for an additional week of travel similar to the first year if needed. Meaning that all calculations were done using the same values and assumptions of the first year, including enough budget for 34 team members. This was included to account for any budget required to travel to testing locations or in-person meetings.

The third year, there will be another week of travel that also does not include the ten technicians. Because the location of travel will be the same as the first, the same values for meals and lodging were used. However, there are 10 less team members traveling so the total values were multiplied by 24 team members.

In the fourth year, the rover is launched. There will be a one week meeting prior to the launch date, in which all but the technicians will convene at Cape Canaveral. Following the launch, there will be another week for the team to celebrate, being joined by the ten technicians. According to the U.S. General Services Administration tool, in Cape Canaveral the per diem for meals is $55 on days of travel and $74 on normal days. The calculations were broken into two groups: team members staying consecutively for the two weeks and the additional technicians staying for only one week. For the consecutive stay, there would be 12 days of non-travel and 2 days of travel. For the technicians, there would be 5 days of non-travel and 2 days of travel. The lodging fee is $215 a night with the majority of the team needing 13 nights of stay and the ten technicians would only need 6 nights of stay. Multiplying each group by the amount of team members that correspond (29 members staying 2 consecutive weeks, 10 members staying 1 week) gives a total per diem cost of $34k and hotel cost of $94k.

After the launch, more scientists are brought onboard the team to meet science objectives. There will be one week of travel for the entire team to get situated with new tasks, goals, and staff. Once again, the calculations for this year used the per diem costs for Washington D.C like in the first and third year. This year, 44 team members will be traveling.

In the final year, there will be a week of travel for only scientists, admin, and managers to follow up on the mission objectives and update on progress made. Later in the year, there will be a separate week of travel for the current entire team to close out the mission and celebrate. Using the same values as the first, third, and fifth year, the first week was calculated with 29 members and the second week was calculated with all 44 members of the team.

Each year was given a transportation budget that correlated with the amount of staff and consecutive weeks of travel in that year. All years of travel were also given a ten percent margin of that year's budget before inflation.

TRAVEL							
Total Flights Cost	$ 27,200	$ 27,200	$ 23,200	$ 31,200	$ 35,200	$ 58,400	**$ 202,400**
Total Hotel Cost	$ 53,040	$ 53,040	$ 45,240	$ 93,955	$ 68,640	$ 113,880	**$ 427,795**
Total Transportation Cost	$ 1,000	$ 1,000	$ 1,000	$ 2,000	$ 2,000	$ 4,000	**$ 11,000**
Total Per Diem Cost	$ 17,510	$ 17,510	$ 14,935	$ 33,742	$ 22,660	$ 37,595	**$ 143,952**
Travel Margin	$ 10,000	$ 10,000	$ 9,000	$ 16,000	$ 13,000	$ 21,400	**$ 79,400**
Total Travel Costs	$ 108,750	$ 111,578	$ 98,231	$ 190,695	$ 156,216	$ 265,861	**$ 931,330**

Figure 5.3.4.1 Travel Expense Breakdown

5.3.5 Outreach Budget

The total budget allocated for outreach is $1.78 Million, which is roughly one percent of the total mission budget. The primary bulk of the budget is directed towards the first and second year, before the rocket is launched, to build momentum and public approval for the mission.

In the first and second year, a majority of the costs will go to outreach materials. The primary focus of these two years is targeting schools, whether they are primary, secondary, or college level. These school visits will require lots of funding towards activities and associated materials. According to NASA, building a rover following the

JPL guide can cost as little as $2,500. For these reasons, the outreach materials budget is very high to accommodate funding for as many visits and rover projects for schools as possible. In later years, the outreach material cost is substantially decreased as there is less support to keep funding rover projects.

Venue costs for colleges are around $1k for a full-day rental (UMD). Using this information, each year was given a substantial amount for multiple days of renting out college-level sized conference areas or balancing fewer days of renting for larger venue locations.

Travel, service, and personnel costs remain constant throughout the years to accommodate any times of need. Personnel makes up the least of the budget as part of the administrative team will help with outreach planning. At most, some workers or volunteers will be hired on a need-by-need basis. Travelling is kept at a minimum and will only be used for speakers and event presenters.

Lastly, roughly a 10% margin of the total outreach cost for each year was applied for any issues that may arise.

OUTREACH							
Total Outreach Materials	$ 275,000	$ 275,000	$ 50,000	$ 50,000	$ 50,000	$ 50,000	**$ 750,000**
Total Outreach Venue Costs	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	**$ 120,000**
Total Outreach Travel Costs	$ 60,000	$ 60,000	$ 60,000	$ 60,000	$ 60,000	$ 60,000	**$ 360,000**
Total Outreach Services Costs	$ 30,000	$ 30,000	$ 30,000	$ 30,000	$ 30,000	$ 30,000	**$ 180,000**
Total Outreach Personnel Costs	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	**$ 120,000**
Outreach Margin	$ 40,000	$ 40,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	**$ 160,000**
Total Outreach Costs	$ 445,000	$ 456,570	$ 210,400	$ 215,600	$ 220,800	$ 226,000	**$ 1,774,370**

Figure 5.3.5.1 Outreach Expense Breakdown

5.3.6 Direct Costs

When calculating the overall cost for each subsystem and related testing, the Mission Concept Cost Estimate Tool (MCCET) provided by the academy was utilized if there was no information easily accessible online on certain parts.

For the mechanical subsystem, costs come from component mass, power draw, manufacturing, assembly, and testing.

The overall mass component of the current subsystem is 38.928kgs. Using the NICM model with a 50 watt power draw for the drive/mobility system, this yields a result of $7,514,774.87 based on the CER equation for the mech subsystem:

$$219 * MechMass^{0.41} * TotalMaxPwr^{0.52}$$

This value is in 2004 dollars, so adjusting for 2024 inflation this yields a mechanical budget of $12,500,000 rounded up for margin. For additive manufacturing, the wheels themselves are around 4kg total so a conservative estimate for materials, production, qualification, and shipping for four tires made of aluminum alloy would cost roughly $2,000 using a rough estimate at $100 per kilogram for material costs. For chassis development including manufacture, the 12 million dollar value includes this. We estimate an additional two million in facilities testing costs at Johnson or Marshall, conservatively five million.

CDH Direct Costs:

The direct cost of the CDH subsystem is $5,500,000. This estimate includes wrap costs and testing costs. This estimate was developed with the MCCET calculator using the Software and electronics subsystem formulas. The software formula is 236 * ElecMass^0.69. This equation applies to the hardware components the system is running on, which is the OBC, Memory, and storage. These components and their redundant duplicates have a mass of 1.131 kilograms. When the result is adjusted for inflation, the price of these components is less than $500,000. The wrap costs, including management, systems engineering, product assurance, and integration and testing costs raise the price to $600,000. Test facility costs add another $200,000.

The component prices calculated with the electronics subsystem formula (1516 * ElecMass^0.74) include the transponder and antenna. The mass of these components is 1.128 kilograms. Adjusted for inflation, the price is $2,800,000. The wrap costs raise this price to $3,600,000. The test facility costs add an additional $1,100,000.

Thermal Direct Costs:

The total cost of the thermal subsystem is $786.16 which is the summed price that comes from the following components: 30 sq ft of multilayer insulation, computer heatsink, QT Py, QT Py Temperature Sensor extension, 16 sq ft of UV resistant tarp, Behr's Ultra Pure White Dynasty Semi-Gloss paint, 2 of DIYhz's Water Cooling Computer Radiator, and 1 canister of 50PPM Liquid Ammonia. Given that the rover requires 30 square feet of area to cover in insulation and assuming that the primary suppliers are indeed what are used, then the cost calculation without shipping is:

Insulation: $\$16.15 = \frac{\$376.95}{700ft^2} * 30ft^2$

Heatsink: $\$64.95$

QT Py: $\$12.90 = \$9.95(OS) + \$2.95(Temp\ Sensor)$

UV Tarp: $\$2.18$

Paint: $\$79.98$

Radiators: $\$100.00 = 2 * \$50.00$

Coolant: $\$510.00$

Total:
$\$786.16 = \$16.15 + \$64.95 + \$12.90 + \$2.18 + \$79.98 + \$100.00 + \$510.00$

Instrumentation Direct Costs:

The direct costs for the instrumentation subsystem are $63,400,000. The VAPoR system, based on body-mounted in-situ calculations, had a manufacturing cost of $47,200,000. The VAPoR system has an additional testing cost of $14,200,000. These costs have been adjusted for inflation in 2024. The instrumentation subsystem also includes a robotic scooping arm to transfer samples to the VAPoR system. There is no direct data on the COLD Arm's mass or maximum power draw. However, its lack of heating components make it a much lighter, and therefore less expensive, robotic scoop arm as compared to previous missions (NASA 2022). Therefore, cost estimates were completed by comparing the NASA Mars Curiosity Rover. It must be noted that Curiosity's robotic arm is over a foot longer than the COLD Arm, and contains additional tools that the COLD Arm does not contain, further adding weight. The Curiosity arm and testing functions weigh 33 kg. It is estimated that the COLD arm would weigh approximately half that, as its weight is significantly smaller than that of the Curiosity Rover's mechanical arm (NASA 2010). It was not possible to source the maximum power draw. The total cost of manufacturing and testing the COLD Arm is approximately $2,000,000.

VAPoR System:

Body-mounted In-situ Instrument: 652 * TotalMass^0.62 * TotalMaxPwr^0.44

- Total mass (maximum): 15 kg
- Total power draw (maximum): 60 W

$652 \bullet 15^{0.62} \bullet 60^{0.44} = 21174.38116$

Total: The price and testing costs, when adjusted for inflation in 2024, are $47,200,000 and $14,200,000 respectively.

COLD Arm:
Mechanical Systems: 219 * MechMass^0.41 * TotalMaxPwr^0.52

- Total Mass: approximately 17 kg
- Max Power: N/A

$219 \bullet 17^{0.41} = 699.72$

Total: The price and testing costs, when adjusted for inflation in 2024, are $1,500,000 and $500,000 respectively.

5.4 Scope Management

5.4.1 Change Control Management

To create changes to the rover, timeline, or any other part of the mission, the change control process requires a Change Request Form and a Change Control Board (CCB). If a team member believes that a change not required through a Request For Action (RFA) or Advisory (ADV) is necessary or will improve the project, the team member must first contact the Project Manager through Discord for approval. The Project Manager will decide if the proposed change will benefit the project, and then either decline or move forward with the change. For the change to be implemented, the Project Manager must fill out a Change Request Form.

Once the form has been completed, a virtual Change Control Board meeting will take place. In this meeting, L'SPACE mentors and advisors will serve as stakeholders and Subject Matter Experts (SMEs) to discuss and consider the proposed change. A minimum of one team lead is required to attend the CCB meeting. The justifications for the change will be evaluated and the request will either be approved or declined. If the change request is declined, the team will not be allowed to move forward with implementing the change. Should the change be approved, the team will create a plan of action and adjust the schedule to include the change's implementation.

The change control process will be managed through a Change Tracking Document. This document will be implemented as a shared spreadsheet recording all changes made to the project. The Change Tracking Document will define changes to scope, store procedures for change identification, and track the status of all of the project's change requests.

5.4.2 Scope Control Management

In scope control management, it is necessary for the team to have multiple strategies for downscoping. Downscoping is necessary if there are budget cuts, if the project is over schedule, or if the project is over cost. If scope control is needed, the team will first discuss what is needed, why it is needed, and what next steps should be taken. It is integral to approach scope control holistically, so all subsystems are prioritized equally, and unnecessary cuts aren't made. As the programmatic team is cognizant of how the budgets of the separate subsystems are composed, they will be primarily responsible for managing scope control decisions. Their first approach will be to review the subsystems to see if any have excessive costs. The programmatics team will then decide whether to reduce the budget or extent of certain elements, to take on more risk to cut costs, or to leave subsystems as is. While doing this, they will communicate and work closely with the members of each subsystem to ensure that cuts are appropriate and enable the subsystem to function as intended. The subsystems contribute to the largest direct costs, so managing these will produce the largest descoping capabilities. The next steps for descoping will be to assess personnel, to determine whether individuals need to be added or removed. The team can also take steps to modify production processes to ensure greater control of both cost and timeline. In the case of adding scope through increased resources, the team will invest time and money into increasing the TRL level of components through testing, which will decrease risk. The programmatics team will prioritize working with both the engineering and science sub-teams to decrease risk. Focusing on safety and spacecraft function will lead to the completion of overall mission goals with greater ease.

A recent descope that impacted the team was reducing the budget and limiting the number of personnel. Cutting down the budget led to reduced access to resources, such as tools and materials used to develop the rover. The team had to consider alternatives to resources that can satisfy the budget cut. Moreover, the team had to narrow the scope of the mission and focus on the priorities. This allowed the team to spend more on the essentials, such as personnel. By adjusting the team's strategies following the descope, subteams were able to develop cost-effective ways to redesign the mission.

5.5 Outreach Summary

Mission Statement: To spread enthusiasm for lunar exploration by connecting diverse populations with the wonders of space science and the potential of future Moon missions.

To effectively educate and raise awareness of the team's mission, the outreach plan involves connecting with a diverse range of age groups and areas of the public through various events.

Below you will find the key focus areas:

Key Focus Areas	

Enhance Public Perception	It is an important aspect to inform the public about the mission objectives, lunar exploration significance and the potential scientific breakthroughs
Spark Public Enthusiasm for Space Research	Showcase how aerospace advancements shape our world and fuel future discoveries
Broaden Participation	Tailor outreach to diverse groups, focusing on inclusivity across educational backgrounds and underserved communities
Ignite STEM Passion	Showcase aerospace innovation to spark career aspirations in sincere and technology among youth

Table 5.5.1 Key Focus Areas for Outreach

Our engagement strategies include:

1. **Primary Schools:**

Activity	Information
"Moon Tales" narrative sessions	Captivate children with compelling narratives illustrating the mission, rovers, and the lunar surface.
Interactive Discovery Labs	Practical demonstrations unveiling core concepts in astronauts and robotic engineering.
Creative Lunar Challenge:	Inspire youth to explore space concepts through visual and written expression.

Table 5.5.2 Primary Schools Activities

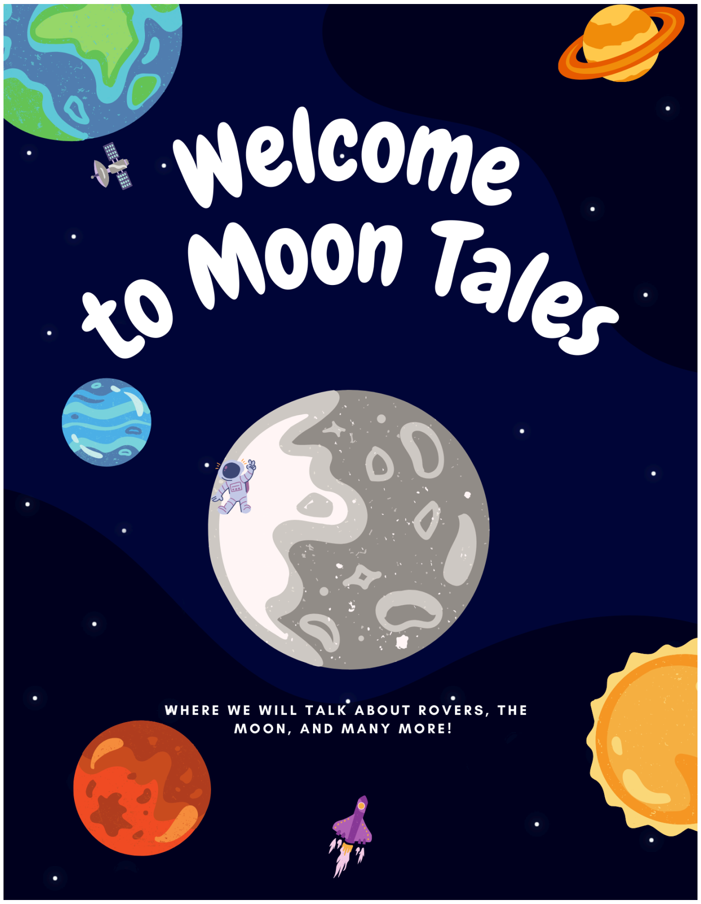


Figure 5.5.1: Sample flyers

Students from primary schools are more likely to be less knowledgeable about space and engineering. For primary schools, the mission team will collaborate with educators to host visits. At these visits, students will be able to experience a fun and engaging presentation on the history of the galaxy and how the planets and moon were formed. The presenter will perform safe experiments that replicate the science that NASA hopes to achieve through the moon missions, as well as possibly showcase real samples of moon debris to the audience. Lastly, the mission team can also develop a small rover similar to the actual mission rover that will be introduced near the end of the presentation. This small rover will be developed in conjunction with the JPL-Caltech lab similarly to that of the ROV-E Rover for the Mars missions (NASA, 2024). After the presentation, students will be provided time in their classrooms to learn more about the team's mission rover and different types of space instruments. There will then be an activity where students can design their own rover through drawings. The goal of interacting with primary schools is to facilitate a sense of creativity and imagination from a young age. By instilling these traits, they will grow to have greater interest in NASA missions on a more advanced level.

2. **Secondary Schools:**

Activity	Information
Lunar Lab Challenge	Develop a series of problem-solving stations where students work in teams to tackle simulated lunar mission scenarios.
"Future Frontiers Expo"	Organize interactive displays showcasing cutting-edge space technologies and their Earth applications.

Table 5.5.3 Secondary School Activities

While most students in secondary school will also only have general knowledge about outer space, their grasp of science concepts is far more developed than primary school students. Because of this, the activities at secondary schools will be educationally more in-depth and specialized. Schools will be provided with basic funding and full educational resources to develop their own rover. Some of these resources are already provided by NASA JPL-Caltech online and can be modified to fit the Lunar mission objectives more if needed (NASA JPL-Caltech, n.d.).

3. **Universities and Colleges:**

Activity	Information
Lunar Innovation Labs	Establish on-campus research hubs where students can contribute to ongoing lunar studies, develop new technologies, and participate in data analysis from current missions.
Space Exploration Symposia	Organize annual multi-day events featuring keynote speeches, panel discussions, and interactive workshops on cutting-edge lunar research and emerging space technologies.
Aerospace Career Accelerator	Launch a comprehensive program combining online courses, hands-on

	projects, and industry placements to fast-track students into space sector careers.

Table 5.5.4 College Activities

College students are more likely to have a higher understanding of the space sciences and engineering concepts compared to the adolescent population. The mission team will partner with various universities, including Historically Black colleges and community colleges, to deliver summits and host educational talks. Opening the doors to students of different backgrounds will facilitate more representation and diversity in the workforce, encouraging people of all kinds to pursue a career in space exploration. At these summits, there will be a wide variety of workshops that allow students to explore various aspects of mission development phases, giving them a preliminary experience into the inner workings of a NASA mission. There will also be guest speakers that provide insight to the current objectives of the Lunar mission and what NASA hopes to achieve beyond this mission. These speakers will include a diverse representation of leadership at NASA. Students will have the opportunity to ask questions in a larger talk environment or small panel settings. On a smaller scale, the mission team will work with universities to deliver seminars that involve guest speakers and interactions via questioning, but no further hands-on activities.

4. **Local Communities**

Activity	Information
"Moonshot Dialogues	Host interactive meetings where residents can discuss lunar exploration's societal impacts with experts, fostering community-wide conversations about space science.
Lunar Legacy Roadshow	Develop a mobile, high-tech exhibition featuring reality experiences, lunar surface replicas, and real-time mission updates, bringing the Moon to neighborhoods.
Cosmic Block Parties	Organize family-friendly outdoor events combining stargazing sessions, DIY rocket launches, space-themed art installations, and talks by local STEM professionals.

Table 5.5.4 Local Communities Activities

Additionally, there will be events for members of the general public and professional events for those who work in the space industry. The general public, similar to adolescents, is likely to have very basic to no understanding of NASA's missions or goals. To make engaging with the Lunar mission easier, the mission team will utilize the many diversely-located centers across the country, which include the Goddard Visitor Center, Houston Space Center, and the Kennedy Space Center. These visiting centers will allow residents of local areas to participate in learning activities without having to travel large distances. Similar to the visits to primary and secondary schools, these events will provide an introduction to the Lunar mission. Visitors will have the opportunity to experience exhibits, learning about the moon, its resources and dangers, and areas of interest to NASA (PSRs). There will be an activity that will allow them to design their own rover while simultaneously learning about instruments, data collection tools, and other parts of the rover that help it achieve its goals.

Such activities can also be hosted at public libraries. Public libraries are free resources, and this allows the team to connect with lower socioeconomic communities without expending too many additional costs.

For industry partners and workers, the mission team plans to host professional talks that dive deeper into the research NASA is trying to accomplish. These discussions may be done in collaboration with TED as an official TED or TEDx talk. Through a professional setting, attendees will receive quality insight into the technology and scientific information that NASA is using and acquiring in regards to moon exploration. They will leave with a much more advanced perception of NASA's goals, facilitating future collaboration in possible research areas.

TED Conferences are also not limited to those working in a similar field as the speaker, giving our mission access to professionals across various industries. By expanding the mission's reach, there is the possibility of future multidisciplinary collaboration. These presentations will occur closer to phases E and F, after the mission has been successfully launched and data has been collected and studied.

5. Underrepresented Communities

Activity	Information
Cosmic Connections	Partner with community leaders and cultural organizations to create space science programs that integrate local traditions, storytelling, and indigenous

	knowledge about the night sky.
Launchpad Fellowships	Implement a holistic support system including mentorship, financial aid, and guaranteed internships to propel underrepresented students into aerospace careers.
Universal Space	Make learning resources that showcase diverse role models in space exploration and connect lunar missions to various cultural perspectives and histories

Table 5.5.5 Underrepresented Activities

To make resources as widespread and accessible as possible, the mission team will also coordinate a series of webinars and post education material on NASA's website both for the general public and educators. This is a common tool used in the past by NASA (NASA, 2024).

For digital engagement we have several options:

"Lunar Pulse" Social Network: Launch a dedicated space exploration social platform with elements, allowing users to track mission progress, participate in citizen science projects, and interact with space professionals.

"MoonBase" Interactive Portal: Develop an immersive online hub featuring 3D mission simulations, real-time data visualizations, and personalized learning paths for visitors of all ages and backgrounds.

"Cosmic Chronicles" Media Partnerships: Collaborate with diverse content creators, from podcasters to TikTok influencers, to produce authentic, accessible stories about lunar exploration's impact on daily life and future possibilities.

"Lunar Lens" Multimedia Series: Create a range of visual content, from short-form explainer animations to feature-length documentaries, using cutting-edge graphics to simplify complex mission concepts and showcase behind-the-scenes mission preparations.

Evaluation and Feedback

We will use a comprehensive approach to assess and strengthen our outreach initiatives:

1. Impact Assessment
    - Distribute post-event surveys to participants.
    - Analyze qualitative feedback from attendees.
    - Track changes in public awareness and attitudes over time.

2. Reach and Engagement Analysis
    - Monitor digital metrics (social media interactions, website visits).
    - Measure event attendance and participation rates.
    - Evaluate the effectiveness of different communication channels.

3. Stakeholder Collaboration Review
    - Conduct regular check-ins with partner organizations.
    - Assess the outcomes of joint initiatives.
    - Identify opportunities for expanding and strengthening partnerships.

4. Continuous Improvement
    - Use gathered insights to refine outreach strategies.
    - Implement data-driven adjustments to program content and delivery.
    - Foster a culture of adaptability and responsiveness to community needs.

6. Conclusion

The team has deliberately worked the last 15 weeks to complete the entirety of this document. This document has showcased the integration of this mission and in detail described the 2028 Lunar mission where NASA will use a rover to accomplish 2 main goals. First goal the team will focus on is to determine the water ice abundance in lunar regolith within and around Permanently Shadowed Regions (PSRs). The team will accomplish such goal by taking several samples of the lunar's regolith. The second goal is to Investigate isotopic variations in lunar regolith to understand ancient solar and cosmic ray activity with the samples obtained by the rover. This document was broken down into 3 other smaller documents and later on combined into what we know as the PDR. The MCR was the first part of this document where the team determined the underlying cause of the mission and its objectives as well as the science instruments used for the mission. The team then worked on the second portion of this document called SRR which combined the engineering and programmatic sub-teams to work rigorously to come up with the rover design, budget and scheduling necessary to meet the team's goals. Lastly, the team worked on the final document that helped the PDR come to life called MDR. The MDR took budgeting and scheduling to the next level by incorporating suppliers & lead times for our selected components. Through this process the team discovered the uniqueness of the mission and developed a plan to hone in their skills, expertise and resources and accomplish the mission. After the PDR has been submitted the team will present this proposal to the panel in the search of additional feedback. The virtual presentation not only will put the team's communication to the test but also their ability to deliver technical information in a clear and robust manner under 30 mins.

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Appendix

TBD / TBR #	Plans and Timeline for Resolution
1	Power retention- within a week
2	Power distribution - within a week
3	Cost of power components - within a week

Table Appendix 1: TBD/TBR Items and Plans for Resolution

Request for Action (RFA)		
RFA ID	**Section #**	**Action**
MCR-RFA-1	1.2	Include citations for the science objectives. - HE
MCR-RFA-2	All	Include citations for anything that is not common knowledge and came from an internet source. Especially in areas that mention specific reports. - HE
MCR-RFA-3	1.5	Must include information regarding planetary protection concerns. - SR
MCR-RFA-4	1.10	This section has a high probability of AI. Revise. - JM
MCR-RFA-5	All	Provide statement of AI usage - JM
MCR-RFA-6		
MCR-RFA-7		
MCR-RFA-8		
MCR-RFA-9		
MCR-RF		

A-10		
MCR-RF A-11		
MCR-RF A-12		
MCR-RF A-13		
MCR-RF A-14		
MCR-RF A-15		

Advisory (ADV)		
ADV ID	**Section #**	**Recommendation**
MCR-AD V-1	1.4	Customer reqs should be met. - JD
MCR-AD V-2	1.7	Missing dates for this section. - JD
MCR-AD V-3	1.10	Include mission objectives, vehicle design, and customer constraints in your summary. In addition, provide clear and detailed next steps for the SRR, avoiding general statements such as "If the team had more time." - FH
MCR-AD V-4	1.9.2	Include a narrative regarding the schedule. Whether or not you are meeting the customer constraints is just one small piece, the reader needs to understand *why* the mission is on time or under budget. - JR
MCR-AD V-5	1.1	Rephrase to clearly state the science goals and the objectives. - HE
MCR-AD V-6	1.3	Include more specific characteristics about the mission location and its features. Quantifiable parameters such as coordinates are needed. - HE
MCR-AD V-7		
MCR-AD V-8		
MCR-AD V-9		
MCR-AD		

V-10		
MCR-AD V-11		
MCR-AD V-12		
MCR-AD V-13		
MCR-AD V-14		
MCR-AD V-15		

Request for Action (RFA)		
RFA ID	**Section #**	**Action**
SRR-RFA-1	1.2	Include citations for the science objectives. - KV
SRR-RFA-2	1.5.6.1	The table contains some TBD and a completely empty roll that should be eliminated. -KV
SRR-RFA-3	1.5.4.2	Please revise the TRL of CDH components. No TRL can be 9 at this stage. -AV
SRR-RFA-4	1.5.4.2	Flowchart should cover the communication between all subsystems and how telemetry occurs. Please look at the provided flowchart example. -AV
SRR-RFA-5	1.5.3.1	Fix formatting, include more lower level reqs and child reqs if applicable. -JD
SRR-RFA-6	1.5.3.2	No information present needs to be included. -JD
SRR-RFA-7	1.5.3.3	No information present needs to be included. -JD
SRR-RFA-8	1.4	JN - Add all of the requirements to your narrative and the missing ones to your table (Slope). Add dimensions when talking about your allotted volume, don't simply put X cubic feet.
SRR-RFA-9	1.5.5.2	JN - Provide missing sections with high levels of detail
SRR-RFA-10	1.5.5.3	JN - Provide a trade study and narrative for each thermal subsystem
SRR-RFA-11	1.6	Complete risk statements -TR
SRR-RFA-12	1.6	Include risk matrix -TR

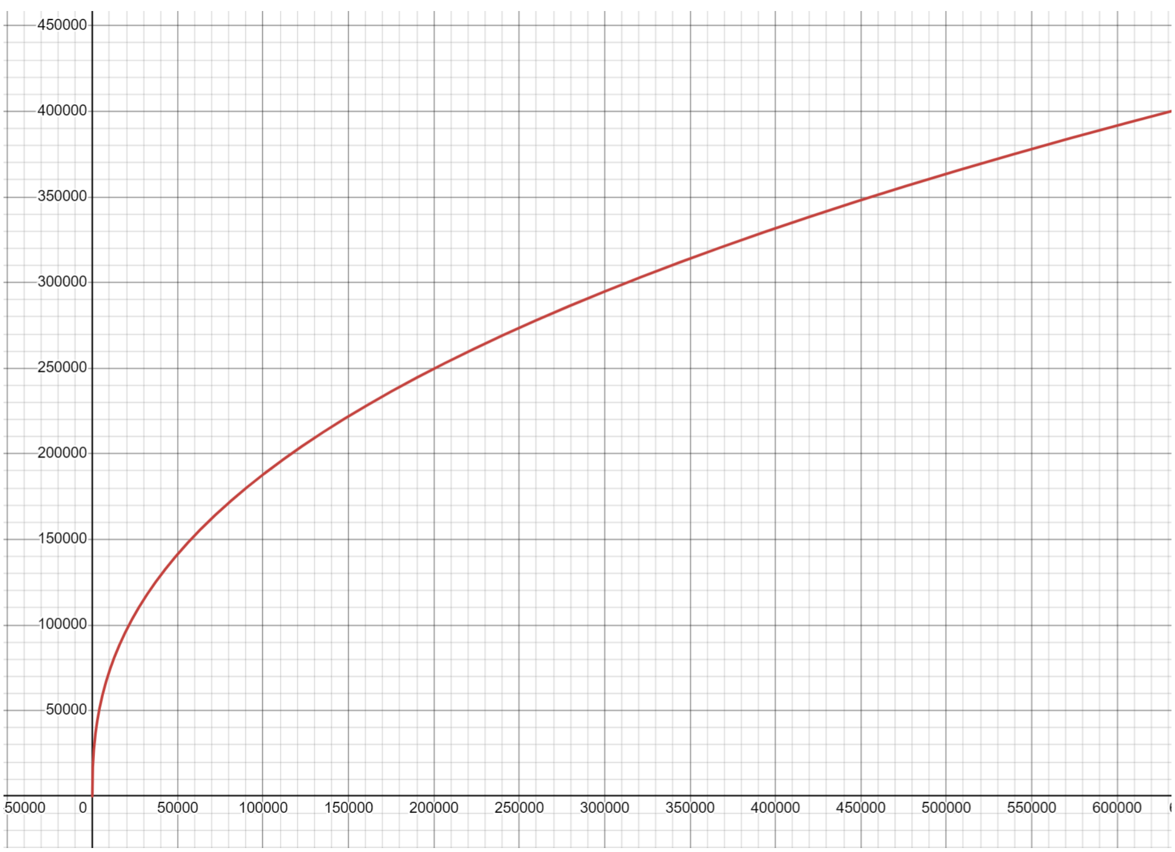
SRR-RFA-13	1.6	Include RIDM and CRM processes in risk management method overviews. -TR
SRR-RFA-14	1.5.7	Complete missing thermal sections. - JN
SRR-RFA-15	1.5.8	Add a narrative explaining the N^2 chart and improve the formatting making it easier to follow. - JN
SRR-RFA-16	1.7.3	Complete and include a schedule estimate for phases C-F of your mission. -JR
SRR-RFA-17	1.5.2.1	SN – Include more requirements that define the functions of each subsystem
SRR-RFA-18	1.5.2.2	SN – VIPER has 5X the mass of your mission, you cannot use its mechanical system without extensive modification. Design a mechanical system that fits your unique mission.
SRR-RFA-19	1.5.2.2	SN – This section should go into more detail about the functions of each subassembly.
SRR-RFA-20	1.5.2.2	SN – You are missing guidance, navigation, and control hardware. You should have obstacle-sensing capabilities and motion/tilt sensing.
SRR-RFA-21	1.5.2.3	SN – You should have trade studies for every subassembly. Conduct trade studies for GNC, structure, and sample collection (and any new ones) and incorporate the results into your report.
SRR-RFA-22	1.7.4	TC - Develop a comprehensive change control and tracking process and document this for the team.
SRR-RFA-23	1.5.1	JN - Add a top level requirements table to this section. Also, discuss every subsystem in the overview.

Advisory (ADV)

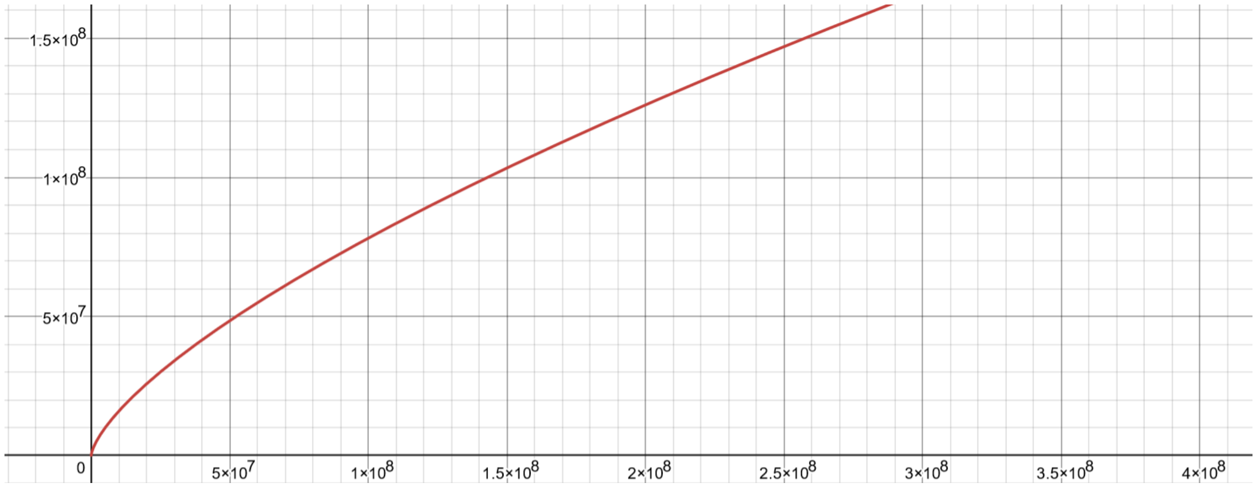
ADV ID	Section #	Recommendation
SRR-ADV-1	1.5.6.1	The requirements could be a little more specific. -KV
SRR-ADV-2	1.5.6.2	The overall TRL for the entire system is not included but because you have one instrument then that should be the TRL and should be mentioned. -KV
SRR-ADV-3	1.5.6.3	The font seems different to the rest as well as the way it is organized, try adjusting it. -KV
SRR-ADV-4	1.5.4.1	The requirement section is missing a lot of detail. Will the subsystem store information? How will the telemetry work? Add more details to also make the requirements SMART. -AV
SRR-ADV-5	1.4	JN - Remove unnecessary TBD's
SRR-ADV-6	1.5.5.1	JN - Fix your relative subsystem section to accurately list all subsystems affected.

SRR-ADV-7	1.5.5.3	JN - Refine your explanations to also explain why you selected the criteria for the trade study
SRR-ADV-8	1.8	Include further detail on what was built on for programmatics cost/schedule in SRR. -TR
SRR-ADV-9	1.7.2	Work on adding specifics for the thermal and power system when possible. - JR
SRR-ADV-10	1.3	Provide more context on the caption of the figures and on the figures themselves. -KV
SRR-ADV-11	1.5.1	JN - Add some shading or color to the tables to make them look more professional and easier to read.
SRR-ADV-12		
SRR-ADV-13		
SRR-ADV-14		
SRR-ADV-15		

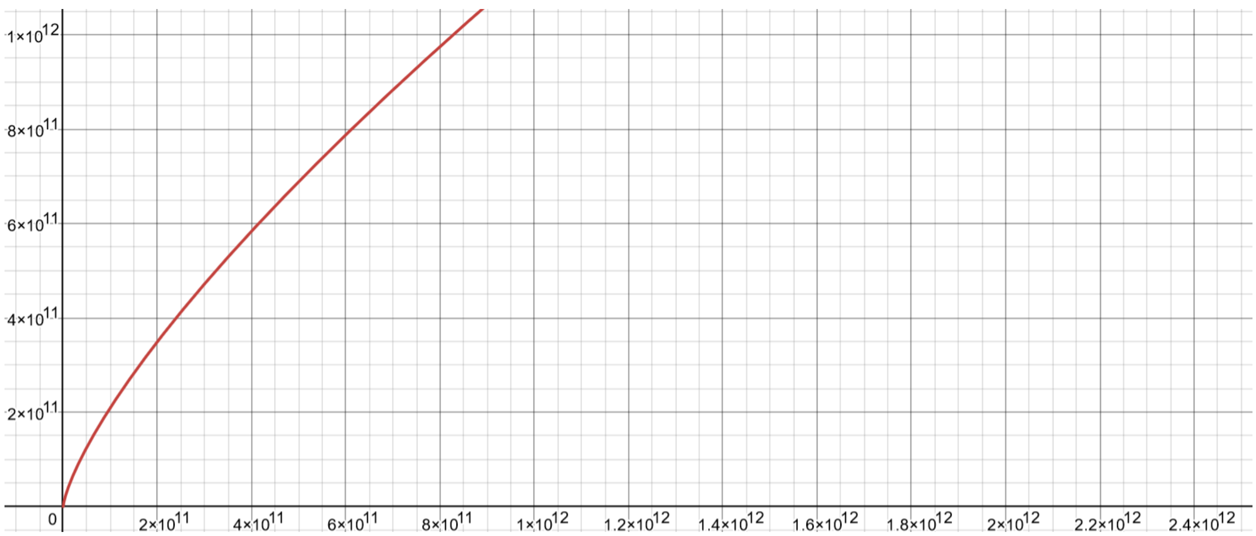
Mech system cost curve at a constant 50 watts of power usage (x-axis is mass in kg, y is cost in thousands of 2004 USD):

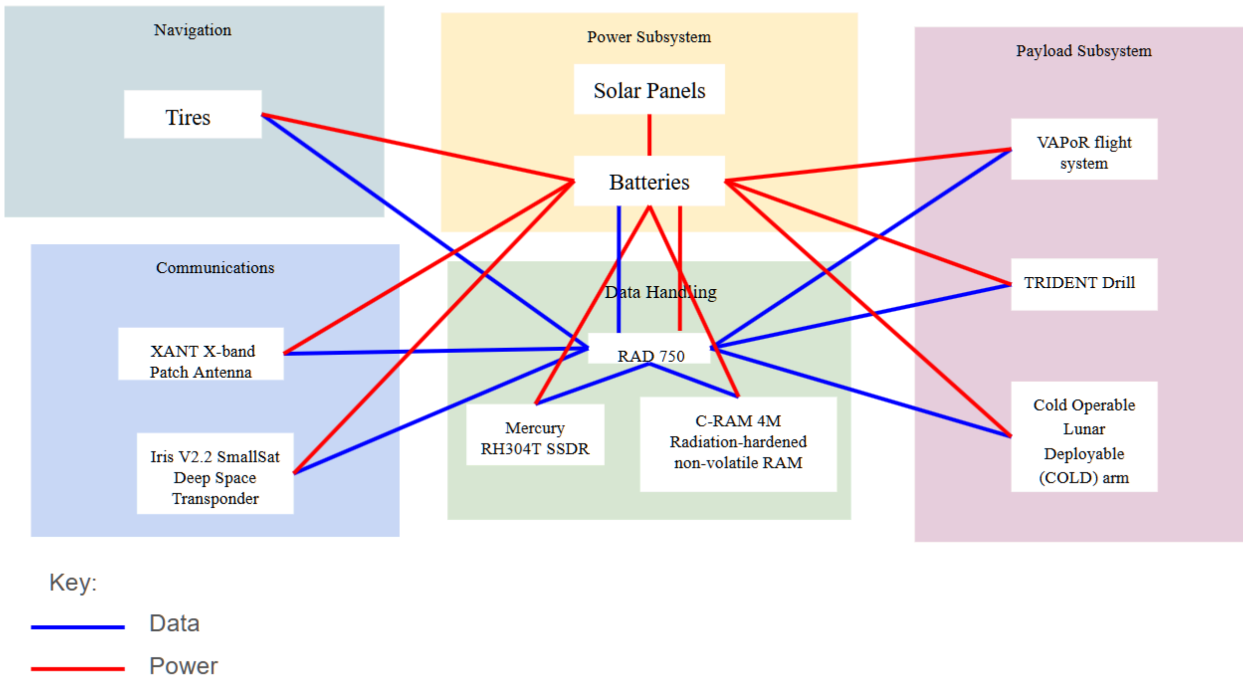


CDH software subsystem cost curve (x-axis = mass in kg, y = cost in thousands dollars, 2004):



CDH Electronic subsystem cost curve (x-axis = mass in kg, y = cost in thousands dollars, 2004):





Block Diagram with all the subsystems and how they interface

Electrical Schematic Block Diagram: