Preliminary Design Review (PDR)

“CHILLY”

(MCA Team 09)

Commanded Harvesting of Ice Lunar Lander Yield

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Table of Acronyms

Acronym	Definition
ADV	Advisory
CCB	Change Control Board
CDH	Command & Data Handling System
CDR	Critical Design Review
CER	Cost Estimating Relationship
CMOS	Complementary Metal Oxide Semiconductor
CMU	Carnegie Mellon University
CNSA	China National Space Administration
ConOps	Concept of Operations
CPU	Central Processing Unit
CRF	Change Request Form
CSSL	Communication Systems Simulation Laboratory
DDR	Double Data Rate
FMEA	Failure Mode and Effects Analysis
GNC	Guidance, Navigation and Control
GPR	Ground Penetrating Radar
MCCET	Mission Concept Cost Estimate Tool
MCR	Mission Concept Review
MDR	Mission Definition Review
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
NCIM	NASA Instrument Cost Model
NIRVSS	Near-Infrared Volatiles Spectrometer System
PCM	Phase Change Material
PDR	Preliminary Design Review
PDU	Power Distribution Unit
PSR	Permanently Shadowed Region
RFA	Request For Action
RTG	Radioisotope Thermoelectric Generator
SDRAM	Synchronous Dynamic Random Access Memory
SEE	Single Event Effect
SRR	System Requirements Review
STM	Science Traceability Matrix
TBD	To Be Determined
TBR	To Be Resolved

TRN	Terrain Relative Navigation
TRL	Technology Readiness Level
USD	United States Dollar

1. Mission Overview

1.1. Mission Statement

The goal of this mission is to study the composition of water-ice and other volatiles during phase changes within the permanently shadowed regions (PSRs) of the Leibnitz Beta Plateau on the moon. This is being done to measure the viability of long-term settlements on the moon that would use these resources to survive. The two Artemis science goals chosen for this mission are 2a and 6n. Goal 2a refers to determining water ice abundance in lunar regolith while 6n concerns the change in hydrogen, oxygen, and other sedimentary particles within the water ice during phase changes. Each science goal has different objectives, meaning the team will need to measure temperature, pressure, and flow rate measurements made during liquefaction and condensation; ice density, surface tension, and temperature during phase transitions of the water-ice; and the concentration and composition of water-ice in the first meter of regolith on one of the permanently shadowed regions. The data for this mission will be collected using instruments aboard a rover. Using a rover for the mission will increase the area of water-ice deposits that can be tested and allow for a wider range of the permanently shadowed region to be analyzed. The specific instruments that will engage in the experimentation of the water ice are the Ground Penetrating Radar (GPR) and the Near Infrared Volatile Spectrometer Subsystem (NIRVSS). Both of these instruments have capabilities to detect the composition of volatiles such as hydrogen and oxygen as well as the presence of water ice in the lunar regolith and can examine how these aspects change in different conditions. The schedule prior to the mission and phases during the mission have been outlined in this document. The manufacturers for each subsystem of the rover, including the science instrumentation, have also been stated along with lead times and backup suppliers in case they are needed. Lastly, a comprehensive list of risks has been compiled and strategies to manage said risks are also described. As a whole, this mission aims to significantly advance our understanding of the Moon's formation and possible geological history, with potential for enrichment, especially drinking water, oxygen production, and fuel for future missions. This not only contributes advanced learning to scientific knowledge but also supports the long-term goal of putting man on the moon.

1.2. Science Traceability Matrix

The CHILLY mission will be focused on achieving 2 distinct Artemis Science Goals which are outlined in the Science Traceability Matrix (Table 1). The first is the consumer given goal 2a, regarding water ice depth and composition. The specific science objective within this goal is to find the abundance of water ice in the regolith for CHILLY's mission location, the Leibnitz Beta Plateau [4]. The second goal that has been chosen is 6n: studying water ice phase changes and gas movement. Within 6n, the first objective is to study the effects of partial-g on the condensation of hydrogen and oxygen during the liquefaction process. Partial-g is simply any gravitational force that is less than Earth's as gravity on the moon is one sixth of Earth's [37]. THe second objective within 6n is to examine the solid-liquid phase change of the water ice and its sedimentary composition. These objectives will be completed by studying the water ice deposits in the PSRs of the Leibnitz Beta Plateau through the use of two instruments, a strata ground penetrating radar (GPR) and a Near-Infrared Volatiles Spectrometer System (NIRVSS). When combined, these two will be able to allow the mission goals to be met with high precision in every required aspect. The GPR will allow the rover to make a two or three dimensional map of the undergrowth regolith inside the mission area [63]. This is done by sending high frequency radiation into the regolith and measuring the attenuation of the reflected waves. This allows for the GPR to measure the depth and lateral distance of any differing materials in the ground. The NIRVSS is a suite of instruments that include 2 spectrometers of differing wavelength spectrometers, high definition CMOS sensor, LED's for said sensor, and a longwave calibration sensor [40]. With these, the NIRVSS will be able to monitor changes in surface reflectance, composition, volatile content, and temperature with high precision.

Table 1. *Science Traceability Matrix*

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
Artemis Science Goal 6n: Study the conversion of water-ice to gaseous hydrogen and oxygen, and liquefaction of gasses for propellant storage	Investigate condensation of hydrogen and oxygen in partial-g during liquefaction process	Identify impact of environment, temperature; material composition; etc, on the condensation of hydrogen, oxygen, and water during the liquefaction process of water-ice.	Measure gas and liquid temperatures, ambient temperature (during condensation), system pressure, partial pressures, gas and liquid density, and flow rates of different gasses.	Spectral Resolution:	~ 50 nm	~ 20 nm	**Near-Infrared Volatiles Spectrometer System (NIRVSS)**	Mission shall measure physical parameters of hydrogen, oxygen, and water condensation of collected water-ice samples.
				Temperature Ranges:	-50°C To 50°C	-173+ °C		
	Examine the influence of gravity on solid-liquid phase change of water ice including sedimentation	Identify changes in sedimentation processes of regolith in liquid water in lunar gravity compared to	Measure composition of liquid water and location of solid regolith over time as regolith	Spectral Resolution:	~ 50 nm	~ 20 nm	**Near-Infrared Volatiles Spectrometer System (NIRVSS) & Ground Penetration Radar**	Mission shall measure the sedimentation process of lunar regolith in liquid water and the effects of lunar gravity on said process.
				Temperature Ranges:	+/- 5°C from 0°C	Above -173 °C		
				Distance Resolution:	Below 5 cm	~ 3 cm		

	of regolith in the liquid water.	earth gravity.	particles separate.				**(GPR)**	

Artemis Science Goal 2a: Determine the Compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions.	Determine the water ice abundance of at least one of the 13 Artemis III landing site locations in or near a PSR, within the top 1 meter of regolith to at least +/- 5% accuracy	Identify presence and concentration of ground water-ice in the first meter of lunar regolith.	Measure concentration and distribution of water-ice in the first meter of regolith in a permanently shadowed region within an accuracy of +/- 5%.	Wavelength Range:	100 - 1000 MHz	25 - 1500 MHz	**Ground Penetrating Radar (GPR) & Near-Infrared Volatiles Spectrometer System (NIRVSS)**	Mission shall measure the groundwater-ice content of the first meter of regolith within +/- 5% accuracy inside of the PSR located in the Liebnitz Beta Plateau to measure availability of water, oxygen, and hydrogen.
				Distance Resolution:	Below 5 cm	< 1 cm		
				Lateral Resolution	Below 5 cm	~ 1.8 cm		

1.3. Summary of Mission Location

Out of the 13 Artemis III Landing Sites (*Fig. 1*), the Leibnitz Beta Plateau (*Fig. 2*) will be the mission location and landing site. Multiple factors have been considered when making this decision, such as terrain, permanently shadowed regions, illumination, and communication conditions. The topography of the Leibnitz Beta Plateau is favorable to the proposed rover mission due to its minimal slope changes, >8° [22]. The relatively flat terrain will allow the rover to move around easily and conduct scientific experiments without navigating extreme elevation changes. Along with the favorable terrain, the Leibnitz Beta Plateau is rich in permanently shadowed regions (PSRs) and has PSRs near it (*Fig. 3*). This is a key characteristic that was considered when choosing the mission location as PSRs are likely to host ice deposits, which is the focus of this mission. In fact, 78% of the PSR area located in the Liebnitz Beta Plateau is favorable to water-ice [31]. The chosen center for the 100m landing radius for this mission will be (-85.203°N, 33.258°E) due to this area covering some of a large PSR where water ice can be examined and samples can be collected to be further analyzed (*Fig. 4*). However, the western half of the 100m landing radius is a non-PSR area where the rover can possibly analyze the water ice and sediment samples in relatively warmer temperatures as well as recharge in the sunlight using solar panels. A crucial third aspect that has been evaluated when choosing this location is the illumination of the selected area. As previously stated, the rover will use solar power as an energy source to conduct the proposed water-ice deposit experiments. Therefore, illumination of the mission location needs to be analyzed to ensure that enough sunlight can be harnessed to fulfill the needs of the rover. Although the Leibnitz Beta Plateau is a PSR-rich area, it also has areas of high illumination, partially due to its high elevation [22]. The chosen 100m radius covers both the PSR and the areas of high elevation where enough illumination is present to power solar panels (*Fig. 4*). Arguably the most important consideration relates to the communication conditions, specifically between the mission and Earth. A vast amount of data will be collected in this mission and due to its complexity, good communication is vital to mitigate any issues that occur over the duration of the mission and ensure success. The Leibnitz Beta Plateau is one of the best candidates for mission location when specifically considering its communicability as some areas of this region even reach maximum communication conditions of 100% (*Fig. 5*). The chosen 100m radius landing site at the Leibnitz Beta Plateau hosts reliable communication conditions along with fulfilling the mission's needs for ideal terrain, PSRs and high illumination areas, making it an ideal candidate for this mission and its experiments as seen by the data collected in the lunar south pole (*Table 2*).

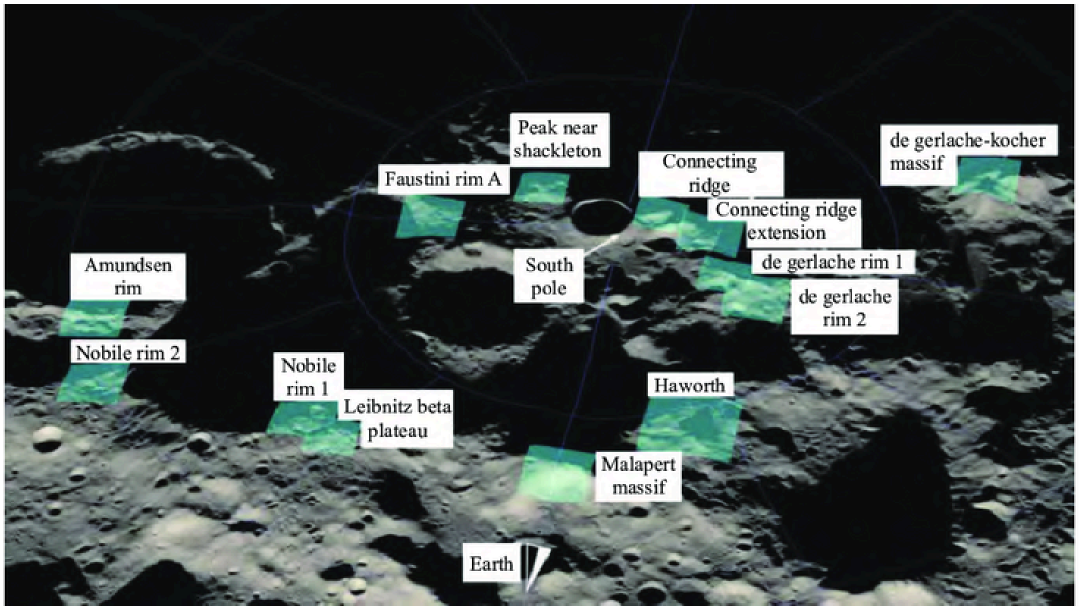


Figure 1. 13 pre-selected landing zones for the Artemis III landing mission [22]

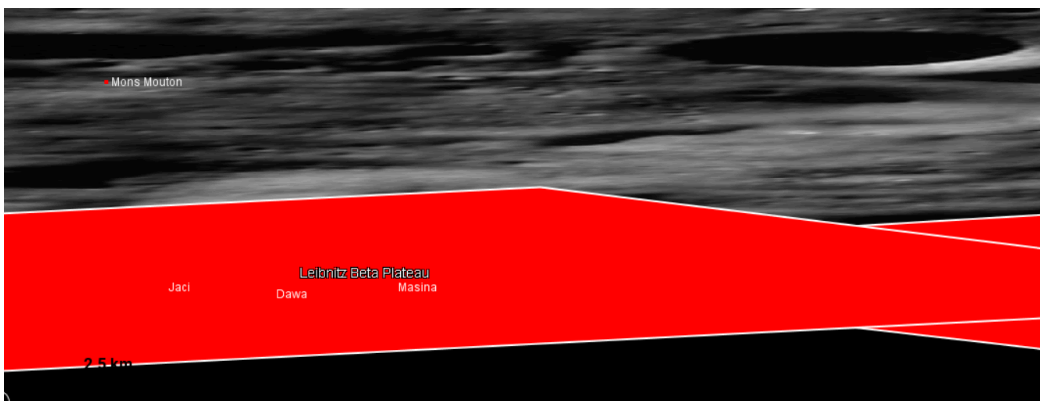


Figure 2. JMARS Map of Leibnitz Beta Plateau

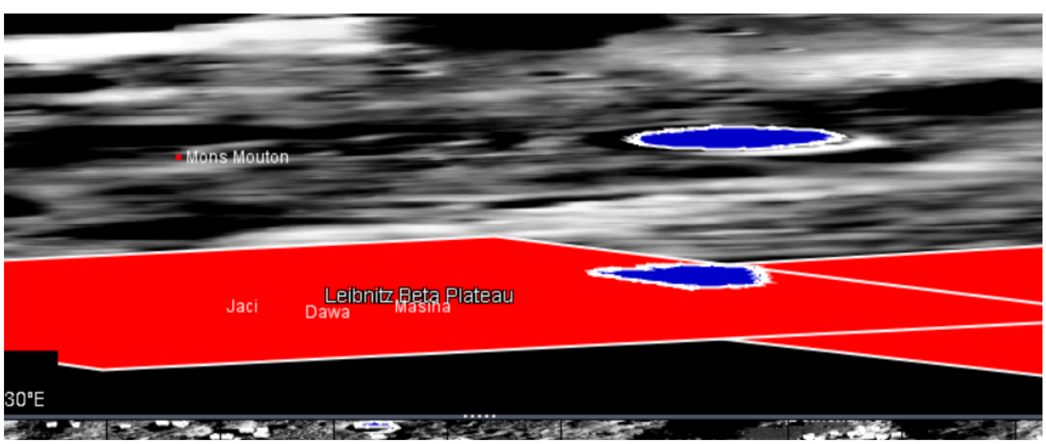


Figure 3. Large PSRs (in blue) in or near the Leibnitz Beta Plateau

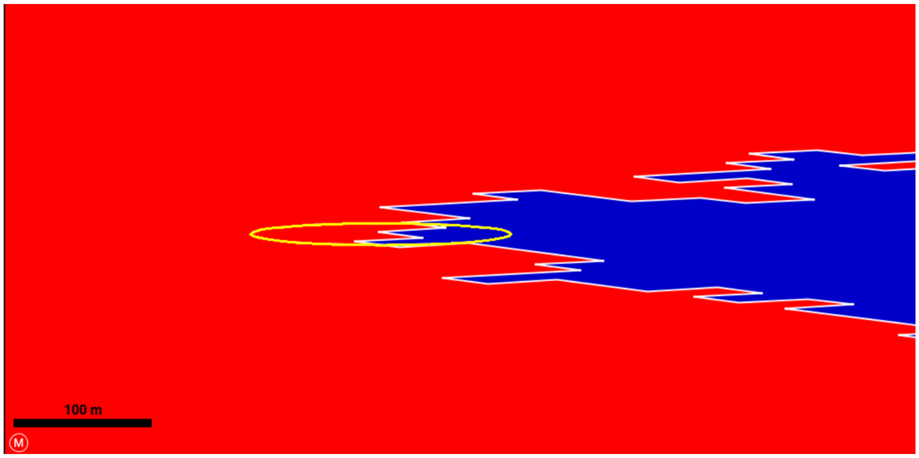


Figure 4. 100m Radius Landing Region (circle in yellow)

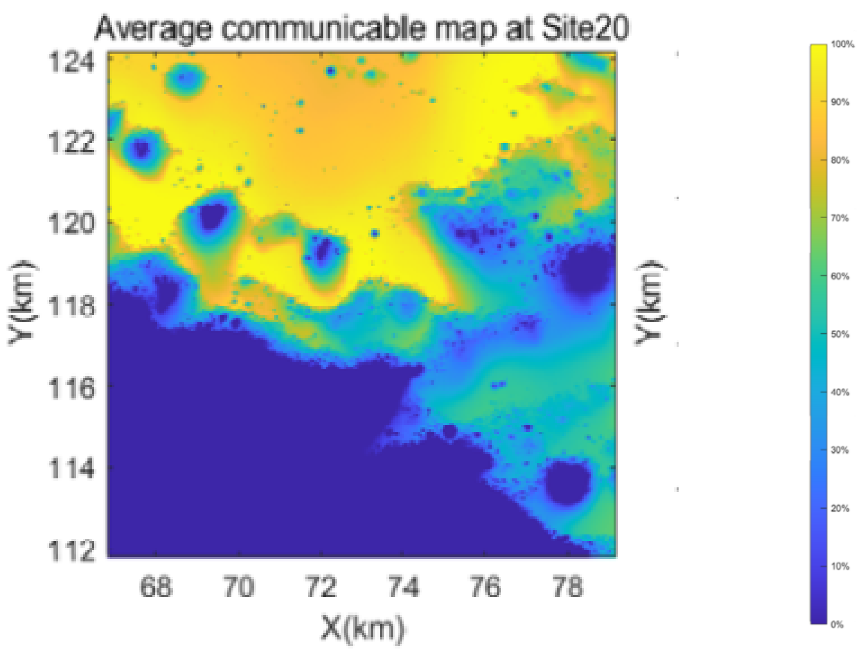


Figure 5. *Communicable Map of Leibnitz Beta Plateau*

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

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

1.4. Mission Requirements

This mission must adhere to the customer constraints specified in the mission task document. As the vehicle is a secondary payload aboard a primary vehicle, there are mass and volume constraints that may not be exceeded by any amount. The vehicle's total mass shall not exceed 85 kg and shall not exceed a stored configuration volume of 1.5m in length, width, and height. Post-deployment, it is allowable for the vehicle to expand to a larger volume. Additionally, the total cost of the mission, including the cost of the system, salaries, travel, outreach, and other expenses, shall not exceed a total cost of $225 million. Since it is a secondary payload, launch and cruise costs are assigned to the primary payload. The vehicle must be ready for launch by September 1st, 2028 at Cape Canaveral, adjacent to the Kennedy Space Center.

The customer has also imposed constraints on the science instrumentation of the vehicle. All of the mission's science objectives shall be achievable with no more than two science instruments in total. This includes duplicates and instrument suites with more than one instrument. Furthermore, the vehicle is prohibited from using a Radioisotope Thermoelectric Generator (RTG) and any derivative thereof. The total amount of allowable radioactive material is limited to a cumulative maximum mass of 5 g. If any of the customer constraints stated above are exceeded by any amount, the mission will be subject to cancellation.

The mission requirements are shown below in Table 3. This table outlines the top-level specifications, derived from the customer requirements outlined above and science traceability matrix (STM), that are necessary for a successful mission. Failure to meet any of the mission and system requirements will jeopardize the mission.

Table 3. *Top-Level Mission Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mission Reqs							
MR-1	The vehicle shall be ready for launch from Cape Canaveral by September 1st, 2028.	Since the vehicle is a secondary payload, it must be ready for launch when the primary payload launches.	Customer	MEC-2 EPS-11	Inspection	All	Met
MR-2	The system shall operate within a 10 km radius from the landing location in Leibnitz Beta Plateau.	The site the vehicle is investigating cannot exceed a distance of 10 km from the landing site as specified in the mission task document.	Customer	MEC-1 CDH-3	Analysis	All	Met
MR-3	The system shall have a mission lifespan of 20 weeks.	The minimum amount of time to acquire sufficient data to satisfy the science objectives.	Customer	MEC-2 MEC-9 TCS-2 TCS-3 TCS-6 TCS-7 EPS-1 EPS-2 EPS-6 EPS-7 EPS-10 CDH-5 CDH-7 PAY-3	Test	All	Met
MR-4	The system shall have a total mass less than 85 kg.	The mass of the system cannot exceed a mass of 85 kg due to being a secondary payload as specified by the customer in the mission	Customer	MEC-8 TCS-4 EPS-4 CDH-4 PAY-2	Inspection	All	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		task document.					
MR-5	The system shall have a total volume less than a Length 1.5m x Width 1.5m x Height 1.5m for the stored configuration prior to deployment.	The volume of the system cannot exceed the allowed volume due to being a secondary payload as specified by the customer in the mission task document.	Customer	MEC-10	Inspection	All	Met
MR-6	The mission shall have a cost less than $225M.	The mission may not exceed the allowed budget specified by the customer in the mission task document.	Customer	MEC-7 TCS-5 CDH-2 EPS-12 PAY-1	Inspection	All	Met
MR-7	The system shall support instrumentation to collect data to achieve science goal 2a.	The system must be capable of satisfying the science objective in order to accomplish the science goal 2a as specified in the mission task document.	Science Goal 2a	MEC-3 MEC-4 EPS-2 CDH-1 PAY-5	Analysis	All	Met
MR-8	The system shall support instrumentation to collect data to achieve science goal 6n.	The system must be able to satisfy the science objectives in order to accomplish the science goal 6n as specified in the mission task document and the Artemis III Science Definition Team Report.	Science Goal 6n	MEC-3 MEC-4 EPS-2 CDH-1 PAY-4	Analysis	All	Met
System Reqs							
SYS-1	Any radioactive material used by the system shall have a cumulative mass less than 5g.	The system can not use more than 5g of radioactive material in total as specified by the customer in the mission	Customer	TCS-8 EPS-9	Inspection	Power Payload	Met

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

1.5. Concept of Operations (ConOps)

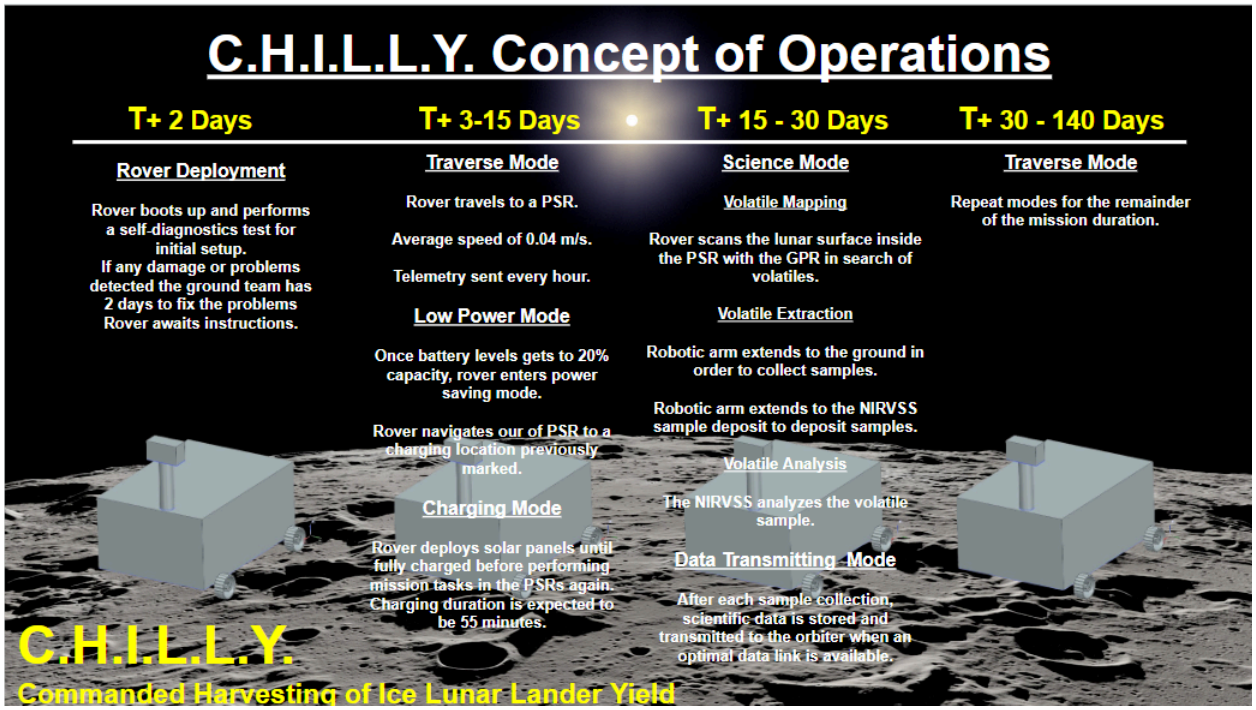


Figure 6. *CHILLY Mission Concept of Operations*

The concept of operations (ConOps), outlined below in Figure , describes the procedures necessary for the CHILLY mission to be a success. The mission duration is expected to last around 20 weeks and starts after landing on the lunar surface. After 20 weeks the components on CHILLY are expected to be worn and possibly not suitable for use. The ConOps begins with the rover activation phase. After landing on the lunar surface, the rover boots up and performs a self-diagnostics test for initial setup in order to assess any possible damages caused by transportation. In the case that the system has detected some damages to CHILLY we have dedicated a day to assess and fix any potential problems that may have arisen from transport. CHILLY then waits for instructions to begin the next phase.

The next phase is the traversing phase. During the traverse mode, the rover travels on the lunar surface at a speed of 0.04 meters per second. While traveling, the rover detects

and avoids hazards using its onboard camera as it navigates to the first chosen PSR. During the travel to the first PSR CHILLY will mark out close charging locations near the PSR. Additionally, systems' health telemetry is sent to mission control every hour. When the battery of the rover gets low at 20% battery health, the rover enters a low power mode. During low power mode, non-essential systems, except the mechanical system and telecommunications, are turned off in order to preserve power. The rover then navigates out of the PSR and travels to a charging position that was previously marked. Charging is expected to take 55 minutes at %100 sunlight. Once there, the rover enters charging mode. During charging mode, the solar panels are deployed by the mechanical subsystem to the optimal charging position. CHILLY will stay in charging mode until fully charged. Once charged, it will navigate back to the PSR. The next phase is science mode. While in the PSR, CHILLY scans the lunar surface with the Ground Penetrating Radar (GPR) in search of volatiles. Additionally, the GPR will be mapping out the water ice abundance within the PSR. It will help identify the regolith-to-ice ratio by measuring the average radius of the ice particles as well as the overall shape in order to accomplish science goal 2a. After the rover finds ice particles, the mechanical arm with the Nano Drill extends to the ground in order for the drill to collect samples. After an adequate amount is collected (5 grams minimum), the robotic arm then extends to the NIRVSS to deposit the samples into the sample deposit located on the outside of the rover. The NIRVSS then analyzes the volatile sample in order to accomplish science goal 6n. In the case that ice particles are not detected within the PSR region CHILLY will navigate to the next nearest PSR. 3 PSR's will be identified prior to launch as candidates for CHILLY to navigate to and explore. After collecting enough scientific data, the data is stored by the CDH subsystem and transmitted to mission control when an optimal data link is available. The rover then repeats modes for the remainder of the mission duration or until CHILLY is no longer operational. After the mission is completed, the CHILLY rover will navigate to a safe location on the lunar surface. Once there, the rover will perform a complete system shut off. This will be the CHILLY rover's final resting place. It far exceeds the mission's budget to send the rover back to earth, so the rover will remain on the moon where it can be possibly retrieved at a later date.

1.6. Vehicle Design Summary

In order to satisfy the science objectives chosen for the mission, the spacecraft chosen is a rover. This rover will be designed to traverse the lunar surface, more specifically, the terrain within the Leibnitz Beta Plateau. Inside the designated area, the rover will traverse to a PSR in order to collect scientific data on the ice deposits outlined in the STM. It will then transmit the scientific data to the primary mission orbiter. The rover will have five different subsystems (mechanical, power, CDH, thermal, and the payload). Shown in the sketches below, are the designs of the rover. The mechanical subsystem will support the payload subsystem through the use of a mechanical arm which is also shown below. Additionally, all of the other subsystems will be housed within the mechanical structure subassembly (the rover's body) shown below.

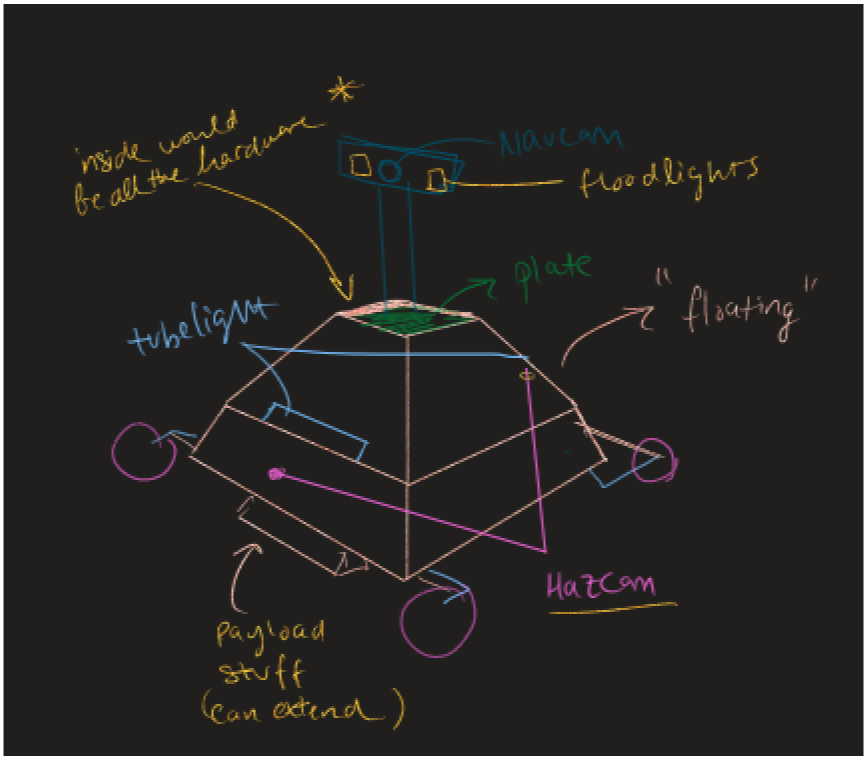


Figure 7. *A creative illustration of the rover*

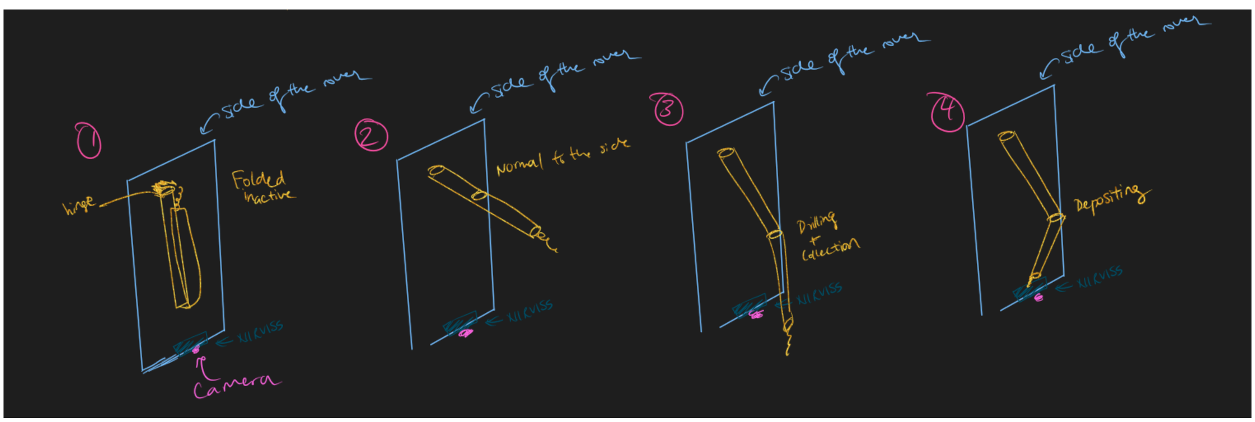


Figure 8. The mechanical arm assembly

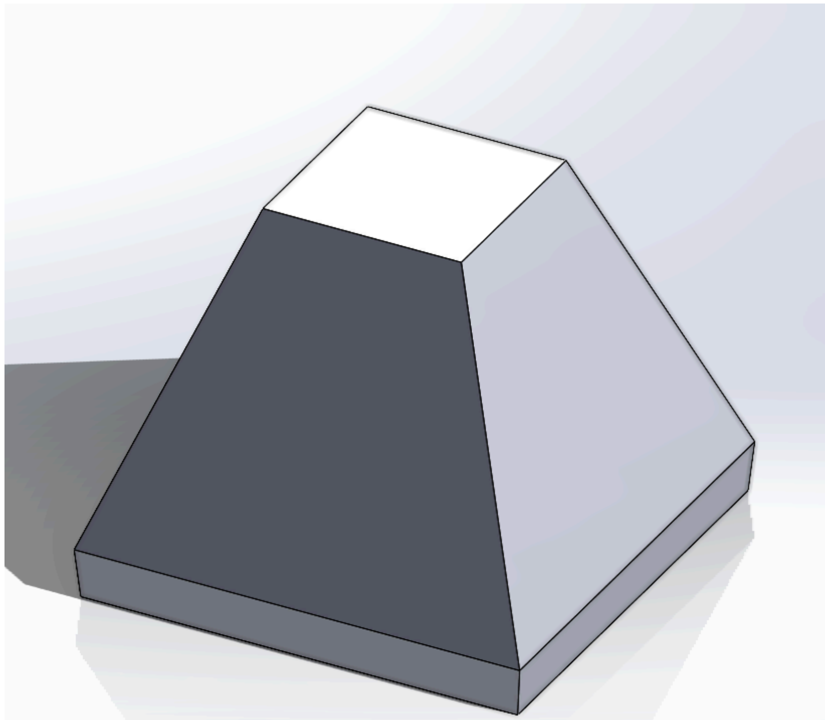


Figure 9. *Body of the rover that will house the internal components*

1.7. Science Instrumentation Summary

The CHILLY mission rover will consist of two main science instruments, a Strata Ground Penetrating Radar (GPR) and a Near Infrared Volatile Spectrometer System (NIRVSS). The GPR is a significant and necessary tool for this mission as it is the primary instrument that will fulfill the customer given goal (2a) of measuring the water ice abundance in the top 1 meter of the lunar regolith with an accuracy of at least +/- 5%. The GPR measures water ice abundance by measuring permittivity, an electromagnetic property that indicates the presence of water ice as well as other structures in the lunar regolith [14]. Electromagnetic waves are a crucial indicator of composition of the lunar regolith as waves reflect or refract when coming into contact with different materials. Analyzing the behavior of the electromagnetic waves provides data about the composition of the lunar surface and subsurface [27]. The electromagnetic capabilities of the GPR will help to fulfill science objective 6n which includes analyzing the sedimentation of the lunar regolith. Additionally, the GPR is capable of mapping accurate water ice structures up to 10 meters below the surface, demonstrating that goal 2a, identifying water ice in the top 1 meter of the regolith, will be easily fulfilled [28].

NIRVSS is a NASA-Ames designed multi-component instrument used to retrieve spectral and imaging data within lunar permanently shaded regions (PSRs). In this mission, the NIRVSS instrumentation will be used to identify lunar surface composition, morphology, and thermophysical properties [56]. The primary scientific objectives to be fulfilled by this instrument will include the identification of hydrogen and oxygen concentrations (6n). Additionally, the NIRVSS will further help measure the lunar surface's thermophysical responses to characterize surface materials and their behavior under microgravity. Observations obtained from the NIRVSS will ultimately provide insight into lunar surface composition, variation in volatiles including water, hydrogen, and oxygen, fulfilling the (6n) science objective.

1.8. Programmatic Summary

1.8.1. Team Introduction

Team 9 consists of 12 people from across the United States all providing different expertise and skills to the mission:

Table 4. *Team Introduction*

Name	College/University	Team Role(s)	Experience
Omor Almamun	Texas A&M University - College Station, TX	Primary Thermal Engineer	Aerospace Engineering major proficient in thermodynamics to understand thermal analysis and prompt engineering to leverage AI in the design process
Michael Alvarez	Texas A&M University - College Station, TX	Secondary Thermal Engineer	General Engineering major (research, communication, team player)
Samuel Brauer	University of Colorado Boulder - Boulder, CO	Project Manager	Aerospace Engineering major, proficient in advanced mathematics, leadership roles from past teams, experienced in coding and CAD modeling, communication skills
Nathan Etheridge	The University of Texas at Austin - Austin, TX	Deputy Project Manager of Resources	Budgeting and STEM Experience, Electrical/Computer Engineering Skills, Proficiency in advanced math and statistics
Sonali Garg	Purdue Univeristy - West Lafayette, IN	Chief Scientist	Materials Science Engineering major, aerospace design and thermodynamics course skills, active leadership in research organizations, space architecture research, proficiency is physics
Arely Herrera	Cornell University - Ithaca, NY	Scientist, Programmatics	Biological Sciences Major; Research experience with laboratory techniques and data analysis

Kanishka Kamal	Texas A&M University - College Station, TX	Primary Mechanical Engineer	Aerospace Engineering major, CAD experience, Mechanical/Aerospace design experience from extracurricular work, Research & communication skills
Mackenzie Lloyd	Texas A&M University - College Station, TX	Lead Systems Engineer, Secondary Mechanical Engineer	Leadership experience from previous project teams, experience with dealing with communication between various subteams from previous project teams, Aerospace Engineering major, CAD experience
Hiromi Nurse	University of Nebraska Omaha - Omaha, NE	Scientist, Programmatics	Physics & Computer Science major; Experienced in physics and data analytics with a strong background in algorithm development
Thanh Pham	University of Houston - Houston, TX	Primary Electrical Engineer, Secondary Computer Engineer	Computer Engineering Major; Experienced in coding, CAD modeling, interfacing with microcontrollers, and time management/ teamwork soft skills
Andrew Tran	Texas A&M University - College Station, TX	Primary Computer Engineer, Secondary Electrical Engineer	Computer Engineering Major; Proficient in embedded systems management/design , experienced in software-hardware integration
Troy Tran	University of Texas at Arlington - Arlington,TX	Primary Computer Engineer, Secondary Electrical Engineer	Computer Science Major; Experienced in both high level and low level programming languages as well as proficient in algorithm design and optimization as well as rocketry

1.8.2. Team Management Overview

Team 9’s team consists of 12 people divided into three sub-teams:

1. Programmatics: The main management team responsible for overseeing the schedule, cost, and outreach of the mission. Handles tasks related to the mission’s timeline and budget. The primary method of communication between the Project Manager and the other sub-teams. All Programmatics members report to the Deputy Project Manager of Resources.
2. Science: Led by the Chief Scientist, this team handles research and analysis tasks. Responsibilities include researching mission requirements, selecting necessary instruments, and analyzing related data.

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

Setbacks & Solutions

Despite the decrease in members Team 9 has faced since the beginning of the mission, Team 9 is still well-equipped to address the requirements of the mission and complete the required tasks exceptionally. Team 9 has continued to meet the deadlines required of the mission through constant communication and collaboration throughout the three sub-teams. This sub-team communication has allowed the team to thrive despite the member setbacks faced in recent weeks as the use of organizational tools such as spreadsheets and team calendars allowed for clear communication of all necessary work to all teammates wherever their current location is. These tools also allowed the team to quickly reorganize the team in the event of a team member leaving, allowing for only minimal interruptions in the workflow of the team in emergency events such as the departure of a team member.

Team Organization/Collaboration

Team 9 heavily encourages collaboration between sub-teams and members to accomplish the tasks required of the mission. The team has accomplished constant collaboration through channels such as Discord and Trello, allowing team members to work together through voice channels and other collaboration resources that make global teamwork possible. The current Team 9 Organizational Chart can be found below:

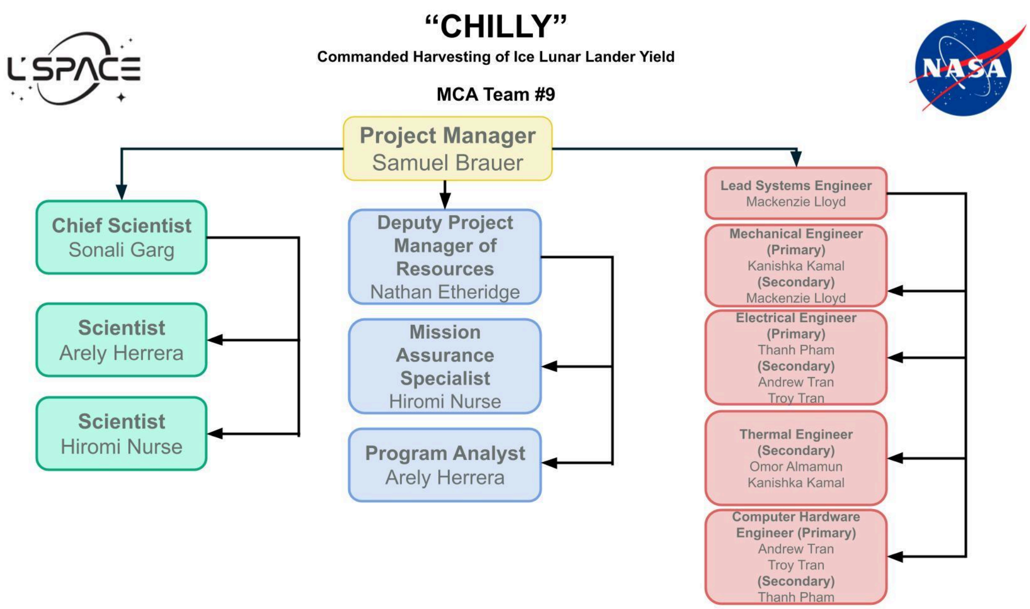


Figure 10. *Team 9 Organizational Chart*

1.8.3. Major Milestones Schedule

Table 5. *Schedule Overview*

ID#	PHASE	ASSIGNED TO	START	END	DAYS
1	**Phase C: Final Design and Fabrication**		8/25/24	7/26/26	701
1.1	Finalize Vehicle Design and obtain approval	Admin/Engineering	8/25/24	9/29/24	36
1.2	Construction of Subsystems	Mechanical/Engineering	11/4/24	2/1/26	455
1.90	Schedule Margin		2/2/26	2/9/26	8
1.10	Finalize Construction and Software Development	All Teams	2/10/26	5/24/26	104
1.11	◆Conduct and Present CDR	All Teams	5/25/26	7/26/26	63
2	**Phase D:System Assembly, Integration and Test**		7/27/26	6/22/27	331

2.3	Conduct Environmental Testing	All Teams	7/27/26	3/4/27	221
2.4	Schedule Margin		3/4/27	3/11/27	8
2.5	Analyze Test Results	All Teams	3/12/27	4/11/27	31
2.6	◆Implement Improvements and Prepare for Test Launch	All Teams	4/12/27	6/22/27	72
3	**Phase D: Test Launch**		4/12/27	8/20/28	497
3.1	Coordinate Logistics	Admin	4/12/27	4/19/27	8
3.2	Final Vehicle Verification	All Teams	4/20/27	6/9/27	51
3.3	Schedule Margin		6/9/27	6/16/27	8
3.4	Transport to Launch Site	All Teams	6/17/27	6/30/27	14
3.5	Initial Test Launch	All Teams	7/1/27	7/15/27	15
3.6	◆ Perform Final Modifications and Prepare for Launch Day	All Teams	7/15/27	8/20/28	403
4	**Phase D: Launch Preparation and Travel**		8/21/28	9/1/28	12
4.1	Travel to Cape Canaveral	Science, Engineering	8/21/28	8/28/28	8
4.2	◆Launch Day	Science, Engineering	8/28/28	9/1/28	5
5	**Phase D: Launch**		9/1/28	9/6/28	6
5.1	Initial Launch	All Teams	9/1/28	9/1/28	1
5.2	Monitor Flight Path	All Teams	9/1/28	9/4/28	4
5.3	◆Estimated Landing on Selected Site	All Teams	9/5/28	9/6/28	2
6	**Phase E: Operations and Sustainment**		9/6/28	1/24/29	141
6.1	Monitor Landing and Vehicle Stability	Mechanical, Software	9/6/28	9/13/28	8
6.2	Conduct Lunar Surface Explorations	Science, Engineering	9/13/28	1/20/29	130
6.3	Monitor Vehicle	Mechanical,	9/13/28	1/20/29	130

	Health	Software			
6.4	◆Conduct water-ice experiments on Lunar Surface	Science, Engineering, Software	9/13/28	1/20/29	130
6.5	Schedule Margin		1/20/29	1/24/29	5
7	**Phase F: Closeout**		1/25/29	11/1/29	281
7.1	Prepare Vehicle for return journey	All Teams	1/25/29	2/19/29	26
7.4	Schedule Margin		2/19/29	2/25/29	7
7.6	Analyze Mission Data	All Teams	2/26/29	8/27/29	183
7.7	◆Prepare and Present detailed mission report	All Teams	8/28/29	11/1/29	66

1.8.4. Budget Overview

Using the aforementioned schedule as a basis for the budget planning, Team 9's mission budget totals $173,727,456. Along with the schedule, analogous missions such as the VIPER mission and the materials researched for Team 9's rover played major roles in forming this cost.[57]This total cost includes all significant factors in the mission budget including:

1. Personnel Costs: $15,272,146
2. Travel Costs: $1,378,129
3. Outreach Costs: $3,109,350
4. Direct Costs: $146,675,213
5. Facilities and Administrative Costs: $7,292,619

This cost falls below the budget cap of $175,000,000 following the reduction from the initial cap of $225,000,000. By utilizing cost-saving workarounds that allow the mission to perform its science tasks at full capacity while lowering the overall costs, Team 9 has achieved an estimated total cost that leaves us with a margin of $1,272,544 for any minor changes that need to be implemented in the mission. The descopes taken to meet this budget following the budget reduction were:

1. Regenerative Fuel Cells Removed from Power Subsystem (~$11M) - Decreases costs and mass of mission vehicle significantly at the expense of Reduced redundancy in the Power Subsystem due to the removal of the Regenerative Fuel Cells as the secondary power source.
2. Mechanical and Power Subsystem Facilities Reduced (~$15 M) - Allows for significant cut costs in Phases C-D of the mission due to reduced testing for most

components from analogous missions at the expense of Reduced TRL levels in mechanical and power subsystems due to reduced manufacturing and testing facility costs.

3. Technician and Engineering Personnel Reduced (~$3.5M) - Engineering and Technician personnel are reduced from approximately 10 in Phases E-F to 7 due to the completion of the development of the vehicle.
4. Administration and Management Personnel Reduced (~$3.5M) - Administration and Management personnel were reduced in earlier phases of the mission while manufacturing and technical vehicle design were the main focus.
5. Guidance and Navigation Control Subsystem Integration (~$9 M) - Reduction of Guidance/Navigation Control Subsystem to parts integrated primarily in the mechanical subsystem with few standalone components allowing for an overall decreased cost and mass.

2. Overall Vehicle and System Design

2.1. Spacecraft Overview

In order to satisfy the science objectives chosen for the mission, the spacecraft chosen is a rover. This rover will be designed to traverse the lunar surface, more specifically, the terrain within the Leibnitz Beta Plateau. Inside the designated area, the rover will traverse to a PSR in order to collect scientific data on the ice deposits outlined in the STM. It will then transmit the scientific data to the primary mission orbiter. The rover will have five different subsystems (mechanical, power, CDH, thermal, and the payload). The top-level subsystem requirements are shown below in table 6.

Table 6. *Top Level Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mechanical Reqs							
MEC-1	The system shall be capable of traversing the terrain in the Leibnitz Beta Plateau.	The system needs to be able to traverse the terrain in order to satisfy the mission objectives.	MR-2	MEC-5 MEC-1.1 MEC-1.2 MEC-1.3	Test	Mechanical	Met
MEC-2	The mechanical subsystem shall withstand takeoff and landing conditions.	The system needs to be able to handle the takeoff and landing conditions in order to not get damaged. Any damage could jeopardize the mission.	MR-1 MR-3	MEC-2.1 MEC-2.2	Test	Mechanical	Met
MEC-3	The system shall be capable of deploying mechanisms for power consumption and scientific data collection.	The system has a predetermined volume and power from the constraints of being in the primary launch vehicle, so it will need to deploy solar panels for power generation, and deploy the instruments in order to satisfy the mission objectives..	MR-7 MR-8	MEC-3.1 MEC-3.2 MEC-3.3 MEC-3.4	Demonstration	Mechanical	Met
MEC-4	The system shall support the payload in data and sample collection.	The system must support the payload subsystem in order to accomplish the mission goals.	MR-7 MR-8	MEC-4.1 MEC-4.2	Test	Mechanical	Met
MEC-5	The mechanical system shall be able to withstand a temperature range of -233°C to 123°C.	The components and subassemblies in the mechanical subsystem need to be able to expand and contract safely with the temperature fluctuations on the moon's surface.	MEC-1 SYS-2	MEC-5.1 MEC-5.2	Test	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MEC-6	The mechanical system shall be able to navigate in the Leibnitz Beta Plateau.	The system must be capable of navigating to PSRs and out of them. Additionally, the system must be capable of avoiding hazards in order to survive the mission duration.	MR-2	MEC-6.1	Test	Mechanical	Met
MEC-7	The mechanical system shall cost less than $10 million.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-6	MEC-7.1 MEC-7.2 MEC-7.3 MEC-7.4 MEC-7.5	Inspection	Mechanical	Met
MEC-8	The mechanical subsystem shall have a max mass of 30 kg.	The system has a specific mass allowance in order to remain within the rover's mass requirement.	MR-4	MEC-8.1 MEC-8.2 MEC-8.3 MEC-8.4 MEC-8.5	Inspection	Mechanical	Met
MEC-9	The mechanical subsystem shall draw power less than 300 watts.	The total system has a limited amount of power available and will need to be able to run throughout the mission in order to satisfy the mission objectives.	MR-3	MEC-9.1 MEC-9.2 MEC-9.3 MEC-9.4 MEC-9.5	Inspection	Mechanical	Met
MEC-10	The mechanical system shall have a total volume less than a Length 1.5m x Width 1.5m x Height 1.5m for the stored configuration prior to deployment.	The entire mechanical system must be within the required volume amount.	MR-5	N/A	Inspection	Mechanical	Met
Electrical Power System Reqs							
EPS-1	The power subsystem shall provide continuous power to all rover subsystems throughout the mission.	Derived from mission requirement MR-01.	MR-3	EPS-3	Analysis	Power generation	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
EPS-2	The power subsystem shall have a minimum power generation capacity of 200 watts.	Derived from subsystem analysis and power budget.	MR-3 MR-7 MR-8	EPS-2.1	Inspection	Solar Panels, Fuel Cells	Met
EPS-4	The power subsystem shall have a total mass not exceeding 30 kg.	Limits overall system mass to meet mission constraints	MR-4	N/A	Inspection	Power Subsystem	Met
EPS-5	The power subsystem shall operate within the temperature range of -150°C to 100°C.	Ensures system functionality within the extreme temperature ranges of the lunar environment	SYS-2	N/A	Analysis	Thermal Management	Met
EPS-6	The power subsystem shall provide power at a regulated voltage of 28V ± 5%.	Provides stable and consistent power supply to rover components	MR-3	N/A	Inspection	Power Distribution Unit	Met
EPS-7	The power subsystem shall have a reliability of at least 0.95 over the mission duration.	Ensures high reliability to minimize the risk of mission failure	MR-3	EPS-8	Analysis	Power Subsystem	Met
EPS-9	The system shall not have a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof.	The customer requested that the system shall not include a RTG or any derivative thereof in the mission task document.	SYS-1	N/A	Inspection	Power Subsystem	Met
EPS-10	The power subsystem shall be designed to meet all electromagnetic compatibility (EMC) requirements.	It is important for the electrical subsystem to have no interference with the other subsystems.	MR-3	N/A	Inspection	Power Subsystem	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
EPS-11	The power subsystem shall be capable of withstanding transportation, including shocks and vibrations.	The subsystem needs to be able to withstand vibrations and shocks of the launch and landing in order to be operable throughout the mission.	MR-1	N/A	Analysis	Power Subsystem	Met
EPS-12	The power system shall cost less than $30 million.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-6	N/A	Inspection	Power Subsystem	Met
Thermal Control System Reqs (TCS)							
TCS-1	The system shall operate in temperatures ranging from -233°C to 123°C.	The lunar environment presents extreme temperature variations, from the cold of permanently shadowed regions to the heat of lunar daytime and the system needs to be able to operate throughout the entire mission and be able to handle vast fluctuations.	SYS-2	TCS-1.1	Test	Thermal	Met
TCS-2	The thermal control system shall keep other subsystems and instruments within the required operating range of -40°C to 40°C.	The temperature sensitive instruments and components in all of the subsystems need to be protected thermally to ensure they remain withing operating temperature throughout the entire mission.	MR-3	N/A	Analysis	Thermal	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
TCS-3	The thermal control system shall use 10-15% of the total rover's power.	The thermal subsystem cannot use more than the allotted power due to having a limited amount of power for the entire rover.	MR-3	N/A	Inspection	Thermal	Met
TCS-4	The thermal control system shall have a mass less than 20 kg.	The system cannot exceed the mass allowance which is derived from the overall rover mass budget outlined in the Mission Task document. If the mass exceeds this amount, the mission could be subject to cancellation.	MR-4	N/A	Inspection	Thermal	Met
TCS-5	The thermal control system shall cost less than $5 million.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-6	N/A	Inspection	Thermal	Met
TCS-6	The system shall maintain an internal temperature of -40 to 40 degrees Celcius for the duration of the mission.	Ensure systems are able to properly function.	MR-3	TCS-6.1 TCS-6.2	Test	Thermal	Met
TCS-7	The thermal control system shall monitor and report the temperature in real-time.	Real-time data is essential for managing thermal conditions effectively and monitoring critical components.	MR-3	N/A	Test	Thermal	Met
TCS-8	The thermal control system shall have 0g of radioactive material.	The customer limited the amount of radioactive material the system can use.	SYS-1	N/A	Inspection	Thermal	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Command & Data Handling Reqs (CDH)							
CDH-1	The subsystem shall communicate with the primary mission orbiter for the duration of the mission lifetime of TBD.	The system needs to be able to communicate with the orbiter throughout the mission in order to communicate the information collected to accomplish the science objectives.	MR-7 MR-8	CDH-1.1 CDH-6 CDH-8 CDH-9	Demonstration	CDH Subsystem	Met
CDH-2	The subsystem shall cost a max amount of $TBD	The system needs to stay within the mission's assigned budget.	MR-6	CDH-2.1	Inspection	CDH Subsystem	Met
CDH-3	The subsystem shall be able to operate in the lunar environment.	The system needs to remain operational throughout the mission in order to accomplish the mission objectives.	MR-2	CDH-3.1 CDH-3.2	Test	CDH Subsystem	Met
CDH-4	The subsystem shall have a max mass of TBD kg.	The system cannot exceed the mass allowance which is derived from the overall rover mass budget outlined in the Mission Task document. If the mass exceeds this amount, the mission could be subject to cancellation.	MR-4	N/A	Inspection	CDH Subsystem	Met
CDH-5	The CDH system will not consume more than TBD watts per second during peak activity.	Limit the power usage of the CDH system	MR-3	N/A	Analysis	CDH Subsystem	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH-7	CDH employs telemetry monitoring system health and real-time capabilities.	Monitor system health and system capability	MR-3	N/A	Demonstration	CDH Subsystem	Met
Payload Reqs							
PAY-1	The science instruments must be able to measure the spectral resolution of a sample with a resolution of at least 20 nm	The science instruments must be able to differentiate between common materials in the lunar environment complete mission objective 6n	MR-8	N/A	Test	Payload Subsystem	met
PAY-2	The science instrument must be able to resolve temperature differences of a sample from 0°C to 100°C	The science instrument must be able to identify the conditions of water-ice at and above its melting point	MR-8	N/A	Test	Thermal	met
PAY-3	The science instrument must be able to resolve the distance between objects in a sample with an accuracy of 5 cm or less	The science instrument must be able to locate the particulates in suspension of a liquid during the sedimentation process	MR-8	N/A	Test	Payload Subsystem	met
PAY-4	The science instrument must be able to produce radiation within the range of 100 - 1000MHz	The science instrument must be able to produce radiation that is able to penetrate lunar regolith while still be affected by water-ice and other volatiles	MR-7	N/A	Demonstration	Payload Subsystem	met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
PAY-5	The science instrument must be able to resolve the location of underground water-ice and other volatiles within 5cm	The science instrument must be able to determine the water-ice abundance within the top 1m of regolith within 5%	MR-7	SCI-5.1 SCI-5.2	Test	Payload Subsystem	met
PAY-6	The science instruments must be able to operate with 40 W or less for extended periods	The subsystem must be able to operate on battery power over extended periods	MR-3 PAY-3	N/A	Demonstration	Thermal	met
PAY-7	The science instrument must be able to operate within the acceptable temperature ranges provided by the thermal module	The minimum operating temperature of the NIRVSS spectrometers is 289 K	MR-3	N/A	Demonstration	Thermal	met
PAY-8	The science instrument must have the ability to measure lunar surface activity	The science instruments must be able to take measurements of the surface to complete science objectives	MR-3	N/A	Test	Payload Subsystem	met

The mechanical subsystem provides the structure, suspension, locomotion, GNC, a drill for sample collection, and the mechanical components necessary for deployment of the science instrumentation and solar panels. The structure subassembly includes the chassis and frame of the vehicle and will support all of the other components and subsystems. The structure will be made of 7050 Aluminum Alloy which has higher yield strength, fracture toughness, corrosion resistance, and is lighter weight compared to other materials. The suspension subassembly is responsible for ensuring stability and protection of the vehicle from shocks and vibrations. This subassembly includes the springs, dampers, control arms, and linkages. The locomotion subassembly enables the rover's mobility and maneuverability through the use of wheels, motors, and gearboxes. The wheels are composed of sheet metal held together with riveted joints with spokes. Each wheel will have its own Maxon EC-4pole 30 drive motor. The guidance, navigation, and control (GNC) subassembly is in charge of sensing the terrain and movement of the rover (such as tipping and acceleration), as well as, object avoidance to ensure the rover doesn't accidentally damage itself. The GNC subassembly includes the Northrop Grumman LN-200S IMU, two Navcams, two Hazcams, and a lighting system in order for the cameras to see in the PSRs. The sample collection subassembly will include the Honeybee Robotics Nano Drill in order to collect volatile samples and deposit them in the NIRVSS. This subassembly will also include a mechanical arm to deploy the Nano Drill. In addition to these five subassemblies, the mechanical subsystem will also include mechanisms for instrument and solar panel deployment in order to have a storage configuration during transportation within the volume constraint.

The power subsystem provides power generation, power storage, and power distribution. The rover's primary source of power will be solar cell panels. Using smaller solar cells and combining them into one panel will mitigate the risk the lunar dust poses. Additionally, the power subassembly will include a battery system, power distribution units (PDUs), thermal management systems, and health monitoring systems. The battery selected was a Lithium Iron Phosphate (LiFePO4) battery due to its performance, cycle life, cost, safety, and temperature range. Multiple batteries will be designed together in a four pack. The Crane PDU selected will distribute the power to all the other subsystems and components. The thermal management system and health monitoring systems will include important sensors that will monitor the CHILLY rover's voltage, current, temperature, and telemetry in order to analyze and diagnose any electrical issues that may occur.

The Command and Data Handling (CDH) system manages the rover's commands, communications, data storage, and data transmitting. This includes, telemetry, telecommunications, on-board computers, data storage units, and on-board software and processing tools. Its main purpose is to receive the scientific data from the instruments in the payload subsystem and send that data to the primary mission orbiter. The CDH subsystem consists of an application interface, an execution platform, a processing function, sensors and actuators, and data storage. Additionally, the CDH subsystem will keep data on the other subsystems to ensure all components and subassemblies are working efficiently. The subsystem will also relay commands to the other subsystems, and thermal management instructions to the thermal subsystem when a subassembly is overheating for example, in order to ensure mission success.

The thermal subsystem is in charge of regulating the temperatures of all of the other subsystems in order to ensure they are all operating at the required temperatures. The environment on the lunar surface includes extreme cold temperatures in the PSRs and extreme hot temperatures when in the sunlight. Because of this, the thermal subsystem will need to regulate the CHILLY rover's throughout the mission in order to ensure all components remain operational. The thermal subsystem will include thermal surface finishes, insulation, radiators, heaters, louvers, phase change materials, heat pipes, and sensors. It is essential that components and instrumentation remain at their specified operating temperatures in order to maintain the rover's functionality throughout the entire mission.

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

Table 7. *Spacecraft Mass, Volume, and Max Power Draw*

Subassembly	Mass	Volume	Max Power Draw
Mechanical	**38.572 kg**	**4.0836×10^{-2} m³**	**763 W**
Power	**50**	**0.23**	**320**
CDH	?	?	?

Thermal	?	?	?
Payload	**7.6**	**0.0125**	**40**
Total	?	?	?

2.1.1. Mechanical Subsystem Overview

The mechanical subsystem is restricted by dimensions and by weight. To be transported to the moon on a rocket, the subsystem shall have a total volume less than 4.5 m^3 and be within the mission's 85 kg weight limit. The subsystem itself includes the structure, suspension, locomotion, guidance navigation and control (GNC), and sample collection subassemblies.

The structure subassembly includes the chassis and frame, and is in charge of supporting the entire vehicle. It will be capable of handling loads of up to 5000 Newtons and withstanding the environmental hazards on the Moon such as extreme temperature fluctuations throughout the mission.

The suspension subassembly allows for a safer journey for the rover, consisting of springs, dampers, and various linkages. This also requires the suspension to absorb shocks and forces during liftoff since it may be that moment when the suspension will be put under greatest pressure by withstanding vibration of at least 2000 Hz. After having landed on the moon, the rover has to deploy various mechanisms for sample collection and power consumption, also falling within the previously specified weight and volume. Two such subassemblies that are a part of this segment are GNC and sample collection, and will include arms and linkages to assist a smooth process to achieve mission objectives. The Ground Penetrating Radar (GPR) is a scientific instrument that creates images via radio waves bouncing off the ground and received through antennas. This system will need to be deployed 10 cm off the ground. The chosen sample collecting device, the Nano Drill, will also be deployed to effectively drill and collect data.

For greater mobility between the landing site and PSR, the locomotion subassembly comprises wheels that can combat the lunar dust and regolith challenges. The wheels are non-pneumatic and deformable so extreme temperature fluctuations will not pose a threat pressure-wise. The subassembly must also travel across the terrain and be able to traverse cliffs and steep craters with a maximum slope of 15 degrees. To mitigate this, the suspension subassembly provides support to the structures by expanding the range of the wheelbase out and the wheels are independent of one another so the entire chassis will not be affected if, for example, one wheel happens to be compromised in a trench. This scenario, however, will not happen as easily because of the GNC subassembly which will detect hazards at least three meters away and be able to detect sudden declines or changes in the topography. For the GPR to gather the data when deployed, the vehicle must be moving at a speed of 0.5 cm/s for which a gearbox and motor combination is specifically provided for.

Each subassembly has to draw a certain power and must not exceed the predetermined limit to not hinder the success of the mission, as can be seen in *Table #*. Finally, the mechanical subsystem must not surpass the allotted resources in cost that can otherwise be used in other subsystems or personnel. These requirements can be found in further detail in the requirements section of this subsystem.

Table 8. *Mechanical Mass, Volume, and Max Power Draw*

Subassembly	**Mass**	**Volume**	**Max Power Draw**
Structures	15 kg	2.9×10^{-3} m^3	0 W
Suspension	7 kg	8.4×10^{-3} m^3	0 W
Locomotion	5.772 kg	2.03376×10^{-2} m^3	600 W
GNC	6.7 kg	5.8×10^{-3} m^3	83 W
Sample Collection	4.1 kg	3.4×10^{-3} m^3	80 W
Total	38.572 kg	4.0836×10^{-2} m^3	763 W

2.1.1.1. Mechanical Subsystem Requirements

The mechanical subsystem requirements, which baselines the criteria necessary for the subassemblies to provide the best support to the rover, are outlined below in table 9. The subsystem requirements have been derived from the top-level mechanical requirements outlined in both table 8 and in the table below. Mass, power draw, and cost limits have been established for each subassembly based on the top-level mechanical subsystem requirements. The structure subassembly's requirements have been further derived to withstand the stresses and loads the CHILLY rover will encounter during the launch, landing, and throughout the mission [39]. Requirements for the locomotion subassembly have also been created based on torque and gear ratio calculations found in the appendix. Additionally, the sample collection subassembly's requirements have been further derived to include specific criteria necessary to support both the GPR and NIRVSS in accomplishing the CHILLY mission's science goals.

Table 9. *Mechanical Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mechanical Reqs							
MEC-1	The system shall be capable of traversing the terrain in the Leibnitz Beta Plateau.	The system needs to be able to traverse the terrain in order to satisfy the mission objectives.	MR-2	MEC-5 MEC-6 MEC-1.1 MEC-1.2 MEC-1.3	Test	Mechanical	Met
MEC-1.1	The rover shall be capable of traversing a maximum slope of 15 degrees.	The system must be able to traverse the slopes found in the PSRs in the Leibnitz Beta Plateau.	MEC-1	N/A	Demonstration	Mechanical	Met
MEC-1.2	The in-wheel motor with gearbox shall be capable of producing a torque of 2.8 N-m.	The motor with gearbox must be able to produce the calculated torque in order to traverse the lunar surface.	MEC-1	N/A	Inspection	Mechanical	Met
MEC-1.3	The gearboxes shall have a gear ratio of 19.	The gearbox must have the calculated gear ratio in order for the rover to be able to traverse the lunar surface.	MEC-1	N/A	Inspection	Mechanical	Met
MEC-2	The mechanical subsystem shall withstand takeoff and landing conditions.	The system needs to be able to handle the takeoff and landing conditions in order to not get damaged. Any damage could jeopardize the mission.	MR-1 MR-3	MEC-2.1 MEC-2.2	Test	Mechanical	Met
MEC-2.1	The mechanical subsystem shall be able to withstand a maximum vibration level of 2000 hz.	The system needs to be able to handle vibrations caused by	MEC-2	N/A	Test	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		takeoff and landing in order to not get damaged which could jeopardize the mission.					
MEC-2.2	The mechanical subsystem shall be capable of withstanding 5003.1 Newtons.	The system needs to be capable of withstanding expected loads and stresses during operation and transportation.	MEC-2	N/A	Test	Mechanical	Met
MEC-3	The system shall be capable of deploying mechanisms for power consumption and scientific data collection.	The system has a predetermined volume and power from the constraints of being in the primary launch vehicle, so it will need to deploy solar panels for power generation, and deploy the instruments in order to satisfy the mission objectives..	MR-7 MR-8	MEC-3.1 MEC-3.2 MEC-3.3 MEC-3.4	Demonstration	Mechanical	Met
MEC-3.1	The system shall be capable of deploying the Ground Penetrating Radar (GPR) 10 cm off the ground.	The GPR needs to be around 10 cm off the ground in order to have an optimal resolution needed to satisfy the science goals.	MEC-3	N/A	Demonstration	Mechanical	Met
MEC-3.2	The system shall be capable of deploying the chosen sample collection device (the Nano Drill) to the ground.	The system must be able to deploy the Nano Drill to the ground in order to collect samples.	MEC-3	N/A	Demonstration	Mechanical	Met
MEC-3.3	The system shall be capable of deploying the chosen sample collection device (the Nano Drill) to the	The system must be able to deploy the Nano Drill to the NIRVSS in	MEC-3	N/A	Demonstration	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
	NIRVSS.	order to deposit the sample for analysis.					
MEC-3.4	The system shall be capable of deploying the solar panels to their optimal position for power generation.	The system must be capable of deploying the solar panels to the correct position in order to generate the most energy during charging periods.	MEC-3	N/A	Demonstration	Mechanical	Met
MEC-4	The system shall support the payload in data and sample collection.	The system must support the payload subsystem in order to accomplish the mission goals.	MR-7 MR-8	MEC-4.1 MEC-4.2	Test	Mechanical	Met
MEC-4.1	The system shall be capable of collecting volatile samples.	The system must be capable of collecting samples for the payload system to analyze in order to accomplish the science goals.	MEC-4	N/A	Demonstration	Mechanical	Met
MEC-4.2	The system shall be capable of moving 0.5 m/s.	The rover must move at a certain speed in order for the GPR to gather data.	MEC-4	N/A	Inspection	Mechanical	Met
MEC-5	The mechanical system shall be able to withstand a temperature range of -233°C to 123°C.	The components and subassemblies in the mechanical subsystem need to be able to expand and contract safely with the temperature fluctuations on the moon’s surface.	MEC-1 SYS-2	MEC-5.1 MEC-5.2	Test	Mechanical	Met
MEC-5.1	The structure of the rover shall maintain structural integrity within the temperature range of -233°C to	The rover's structure can expand and contract with the	MEC-5	N/A	Test	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
	123°C.	temperature fluctuations of the moon's surface temperature.					
MEC-5.2	The wheels, motors, and gears of the rover shall maintain functionality within the temperature range of -233°C to 123°C.	The locomotion sub assembly must be able to withstand temperatures in order to accomplish all mission goals and survive the mission duration.	MEC-5	N/A	Test	Mechanical	Met
MEC-6	The mechanical system shall be able to navigate in the Leibnitz Beta Plateau.	The system must be capable of navigating to PSRs and out of them. Additionally, the system must be capable of avoiding hazards in order to survive the mission duration.	MEC-1	MEC-6.1	Test	Mechanical	Met
MEC-6.1	The system shall be able to detect environmental hazards and avoid them.	The rover must not get stuck or damaged by environmental hazards in order to successfully accomplish the science goals.	MEC-6	MEC-6.1.1 MEC-6.1.2	Test	Mechanical	Met
MEC-6.1.1	The system shall be able to detect hazards at least 3 meters away.	The rover needs to detect hazards at least 3 meters away in order to avoid the hazard in time.	MEC-6.1	N/A	Test	Mechanical	Met
MEC-6.1.2	The system shall be able to detect cliffs and steep craters.	The system must be able to detect dangerous hazards such as steep craters and cliffs in order to	MEC-6.1	N/A	Test	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		accomplish the mission goals and survive the mission duration.					
MEC-7	The mechanical system shall cost less than $10 million.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-6	MEC-7.1 MEC-7.2 MEC-7.3 MEC-7.4 MEC-7.5	Inspection	Mechanical	Met
MEC-7.1	The structure subassembly shall cost less than $4 million.	The structure subassembly needs to stay within the allocated budget based on the system's assigned budget.	MEC-7	N/A	Inspection	Mechanical	Met
MEC-7.2	The suspension sub assembly shall cost less than $1 million.	The suspension sub assembly needs to stay within the allocated budget based on the system's assigned budget.	MEC-7	N/A	Inspection	Mechanical	Met
MEC-7.3	The locomotion subassembly shall cost less than $2 million.	The locomotion subassembly needs to stay within the allocated budget based on the system's assigned budget.	MEC-7	N/A	Inspection	Mechanical	Met
MEC-7.4	The GNC subassembly shall cost less than $2 million.	The GNC subassembly needs to stay within the allocated budget based on the system's assigned budget.	MEC-7	N/A	Inspection	Mechanical	Met
MEC-7.5	The sample collection subassembly shall cost less than $1 million.	The sample collection subassembly needs to stay within the allocated budget based on the system's assigned	MEC-7	N/A	Inspection	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		budget.					
MEC-8	The mechanical subsystem shall have a max mass of 30 kg.	The system has a specific mass allowance in order to remain within the rover's mass requirement.	MR-4	MEC-8.1 MEC-8.2 MEC-8.3 MEC-8.4 MEC-8.5	Inspection	Mechanical	Met
MEC-8.1	The structure subassembly shall have a max mass of 15 kg.	The structure subassembly needs to stay within the allocated mass in order for the mechanical system to not exceed its allocated mass.	MEC-8	N/A	Inspection	Mechanical	Met
MEC-8.2	The suspension sub assembly shall have a max mass of 7 kg.	The suspension sub assembly needs to stay within the allocated mass in order for the mechanical system to not exceed its allocated mass.	MEC-8	N/A	Inspection	Mechanical	Met
MEC-8.3	The locomotion subassembly shall have a max mass of 4 kg.	The locomotion subassembly needs to stay within the allocated mass in order for the mechanical system to not exceed its allocated mass.	MEC-8	N/A	Inspection	Mechanical	Met
MEC-8.4	The GNC sub assembly shall have a max mass of 2 kg.	The GNC subassembly needs to stay within the allocated mass in order for the mechanical system to not exceed its allocated mass.	MEC-8	N/A	Inspection	Mechanical	Met
MEC-8.5	The sample collection sub assembly shall have a max mass of 2 kg.	The sample collection subassembly needs to	MEC-8	N/A	Inspection	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		stay within the allocated mass in order for the mechanical system to not exceed its allocated mass.					
MEC-9	The mechanical subsystem shall draw power less than 300 watts.	The total system has a limited amount of power available and will need to be able to run throughout the mission in order to satisfy the mission objectives.	MR-3	MEC-9.1 MEC-9.2 MEC-9.3 MEC-9.4 MEC-9.5	Inspection	Mechanical	Met
MEC-9.1	The structure subassembly shall draw less power than 0 watts.	The structure subassembly shall not draw more power than is allocated to it in order to not exceed the system's power allowance.	MEC-9	N/A	Inspection	Mechanical	Met
MEC-9.2	The suspension sub assembly shall draw less power than 25 watts.	The suspension sub assembly shall not draw more power than is allocated to it in order to not exceed the system's power allowance.	MEC-9	N/A	Inspection	Mechanical	Met
MEC-9.3	The locomotion subassembly shall draw less power than 200 watts.	The locomotion subassembly shall not draw more power than is allocated to it in order to not exceed the system's power allowance.	MEC-9	N/A	Inspection	Mechanical	Met
MEC-9.4	The GNC sub assembly shall draw less power than 25 watts.	The GNC sub assembly shall not draw more power than is allocated	MEC-9	N/A	Inspection	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		to it in order to not exceed the system's power allowance.					
MEC-9.5	The sample collection subassembly shall draw less power than 50 watts.	The sample collection subassembly shall not draw more power than is allocated to it in order to not exceed the system's power allowance.	MEC-9	N/A	Inspection	Mechanical	Met
MEC-10	The mechanical system shall have a total volume less than a Length 1.5m x Width 1.5m x Height 1.5m for the stored configuration prior to deployment.	The entire mechanical system must be within the required volume amount.	MR-5	N/A	Inspection	Mechanical	Met

2.1.1.2. Mechanical Sub-Assembly Overview

2.1.1.2.1. Structure Subassembly

The structure subassembly encompasses the chassis and the frame. The chassis is determined to be of a 7050 Aluminum Alloy for its high yield strength and high stress corrosion cracking resistance. This was decided based on the environmental factors after research has shown that rust can form on the airless moon [60]. Though such answers are not yet available, any precaution against fatigue from the environment or from the rover's weight on the chassis should be considered so the system does not collapse. The piping to be utilized is round piping because of greater strength-to-weight ratio results and to prioritize the mass limit.

The frame is similar to the make of the chassis. It is also to be made of 7050 Aluminum Alloy, however in square piping. This hybrid design allows the rover to be better suited to tackle an array of problems. One such problem is the lunar surface which is composed of dust and terrain that can unbalance the vehicle. Having a square-piped frame allows the payload to sit at stable mounts inside the rover while a round-piped chassis combats the external forces from the ground and supports the wheels. Weldments are also easier to make in squared piping so having this option also plays in the economics of the mission.

An additional step is the application of Multi-layer Insulation (MLI) aerogel composite to the body of the rover. This coating assists the rover in heat rejection and insulation. A thin paneling will be added all round for the application of the MLI aerogel. Overall the TRL for this is a six as there have been prototypes created.

Table 10. *Structure Subassembly Mass, Volume, and Max Power Draw*

	Mass	Volume	Max Power Draw
Chassis	9 kg	2.4×10^{-3} m^3	0 W
Frame	6 kg	5×10^{-3} m^3	0 W
Total	15 kg	2.9×10^{-3} m^3	0 W

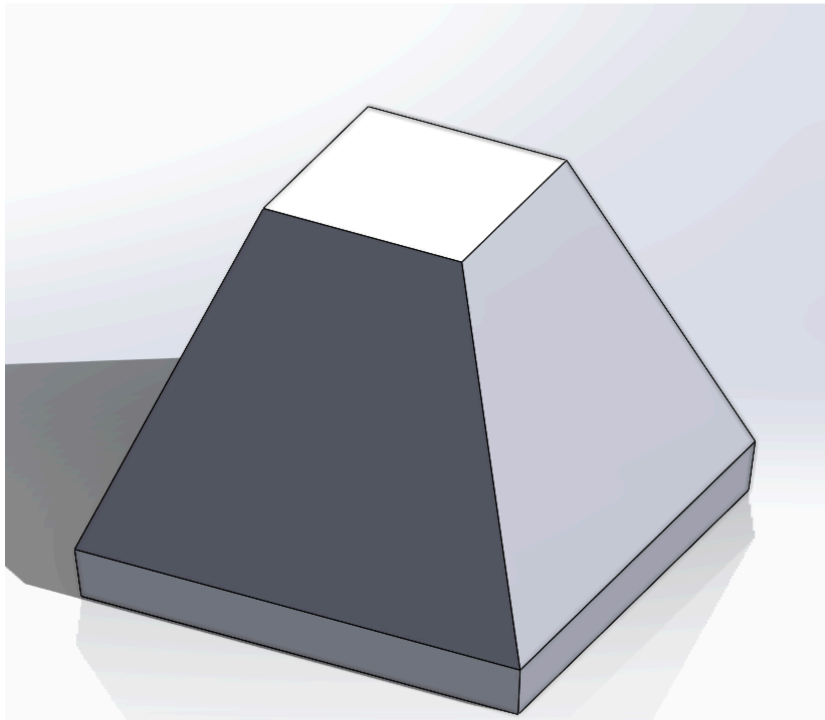


Figure 9. *Body of the rover that will house the internal components*

2.1.1.2.2. Suspension Subassembly

The suspension subassembly consists of components that will contribute to the overarching goal of preventing the wheels from coming out-of-contact with the surface of the moon and to ensure the stability inside the rover's internal units on the wheels. The most important point of the suspension design is the ability to create a transforming chassis which allows the rover to expand itself 33% more than the stowed state. To the CHILLY team, this also was an opportunity to combine independent wheel suspension to provide the best possible approach to the sample collection process and also give more flexibility to the science team in terms of instrument placement. Figure 11 below gives a pictorial demonstration of the linkages and turning angles. According to the Nomad team, the Nomad steers its front and rear pairs by attaching a push-rod to one axis of each linkage and is "driven by two racks which are pulled in opposite directions by a single pinion placed between the two linkages". Control arms and linkages are to be of composite reinforced fiber polymer capable of withstanding the rover's engineering and science equipment. The trade study for this selection can be found in the appendix. Springs will also be placed in strategic locations for shock absorption and for a safer journey, steel springs to act as a solid structure.

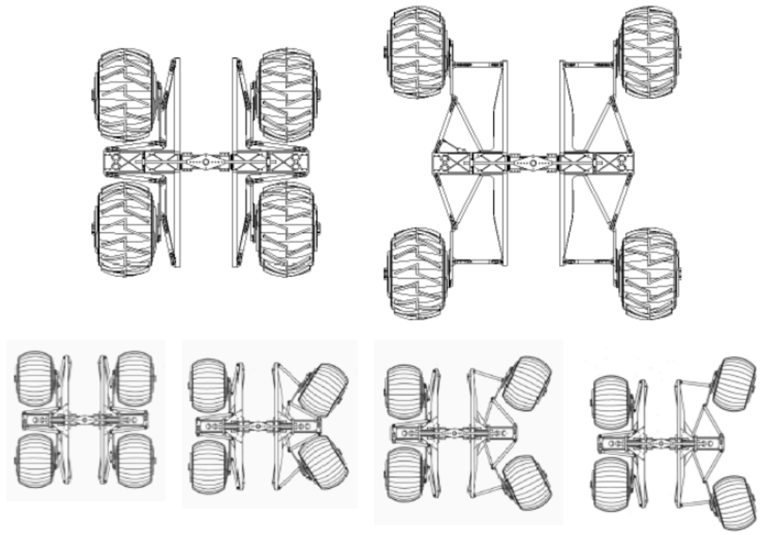


Figure 11. *Nomad chassis stowed and deployed. Source:* Developing Nomad for Robotic Exploration of the Atacama Desert.

In *Table 11* below, some items in the suspension process do not have applicability when it comes to volume, such as springs since they will be coiled near dampers and are thus difficult to know volumes of. Springs and dampers will be constructed of glass-fiber reinforced polymer for a necessary need of reduced weights compared to their steel and alloy counterparts.

Overall the TRL assigned to this subassembly is also a six. There are many instances such as the GFRP and CFRP that are already proven in the automotive industry and are actively being innovated to provide a faster and lighter consumer vehicle and its application to the CHILLY rover is one of similar purpose. However, since the CM lab is the brains behind the Nomad, it is what brings the TRL to a six because it has not made its way to the moon but is performing well in similar environments.

Table 11. *Suspension Subassembly Mass, Volume, and Max Power Draw*

	Mass	Volume	Max Power Draw
Springs	7 kg	N/A	0 W
Dampers	4 kg	3.04×10^{-4} m³	0 W
Control Arms	12 kg	8.1×10^{-3} m³	0 W
Linkages	3 kg	N/A	0 W
Total	26 kg	8.4×10^{-3} m³	0 W

2.1.1.2.3. Locomotion Subassembly

For the locomotion subassembly, wheels have been chosen as the rover's means to traverse the lunar environment. The wheels chosen for the CHILLY rover are a scaled down version of NASA's VIPER rover [62]. This design has been chosen due to the extensive research and testing that has already been done on the VIPER wheels for the same environmental conditions the CHILLY rover will experience throughout the mission on the Moon. Since the CHILLY rover cannot exceed a mass of 85 kg, the wheels need to be scaled down in order to not exceed the mechanical subsystem's allocated mass. These wheels will be 25 cm in diameter and 10 cm wide with spokes. The wheel rim will consist of 50 pieces of aluminum alloy 7050 sheet metal, which is held together by 360 riveted joints. The VIPER wheels the CHILLY wheels are based on have already gone through extensive lunar environment testing at the Simulated Lunar Operations (SLOPE) Laboratory [44]. Since the VIPER wheels have successfully demonstrated that they are capable of traversing the environment at the Moon's South Pole, the TRL level for the wheel is a six. However, since the CHILLY wheels are a scaled down version, the TRL becomes a five as the scaled down version has not been tested in this lab.

Additionally, each wheel will have its own Maxon EC-4pole 30 drive motor. This motor was selected due to its superior environmental suitability and torque supplied, which is shown in the Rover Drive Motor Trade Study found in the appendix. The motors need to be able to withstand the harsh environment on the Moon. This includes lunar dust, extreme temperatures, radiation, etc.. In order to traverse the lunar surface, the motor must produce enough torque to move due to the friction caused by the soft sand on the Moon. The required torque is calculated in the appendix and was 2.71 N-m for each motor. While the Maxon EC-4pole 30 motor only produces 0.15 N-m, gears with the correct gear ratio will increase the total torque produced to the required amount. The TRL for the Maxon EC-4pole 30 drive motor is a six. This motor has been used in previous NASA rover missions, such as the Mars 2020 Perseverance rover, and has been demonstrated in a relevant space environment.

The gearboxes chosen for the CHILLY rover are Bulk Metallic Glass Gears (BMGGs). These gears are ideal for the lunar environment in the PSRs. BMGs were made to withstand extreme freezing temperatures without the need for lubricant or a heater. Additionally, the unique composition of the BMGG metallic glass alloys make these gears tougher than ceramics and twice as strong as steel, with better elastic properties than both [9]. The gear ratio needed to increase the torque of the motors to the required torque has been calculated in the appendix and was 18.67. The BMGs will need to be manufactured with this gear ratio. The TRL for BMGGs is a 6. They have not been used in a space mission yet, but the components have been extensively tested under extreme conditions, such as extreme temperatures and a vacuum, in a simulated space environment.

Table 12. *Locomotion Subassembly Mass, Volume, and Max Power Draw*

	Mass	Volume	Max Power Draw
Wheels	3.184 kg	1.96×10^{-2} m³	0 W
Motors	1.248 kg	1.696×10^{-4} m³	600 W
Gears	1.34 kg	5.68×10^{-4} m³	0 W
Total	5.772 kg	2.03376×10^{-2} m³	600 W

2.1.1.2.4. GNC Subassembly

For the GNC subassembly, an IMU will be implemented for precise navigation. An IMU includes both a gyroscope and accelerometer which will be useful in navigating to PSRs within the Leibnitz Beta Plateau. The IMU selected was the Northrop Grumman LN-200S IMU due to its compact size, low power consumption, and high performance. It offers both precise navigation and stabilization with Micro-electromechanical Systems (MEMS) accelerometers and fiber optic gyroscopes. The trade studies that further justify the chosen IMU can be found in the appendix. Additionally, the LN-200 series has been used in various space applications proving its capability in operating in harsh environmental conditions. The TRL for the IMU is level 6. The LN-200S has previously been demonstrated in relevant space environments through space missions such as satellites, spacecraft, and launch vehicles.

In order to detect hazards and navigate, the CHILLY rover will implement two Navcams and two Hazcams, one front and one rear each cam. These cameras will help the rover avoid dangerous objects and hazards that could otherwise jeopardize the mission. This includes sharp rocks, steep cliffs, steep craters, etc.. Hazcams and Navcams have been previously used in various rover missions, so the TRL is a level 6 as they have been demonstrated in a relevant environment.

Additionally, to help aid the camera system in both navigation and object avoidance, a lighting system will be implemented as well. This will include two LED floodlights positioned next to the Navcams and LED tube lights on the bottom of the CHILLY rover. The PSRs are dark, and without a light source, the cameras will not be capable of performing as they should. The TRL level is a 5 as components of the planned lighting system have been demonstrated previously in various space missions.

Table 13. *GNC Subassembly Mass, Volume, and Max Power Draw*

	Mass	Volume	Max Power Draw
IMU	0.6 kg	5×10^{-4} m³	3 W
Navcams	3 kg	3×10^{-3} m³	20 W
Hazcams	1 kg	1×10^{-3} m³	10 W
LEDs	2.1 kg	1.3×10^{-3} m³	50 W
Total	6.7 kg	5.8×10^{-3} m³	83 W

2.1.1.2.5. Sample Collection Subassembly

In order for the sample collection subassembly to collect the volatile samples necessary to accomplish the CHILLY science goals, a drill will be implemented. The drill selected is the Honeybee Robotics Nano Drill. This drill is small, lightweight, and capable of penetrating the regolith surface of the moon in order to collect icy-regolith. Additionally, the Nano drill is capable of collecting, storing, and depositing the samples. The Rover Sample Collection Trade Study can provide more justification on the choice of the Nano drill and can be found in the appendix. While the Nano Drill has not been used in space yet, the drill has been extensively tested in relevant simulated space environments.

In order to deploy the Nano drill to the ground to collect samples and then to the NIRVSS to deposit them, a mechanical arm will be implemented. This mechanical arm will have three joints and will be located at the back of the CHILLY rover. The mechanical arm will need to be extensively tested in a simulated lunar environment in order to confirm it will remain operational throughout the mission. The TRL is a level 5 as components of the mechanical arm have been demonstrated in space, but the actual mechanical arm configuration has not been. Figure 12 below shows the motions the arm will go through to have a successful drill and collection process.

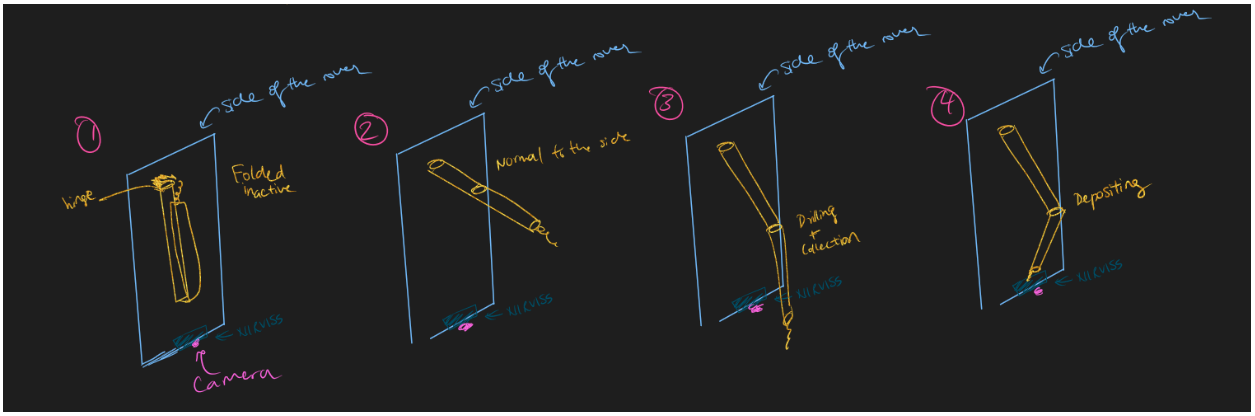


Figure 12. *A series of motion that is illustrated to show the movement of the mechanical arm in action.*

Table 14. *Sample Collection Subassembly Mass, Volume, and Max Power Draw*

	Mass	Volume	Max Power Draw
Drill	0.4 kg	4×10^{-4} m³	50 W
Mechanical Arm	3.7 kg	3×10^{-3} m³	30 W
Total	4.1 kg	3.4×10^{-3} m³	80 W

Outlined below in table 15, is a summary of the TRLs for each subassembly and component in the mechanical subsystem. It also includes the total TRL for the entire mechanical system.

Table 15. *Mechanical Subsystem TRL*

Subassembly/Component	Technology Readiness Level (TRL)	Explanation
Structure Subassembly	6	CM has tested and prototyped this structure and has been in competitive environments that got them recognized for this structural assembly.
Suspension Subassembly	6	Control arms and linkages are a working factor in

		CM’s rover team, however the decision to utilize CFRP and GFRP has been used by the automotive industry for years.
Wheels	5	Scaled down version of VIPER’s wheels which have been tested in a lunar simulated environment.
Drive Motor	6	Has been used in previous NASA Mars rovers and has been demonstrated in a relevant space environment.
Gearbox	6	Has been tested in a relevant simulated space environment.
Locomotion Subassembly	5	The lowest TRL within the subassembly.
IMU	6	Previously demonstrated in relevant space environments through space missions.
Navcams	6	Previously demonstrated in relevant space environments through NASA Mars rover missions.
Hazcams	6	Previously demonstrated in relevant space environments through NASA Mars rover missions.
LED Floodlights	5	Components have been previously demonstrated in relevant space environments.
LED Tube Lights	5	Components have been

		previously demonstrated in relevant space environments.
GNC Subassembly	5	The lowest TRL within the subassembly.
Nano Drill	6	Has been tested in a relevant simulated space environment.
Mechanical Arm	5	Components have been previously demonstrated in relevant space environments.
Sample Collection Subassembly	5	The lowest TRL within the subassembly.
Mechanical Subsystem	5	The lowest TRL within the subsystem.

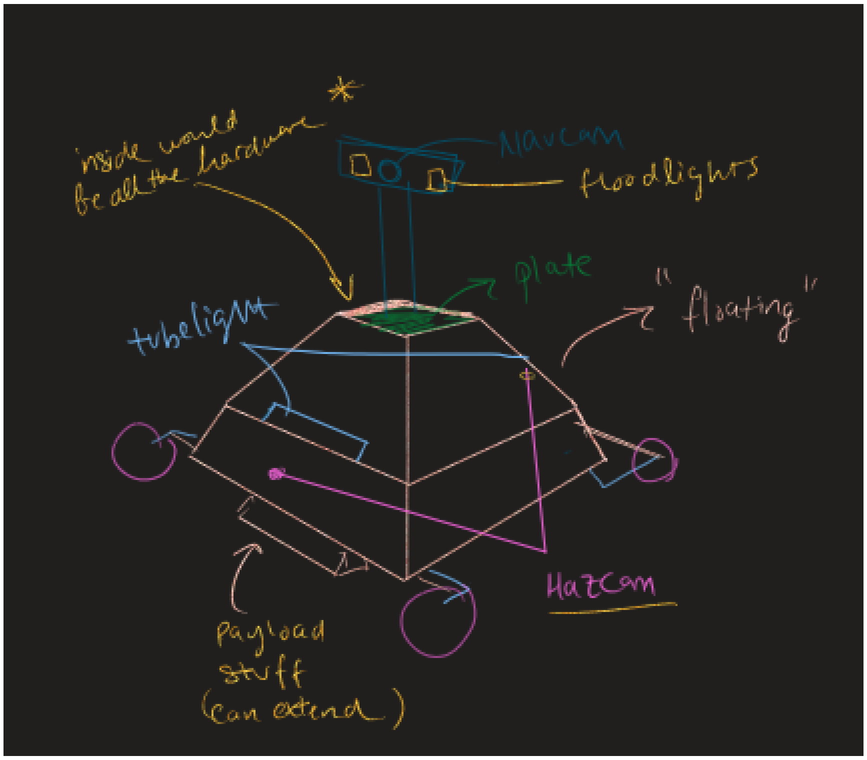


Figure 13.*An rough illustration depicting the mechanical subsystem*

Due to NX licensing issues, a CAD model is still in development so as a stepping stone, the figure above is added to the report to showcase the general idea of where each subassembly comes into play.

2.1.1.3. Mechanical Subsystem Recovery and Redundancy Plans

2.1.1.3.1. Structure Subassembly

The structure subassembly is designed to allow the frame to take the load of the instrumentation while the chassis is to protect the internal components from environmental factors. The only thing in this case in terms of redundancy is to allow the two to have a symbiotic nature, where if one fails, a brace can act as a backup. This primary structure is not expected to be compromised, however the mission destination is on a surface not on Earth so an additional step was the combination of different material properties that combine the suspension and structural components, as well as the hybrid piping to ensure the structural integrity is not lost. The body also protects the chassis and frame from the moon's micrometeoroids, dust, and debris.

2.1.1.3.2. Suspension Subassembly

In regards to the suspension system of the CHILLY rover, there are shock absorption and damping practices in place to reduce the sudden vibrations experienced whether during takeoff or on the moon over the rough terrain. The suspension system also is equipped with backup linkages that add a layer of plans to fall back on in case a part is disengaged. The expanded state of the rover is a layer added to explore the terrain in a more "free" manner, however if necessary, the entirety of the mission can be carried out in the stowed position in case of expansion malfunctions.

2.1.1.3.3. Locomotion Subassembly

The locomotion subassembly is fitted to combat the moon's surface's challenges. To counteract the extreme temperatures, the gearbox is NASA tested and produced to do just that. It is safely stored within the internal components surrounded by the chassis and frame. The motors are each placed in each wheel allowing for independent degrees of freedom that would otherwise be restricted if gone any other route. This means if one of the wheels is trapped in a rough surface, it is capable of freeing the rover through rotating in a decisive manner. The other three wheels are also free to release themselves from the trouble. The expansion feature from the suspension subassembly also works in heavy collaboration with the wheels as this is the system for which the rover can travel.

2.1.1.3.4. GNC Subassembly

The GNC subassembly is designed to operate within the PSRs found in the Moon's South Pole. Having two sets of both Navcams and Hazcams limits the risk because if one camera goes out, there's a backup one. Additionally, there are two different types of LEDs and two LED floodlights, so if any of the LEDs go out, there's enough light for the CHILLY rover to still be able to see in the PSRs. It is unlikely for the IMU to fail, but if it does, the cameras will be sufficient on their own when navigating.

2.1.1.3.5. Sample Collection Subassembly

While it is unlikely for the Nano Drill to fail, the mechanical arm is designed with three different joints. If one of these joints fails, the mechanical arm will still be able to function. It is impractical to include another mechanical arm if the mechanical arm fails, as the mechanical subsystem has mass restrictions. Additionally, it is not feasible to have a backup Nano Drill as it would need a mechanical arm in order to aid in accomplishing the science goals.

2.1.1.4. Mechanical Subsystem Manufacturing and Procurements Plans

2.1.1.4.1. Structure Subassembly

The structural subassembly of the CHILLY rover consists of the chassis, frame, and structural reinforcements. This subassembly will be manufactured in a partnered collaboration with NASA Ames Research Center and Carnegie Mellon University (CMU) as both are prominent names in rover projects and have worked multiple times in partnerships for rover competitions as well, including being well-versed in the design of this particular one. An example of such is the Nomad robot. The chassis for the rover will include a steering actuator and transforming chassis frames to support the independent movement of the wheels. Both the chassis and the frame will be made of a dense aluminum alloy that will withstand the drastic temperature differences on the moon's surface. The dimensions of the chassis/frame assembly come after the decision of the wheels resulting in 90 cm of length and 90 cm of width. To accommodate the robotic arm near the top of the rover, a height measurement of 80 cm was determined to be consistent with the tolerance setting previously applied for the length and width. The lead time determined for this subassembly is within the year, according to CMU's robot project trends.

2.1.1.4.2. Suspension Subassembly

The suspension subassembly is derived from the independent wheel concept. This subassembly will include springs, dampers, control arms and various linkages. These parts will be bought from various suppliers to speed up the assembly process. Astro Aerospace was very involved in the Curiosity Rover's suspension system, and in collaboration with JPL, they will be the main source for the springs and dampers. Carnegie Mellon University, however, would be more suitable to explore viable linkages that would support the load of the wheels intended for the CHILLY rover. The reason it is more reasonable to obtain parts from Astro Aerospace and have Carnegie Mellon research advanced linkages is to allow the two to exercise the best contribution to the rover's assembly. The latter would however be looking at a few months of design and then additional months of testing while the former would take a couple of months to deliver the items to the production.

2.1.1.4.3. Locomotion Subassembly

Wheels

The CHILLY rover will implement a four wheel design with four independent wheel modules. The wheels will be 25 cm in diameter and 10 cm wide composed of rigid sheet metal with spokes, similar to NASA's VIPER wheels. These wheels will be manufactured by Oak Ridge National Laboratory (ORNL). ORNL has been selected because they manufactured VIPER's prototype wheels [43]. ORNL specializes in supercomputing, advanced manufacturing, materials research, neutron science, clean energy, and national security, and has previously proven its reliability to NASA [47]. The lead time to design, manufacture, and deliver the wheels could be anywhere between several weeks to a couple of months since CHILLY is using the same design as VIPER's wheels, just at a smaller scale. If ORNL is unable to manufacture CHILLY's wheels, JPL will manufacture them since they have manufactured rover wheels in the past [24]. Since JPL has not manufactured a wheel similar to CHILLY's before, the lead time should increase by 12 to 24 months.

Motor

Additionally, the Maxon EC-4pole 30 has been selected as the in-wheel motor for the CHILLY rover. Maxon's motors have proven their reliability in other NASA rover missions on the moon. Maxon specializes in mechatronic drive systems in the fields of medical technology, aerospace, robotics, mobility solutions, and automated industrial applications [34]. Since this component is Commercial off the shelf (COTS), the lead time could take several weeks for delivery to a couple months if the item is out of stock and needs to be manufactured. If Maxon is not able to provide the in-wheel motors, Faulhaber's 3242 BX4 will be chosen to replace the Maxon EC-4pole 30. Faulhaber has experience in manufacturing drive systems for space exploration [17] and would make a good backup company. As this product is also COTS, the lead times should be similar.

Gearbox

With the Maxon EC-4pole 30 chosen as the CHILLY rover's in-wheel motor, a gear ratio of at least 19 N-m will be needed. Additionally, due to the extreme cold temperatures found in the PSRs, the CHILLY rover will implement Bulk Metallic Glass Gears (BMGG).

BMGGs can not only withstand temperatures of -200 °C, but it also does not need a heat source or lubrication [42]. JPL has already been manufacturing and testing the gears, so they have been chosen to manufacture them [25] for the CHILLY mission. Since the BMGGs need to be designed, manufactured, and delivered, the lead time can be anywhere between 12 to 24 months. If JPL is unable to provide the gears, Precipart will then manufacture them. Precipart specializes in gears and components for commercial and private jets, defense, and space applications. Additionally, Precipart is both ISO 13485 certified and ITAR certified [51]. The lead time for the design, manufacturing, and delivery of the BMGGs can increase 6 to 12 months since they do not have any experience manufacturing BMGGs.

2.1.1.4.4. GNC Subassembly

IMU

The CHILLY rover will utilize an IMU to track the rover's linear and angular acceleration in order to track the rover's overall motion. The IMU that will be implemented is the Northrop Grumman LN-200S, a commercial off the shelf (COTS) component that is known for its use in other NASA rovers. The LN-200S is designed for short to medium term space missions and is small, lightweight, and highly reliable [52]. Northrop Grumman is also recognized by NASA as a reliable supplier, and since this component is COTS, the lead time should be significantly less. If the component is in stock, the lead time could be between several days to a couple weeks for delivery. However, if the component has to be manufactured, the lead time could then be between several weeks and a couple months to account for manufacturing and delivery. In the event that Northrop Grumman is unable to provide the LN-200S, the CHILLY rover will then implement the Honeywell HG4930 IMU instead. This component is also COTS and should have a similar lead time.

Camera System

Additionally, the CHILLY rover will also be utilizing two hazcams and two navcams for navigation and hazard avoidance. For these components, Jet Propulsion Laboratory (JPL) has been selected as the contractor to manufacture both types of cameras. JPL specializes in robotic space exploration, and was selected due to the fact that they have experience in manufacturing both the hazcam and navcam for Mars rovers. Since the hazcams and navcams need to be designed, fabricated, and delivered, the lead time can range from 12 to 24 months. In the event that JPL is unable to manufacture the cameras, the cameras will then be manufactured by Malin Space Science Systems (MSSS). MSSS specializes in designing, building, and operating space camera systems for government and commercial aerospace customers [32]. The lead time should remain the same.

Lighting System

In order for the cameras to see in the PSRs, LED lights will be implemented on the CHILLY rover. Similar to NASA's VIPER rover, the navcams will be paired with two powerful blue LED headlights. In addition, the hazcams will be paired with blue LED tube lights. These LED lights will be manufactured by JPL. JPL is a reliable contractor and has a proven track record in developing numerous components for other rovers for NASA. Since both types of LED lights need to be designed for the lunar environment, fabricated, and delivered, the lead time can range from 12 to 24 months. If JPL is unable to manufacture these components, Alcon Lighting will then manufacture them. Additionally, Alcon Lighting is working with NASA to create a "Lighting for Space" series which may be beneficial in decreasing lead times. While they are not as reliable as JPL, their experience with LED lighting systems was the reason they were chosen as a backup contractor. Since Alcon Lighting is less experienced than JPL, the lead time can increase from anywhere between 6 to 12 months.

2.1.1.4.5. Sample Collection Subassembly

Drill

The CHILLY rover will utilize a drill in order to collect volatiles for science analysis. The drill that will be implemented is the Honeybee Robotics Nano Drill. This drill is small and lightweight, and is capable of capturing, retaining, and ejecting rock core, icy-soil, and regolith. Honeybee Robotics is a AS9100 certified, NASA-approved flight hardware supplier that is reliable [23]. Since the Nano Drill is COTS, the lead time should be significantly reduced. If the drill is in stock, the lead time could be between several days to a couple weeks for the delivery. However, if the drill has to be manufactured, the lead time could be several weeks to a couple months to account for the manufacturing and delivery. If Honeybee Robotics is unable to provide the Nano Drill, JPL will be used to manufacture a new drill for the CHILLY rover similar to the Nano Drill. However, this will increase the lead time by 12 to 24 months to account for designing, manufacturing, and delivery.

Mechanical Arm

In order for the Nano Drill to reach the ground to capture the icy-regolith, and then reach the NIRVSS to deposit it, the CHILLY rover will implement a mechanical arm capable of operating in extreme cold temperatures. Maxar Space Systems has been selected as the contractor to manufacture the mechanical arm. Maxar has proven its reliability to NASA by providing successful robotic arms on six of NASA's Mars rovers and landers [33]. These Maxar robotic arms were designed to dig, drill, sample, and explore the Martian surface similar to what the Chilly rover's mechanical arm is required to do. Since the mechanical arm needs to be designed, fabricated, and delivered, the lead time can range from 12 to 24 months. In the event that Maxar is unable to manufacture and deliver the mechanical arm, JPL will manufacture them. With another reliable contractor manufacturing them, the lead time should be similar.

2.1.1.5. Mechanical Subsystem Verification Plans

Outlined below in table 16, is the mechanical subsystem's preliminary verification plans. These plans provide further explanation to the various verification methods chosen for the mechanical requirements in table 16. Verification plans are important in reducing the risks and demonstrating the reliability of the mechanical subsystem.

Table 16. *Mechanical Verification Plans*

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
MEC-1	The system shall be capable of traversing the terrain in the Leibnitz Beta Plateau.	Test	In order to verify that the system is capable of traversing the terrain in the specified lunar environment, the system model will need to be tested in a simulated lunar environment with the same environmental conditions and hazards the CHILLY rover may experience throughout the mission.	The rover will need to be tested in a simulated environment with equivalent environmental characteristics and hazards as the Moon's south pole region and PSRs. This test will take place at the Simulated Lunar Operations (SLOPE) Laboratory at NASA's Glenn Research Center. It will traverse around the simulated environment and will be tested in navigating in the fluffy lunar soil, around boulders and craters, and over rocks.
MEC-1.1	The rover shall be capable of traversing a maximum slope of 15 degrees.	Demonstration	In order to verify this, the system needs to demonstrate that it can traverse a slope of 15 degrees. No special equipment is necessary.	In order to demonstrate the rover's capability to move on a slope of 15 degrees, a wedged platform at an angle of 15 degrees will be used. To satisfy this requirement, the rover will traverse up and down the wedge.
MEC-1.2	The in-wheel motor with gearbox shall be capable of producing a torque of 2.8 N-m.	Inspection	In order to verify that the motors can produce the necessary torque, an inspection can be done using a simple instrument.	In order to inspect that the motors produce the required torque, a reaction torque sensor will be used. This method measures how much torque is required to stop the motor from turning which then tells us how much torque it can produce due to Newton's third law.
MEC-1.3	The gearboxes shall have a gear ratio of 19.	Inspection	In order to verify the selected motors have the specified gear ratio, a visual inspection needs to be done.	A visual inspection in order to verify that the selected gears have the correct gear ratio will be done by examining the data sheet.
MEC-2	The mechanical subsystem shall withstand takeoff and landing conditions.	Test	In order to verify that the system will survive launch, a vibration and shocks test will need to be performed using special equipment.	Vibration and shock testing will be accomplished by utilizing a vibration table and fixture that enables 3-axis testing. This table will produce vibrations and shocks equivalent to shocks the system may experience during launch and throughout the mission.

MEC-2.1	The mechanical subsystem shall be able to withstand a maximum vibration level of 2000 hz.	Test	In order to verify this, a test will need to be performed using special equipment.	The vibration testing will be accomplished using a vibration table that enables 3-axis testing. This table will produce vibrations up to 2000 hz in order to verify that the system is capable of withstanding these vibrations.
MEC-2.2	The mechanical subsystem shall be capable of withstanding 5003.1 Newtons.	Test	In order to verify this, a test will need to be performed using special equipment.	The chassis and frame of the rover will have a tensile test performed in order to test the amount of force the chassis and frame will be able to withstand.
MEC-3	The system shall be capable of deploying mechanisms for power consumption and scientific data collection.	Demonstration	The system will need to demonstrate that the mechanisms are capable of reconfiguring the solar panels and sample collection subassembly.	The system will be instructed to deploy the mechanisms, and if they are successfully able to deploy them, this requirement will be satisfied.
MEC-3.1	The system shall be capable of deploying the Ground Penetrating Radar (GPR) 10 cm off the ground.	Demonstration	The system will need to demonstrate that it is capable of deploying the GPR.	The system will be instructed to deploy the GPR, and if the system is successfully able to deploy it, this requirement will be satisfied.
MEC-3.2	The system shall be capable of deploying the chosen sample collection device (the Nano Drill) to the ground.	Demonstration	The system will need to demonstrate that it is capable of deploying the Nano drill to the ground.	The system will be instructed to deploy the Nano Drill to the ground, if the system is successful in completing this task, this requirement is satisfied.
MEC-3.3	The system shall be capable of deploying the chosen sample collection device (the Nano Drill) to the NIRVSS.	Demonstration	The system will need to demonstrate that it is capable of deploying the Nano drill to the NIRVSS.	The system will be instructed to deploy the Nano Drill to the NIRVSS, if the system is successful in doing this, the requirement is met.
MEC-3.4	The system shall be capable of deploying the solar panels to their optimal position for power generation.	Demonstration	The system needs to demonstrate that it can deploy the solar panels to the most optimal angle.	The system will be instructed to deploy the solar panels, if the system is successful in doing this, the requirement has been met.

MEC-4	The system shall support the payload in data and sample collection.	Test	The system needs to demonstrate that it is capable of supporting the payload in sample collection.	The system will need to demonstrate that it fully supports the GPR, NIRVSS, and the Nano Drill in sample collection. This will be done by successfully running the GPR, successfully utilizing the Nano Drill in collecting samples in the lunar environment, and successfully depositing the samples in the NIRVSS for analysis in a simulated environment at the SLOPE.
MEC-4.1	The system shall be capable of collecting volatile samples.	Demonstration	The system needs to demonstrate that it can collect samples.	A simple demonstration will be done to show that the Nano drill can collect samples. This can be done by instructing the sample collection system to collect samples. If the system is successful, the requirement has been met.
MEC-4.2	The system shall be capable of moving 0.5 cm/s.	Inspection	The system needs to show that it can move 0.5cm/s and no special equipment is needed.	The rover will be instructed to move forward at a speed of 0.5 cm/s. If the rover is successful, the requirement has been met.
MEC-5	The mechanical system shall be able to withstand a temperature range of -233°C to 123°C.	Test	In order to verify that the system can operate within the required temperatures, a test will need to be performed as special equipment and a simulated environment is required.	The system will be placed in a simulated environment that will bring temperature levels to the minimum and maximum temperatures specified that the rover will experience throughout the mission.
MEC-5.1	The structure of the rover shall maintain structural integrity within the temperature range of -233°C to 123°C.	Test	In order to verify that the rover will maintain structural integrity, a test will need to be performed using special equipment.	After going through the ranges of temperatures in the previous test above, the structure subassembly will go through a tensile test again to verify it has kept its structural integrity.
MEC-5.2	The wheels, motors, and gears of the rover shall maintain functionality within the temperature range of -233°C to 123°C.	Test	In order to verify that the system will remain functional in the specified temperatures, a test will need to be performed using special equipment and a simulated environment.	Inside the simulated environment, the rover will be instructed to move throughout the extreme temperature ranges in order to verify the locomotion subassembly will remain functional throughout the mission.

MEC-6	The mechanical system shall be able to navigate in the Leibnitz Beta Plateau.	Test	In order to verify that the system will be able to navigate in the lunar environment, a test will need to be performed in a simulated environment.	The rover will be placed inside a simulated lunar environment at the SLOPE and will be instructed to navigate. If the rover is able to navigate safely and accurately in the simulated lunar environment, the requirement will be met.
MEC-6.1	The system shall be able to detect environmental hazards and avoid them.	Test	In order to verify that the system can detect objects and avoid them in the lunar environment, a test will need to be performed in a simulated environment.	Inside the simulated lunar environment at the SLOPE, obstacles and hazards will be placed in order to test that the GNC subassembly can successfully detect and avoid these hazards.
MEC-6.1.1	The system shall be able to detect hazards at least 3 meters away.	Test	In order to verify that the system can detect objects at least 3 meters away in the lunar environment, a test will need to be performed in a simulated environment.	Inside the simulated environment, the GNC subassembly needs to be able to detect the placed obstacles and hazards at least 3 meters away.
MEC-6.1.2	The system shall be able to detect cliffs and steep craters.	Test	In order to verify that the system can avoid steep cliffs and other hazards in the lunar environment, a test will need to be performed in a simulated environment.	The simulated environment at SLOPE will include steep slopes the rover is unable to traverse on. The system will need to identify if the slope is too steep and avoid the hazard.
MEC-7	The mechanical system shall cost less than $10 million.	Inspection	An inspection will need to be done to verify this requirement by visual examinations.	A visual inspection of the system's bill of materials will be performed in order to verify that the specified budget has not been exceeded.
MEC-7.1	The structure subassembly shall cost less than $4 million.	Inspection	An inspection will need to be done to verify this requirement by visual examinations.	A visual inspection of the structure subassembly's bill of materials will be performed in order to verify that the specified budget has not been exceeded.
MEC-7.2	The suspension sub assembly shall cost less than $1 million.	Inspection	An inspection will need to be done to verify this requirement by visual examinations.	A visual inspection of the suspension subassembly's bill of materials will be performed in order to verify that the specified budget has not been exceeded.
MEC-7.3	The locomotion subassembly shall cost less than $2 million.	Inspection	An inspection will need to be done to verify this requirement by visual examinations.	A visual inspection of the locomotion subassembly's bill of materials will be performed in order to verify that the specified budget has

				not been exceeded.
MEC-7.4	The GNC subassembly shall cost less than $2 million.	Inspection	An inspection will need to be done to verify this requirement by visual examinations.	A visual inspection of the GNC subassembly's bill of materials will be performed in order to verify that the specified budget has not been exceeded.
MEC-7.5	The sample collection subassembly shall cost less than $1 million.	Inspection	An inspection will need to be done to verify this requirement by visual examinations.	A visual inspection of the sample collection subassembly's bill of materials will be performed in order to verify that the specified budget has not been exceeded.
MEC-8	The mechanical subsystem shall have a max mass of 30 kg.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of a scale.	The mechanical subsystem will be placed on a scale in order to visually verify it has not exceeded the specified mass.
MEC-8.1	The structure subassembly shall have a max mass of 15 kg.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of a scale.	The structure subassembly will be placed on a scale in order to visually verify it has not exceeded the specified mass.
MEC-8.2	The suspension sub assembly shall have a max mass of 7 kg.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of a scale.	The suspension sub assembly will be placed on a scale in order to visually verify it has not exceeded the specified mass.
MEC-8.3	The locomotion subassembly shall have a max mass of 4 kg.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of a scale.	The locomotion subassembly will be placed on a scale in order to visually verify it has not exceeded the specified mass.
MEC-8.4	The GNC sub assembly shall have a max mass of 2 kg.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of a scale.	The GNC subassembly will be placed on a scale in order to visually verify that it has not exceeded the specified mass.
MEC-8.5	The sample collection sub assembly shall have a max mass of 2 kg.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of a scale.	The sample collection subassembly will be placed on a scale in order to visually verify that it has not exceeded the specified mass.

MEC-9	The mechanical subsystem shall draw power less than 300 watts.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of simple equipment.	A visual inspection will be done with the use of an ammeter. The ammeter will be connected to all of the components within the system and if all of the components' power draw does not exceed the specified amount, the requirement has been met.
MEC-9.1	The structure subassembly shall draw less power than 0 watts.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of simple equipment.	A visual inspection will be done with the use of an ammeter. The ammeter will be connected to all of the components within the system and if all of the components' power draw does not exceed the specified amount, the requirement has been met.
MEC-9.2	The suspension sub assembly shall draw less power than 25 watts.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of simple equipment.	A visual inspection will be done with the use of an ammeter. The ammeter will be connected to all of the components within the system and if all of the components' power draw does not exceed the specified amount, the requirement has been met.
MEC-9.3	The locomotion subassembly shall draw less power than 200 watts.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of simple equipment.	A visual inspection will be done with the use of an ammeter. The ammeter will be connected to all of the components within the system and if all of the components' power draw does not exceed the specified amount, the requirement has been met.
MEC-9.4	The GNC sub assembly shall draw less power than 25 watts.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of simple equipment.	A visual inspection will be done with the use of an ammeter. The ammeter will be connected to all of the components within the system and if all of the components' power draw does not exceed the specified amount, the requirement has been met.
MEC-9.5	The sample collection subassembly shall draw less power than 50 watts.	Inspection	An inspection will need to be done to verify this requirement by visual examinations through the use of simple equipment.	A visual inspection will be done with the use of an ammeter. The ammeter will be connected to all of the components within the system and if all of the components' power draw does not exceed

				the specified amount, the requirement has been met.
MEC-10	The mechanical system shall have a total volume less than a Length 1.5m x Width 1.5m x Height 1.5m for the stored configuration prior to deployment.	Inspection	An inspection will need to be done to verify this requirement by visually examinations through the use of a measuring stick.	A visual inspection will be done with a measuring stick which will measure the length, width, and height of the rover and verify that the rover is within the volume limit.

2.1.2. Power Subsystem Overview

The CHILLY Rover power subsystem consists of solar cell panels, battery systems, power distribution units (PDUs), thermal management systems, and health monitoring systems.

Solar cell panels are the primary source of power for the Rover. To provide sufficient energy to all other subcomponents, the solar cell panels are required to generate at least 200W. Due to the potential risk of lunar dust, which can highly damage any material, small solar cells will be combined into big panels to reduce the risk of total damage. The most optimal solar cells are from Spectrolab, specifically the XTJ version, due to their high efficiency (35%) and power output (9 W/kg). The rover will need around 285 cells to provide the 200W requirement. The deployment and orientation mechanism are added to orient the solar cells for most sunlight absorption in case some solar cells are partially damaged. Software controls of the rover will manage the deployment and orientation, while the health monitoring system ensures the solar cells' performance.

The CHILLY rover will utilize Lithium Iron Phosphate ($LiFePO_4$) because it provides the best balance of performance, cycle life, cost, safety, and temperature range, making it a suitable choice for the battery system of the rover. The main supplier will be SkyLabs from Slovenia, providing the rover with a SKY-NANOeps-BMM battery capable of high capacity, discharge rate, and availability of the technology. Multiple batteries will be designed together at a pack, and the rover will need to recharge 4 packs of batteries to be completely full. This can provide the rover to run from 5 to 10 hours. When the batteries are full, the rover will switch to the direct energy from the solar cell panels, saving the battery's energy during low sun-light periods.

Crane PDU is responsible for distributing the generated and stored power into other subsystem components.

A passive thermal management system is integrated in the rover power subsystem to maintain a suitable temperature. Key things of this passive system include heat sinks, heat pipes, thermal interface materials, and conductive adhesives.

The Health Monitoring System of the CHILLY Rover includes important sensors that ensure the component's health level of the rover relating to voltage, current, temperature, thermal, and telemetry. These sensors will work in overlap, sending the data back to the mainboard to analyze the power system's health. The data will also be sent back to the control team on Earth once every day to analyze and diagnose if any issues occur.

The power requirements of the rover change throughout 5 main phases to be efficient:

- Traverse Phase: The rover will be moving across the lunar surface. Power is mainly drawn from the solar cell panels if the battery is full. Unless there is no solar power, the rover will use the stored energy from the battery until solar power comes back. An approximate power consumption for this phase is 200W.

- Data Collection Phase: The rover will stop moving to operate scientific instruments. The energy used is moderate, ranging from 100W to 150W.

- Data Analysis Phase: The rover will spend time analyzing and collecting samples. This activity may draw from 50W to 100W of power.

- Data Relay Phase: The rover will send the data back to the Earth team. This is a high-performance task that takes around 200W to 250W of power.

- Recharge Phase: The rover will seek out sunlit areas to recharge. Unnecessary components will be turned off for maximum energy savings. The Health Monitoring System will only measure the energy level. This activity will require around 100W to 150W.

In summary, an estimation of total power consumption of the rover's operation for 10 hours is around 1500W (assuming every activity is around 2 hours).

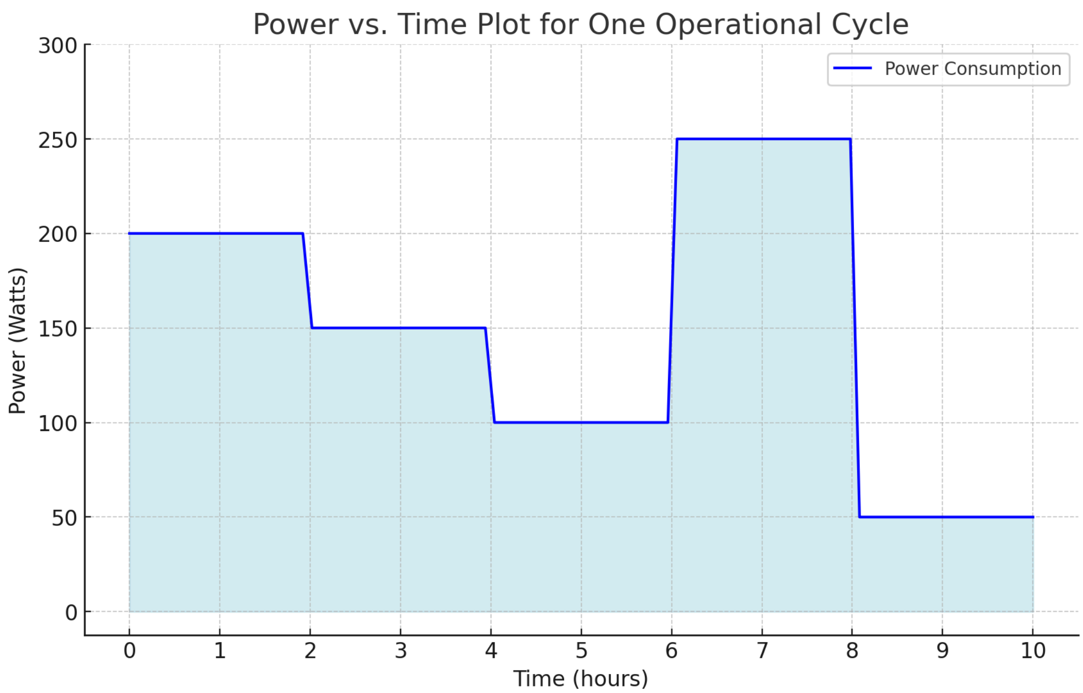


Figure 14. *Power vs Time Plot*

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

Table 17. *Power System Subassemblies*

Subassembly	Mass (kg)	Volume (m^3)	Max Power Draw (W)
Solar Panels	15	0.08	150
Regenerative Fuel Cells	12	0.05	50
Battery System	10	0.04	100
Power Distribution Unit	5	0.02	10
Thermal Management System	6	0.03	5
Health Monitoring System	2	0.01	5
Total	**50**	**0.23**	**320**

2.1.2.1. Power Subsystem Requirements

Outlined below in table 18, are the Power subsystem's requirements. These requirements outline what is expected of the power system in order to have a successful mission.

Table 18. Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Power Subsystem Reqs							
EPS-1	The power subsystem shall provide continuous power to all rover subsystems throughout the mission.	Derived from mission requirement MR-01.	MR-3	EPS-3	Analysis	Power generation	Met
EPS-2	The power subsystem shall have a minimum power generation capacity of 200 watts.	Derived from subsystem analysis and power budget.	MR-3 MR-7 MR-8	EPS-2.1	Inspection	Solar Panels, Fuel Cells	Met
EPS-2.1	The solar panels shall generate at least 200W of power.	Specifies primary power source capacity	EPS-2	N/A	Inspection	Solar Panels	Met
EPS-3	The power subsystem shall store a minimum of 1.5 kWh of energy for use during lunar night.	Ensures energy storage capacity for use during periods without sunlight	EPS-1	EPS-3.1	Inspection	Batteries	Met
EPS-3.1	The batteries shall have a specific energy of at least 200 Wh/kg.	Ensures longevity and reliability.	EPS-3	N/A	Inspection	Batteries	Met
EPS-4	The power subsystem shall have a total mass not exceeding 30 kg.	Limits overall system mass to meet mission constraints	MR-4	N/A	Inspection	Power Subsystem	Met
EPS-5	The power subsystem shall operate within the temperature range of -150°C to 100°C.	Ensures system functionality within the extreme temperature ranges of the lunar environment	SYS-2	N/A	Analysis	Thermal Management	Met
EPS-6	The power subsystem shall provide power at a regulated voltage of 28V ± 5%.	Provides stable and consistent power supply to rover components	MR-3	N/A	Inspection	Power Distribution Unit	Met
EPS-7	The power subsystem shall have a reliability of at least 0.95 over the mission duration.	Ensures high reliability to minimize the risk of mission failure	MR-3	EPS-8	Analysis	Power Subsystem	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
EPS-8	The power subsystem shall include health monitoring systems to report power status and faults.	Allows for real-time monitoring and troubleshooting of the power system	EPS-7	EPS-8.1	Inspection	Health Monitoring System	Met
EPS-8.1	The health monitoring system shall have a data transmission capability to Earth.	Ensures communication capability for remote diagnosis and intervention	EPS-8	N/A	Demonstration	Health Monitoring System	Met
EPS-9	The system shall not have a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof.	The customer requested that the system shall not include a RTG or any derivative thereof in the mission task document.	SYS-1	N/A	Inspection	Power Subsystem	Met
EPS-10	The power subsystem shall be designed to meet all electromagnetic compatibility (EMC) requirements.	It is important for the electrical subsystem to have no interference with the other subsystems.	MR-3	N/A	Inspection	Power Subsystem	Met
EPS-11	The power subsystem shall be capable of withstanding transportation, including shocks and vibrations.	The subsystem needs to be able to withstand vibrations and shocks of the launch and landing in order to be operable throughout the mission.	MR-1	N/A	Analysis	Power Subsystem	Met
EPS-12	The power system shall cost less than $30 million.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-6	N/A	Inspection	Power Subsystem	Met

2.1.2.2. Power Sub-Assembly Overview

Trade studies are essential in evaluating different design options and helping to make well-informed decisions that maximize the power subsystem's performance, dependability, and affordability. The trade studies for each of the power subsystem's subassemblies—solar panels, battery systems, power distribution units (PDUs), thermal management systems, and health monitoring systems—are described in the sections that follow.

Solar Panels

Objective: To determine which solar panel technology is most reliable and efficient for the conditions at the Lunar South Pole.

Table 19. *Solar Panel Trade Studies*

Solar Panels Trade Studies						
Criteria	**Explanation**	**Grade**	**Weight**	**Spectrolab XTJ**	**SolAero**	**Azur Space**
Efficiency (%)	High efficiency is crucial for maximizing power output in limited space	10 = high, 5 = medium 1 = low 0 = Fail	35%	10	10	9
Power Output (W/kg)	Higher power output per kg is beneficial for reducing mass	10 = high, 5 = medium 1 = low 0 = Fail	30%	9	9	8
Cost ($/W)	Lower cost per watt is important for staying within budget	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	8	7

Availability	High availability ensures timely deployment	10 = high, 5 = medium 1 = low 0 = Fail	10.00%	10	9	8
		TOTALS:	**100%**	92.00%	90.00%	82.00%

Spectrolab XTJ stands out the most in efficiency, power output, cost, and availability in the trade study table. Alternatively, **SolAero** with a high score performs slightly under Spectrolab in terms of availability. While **AzurSpace** stays at a third option due to lower performance at slightly higher cost. Spectrolab XTJ provides a TRL score at 7, proving its readiness to be embedded to the rover for the lunar missions.

Spectrolab XT:

- **Efficiency of Solar Cells**: 29.5%
- **Cell Area:** 59.65 cm2
- **Mass Per Area**: 84 mg/cm2
- **Typical Electrical Parameters**:

  Vmp(Voltage at max power) = 2.348 V

  Imp(Current at max power) = 17.02 mA/cm²

- **Power Output per Solar Cells**:

  2.348 V x 0.01702 A/cm2 x 59.65 cm2 = 2.379 W

Required Power Output: 200 W

Number of Spectrolab XTJ Solar Cells Needed:

Number of Solar Cells = Required Power Output / Power Output of one solar cell

= 22.22 kg / 2.379 W = 84.1 cells

The Rover will need approximately 85 Spectrolab XTJ cells to generate 200W.

Meaning the total mass of the solar cells is:
Total mass = Number of Cell x Mass per Area x Cell Area

= 85 cells x 0.084 g/cm2 x 59.65 cm2

= **0.426 kg**

Battery System

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

Table 20. *Batteries Trade Studies*

Batteries Trade Studies						
Criteria	**Explanation**	**Grade**	**Weight**	**Li-Ion**	**LiFePO4**	**Solid-State**
Energy Density (Wh/kg)	Higher energy density is crucial for longer mission duration	10 = high, 5 = medium 1 = low 0 = Fail	35%	8	7	9
Cycle Life	Longer cycle life ensures battery longevity	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	9	8
Cost ($/W)	Lower cost per watt is important for staying within budget	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	8	5
Safety	Safety is valuable in harsh lunar conditions	10 = high, 5 = medium 1 = low 0 = Fail	10.00%	8	8	9

Temperature Range	Wider temperature range is critical for surviving lunar conditions	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	8	9
		TOTALS:	**100%**	76.50%	82.00%	81.00%

Lithium Iron Phosphate (LiFePO4) provides the best balance of performance, cycle life, cost, safety, and temperature range making it a suitable choice for the battery system of the rover. **Solid-State** is also a good alternative, but does not go well with the budget. **Lithium-Ion** does provide decent cost, but relatively underperform to LiFePO4. LiFePO4 has been used in space applications, providing it a TRL score of 7.

The assumed total power consumption of the rover is 1500 W. The best battery supplier is Skylabs with the Nanoeps 158Wh, with a mass of 1.933 kg per pack.

Number of battery packs needed:

Number of Battery Packs = Total Energy Requirement / Battery Capacity per Pack

= 1500 Wh / 158 Wh per pack = 9.49 packs

The rover will need 10 battery packs to operate over 10 hours. In average, every hour takes around 1 battery pack.

Total Weight of Battery packs:
Total Weight = Number of Battery Packs x Mass of One Battery Pack

= 10 packs x 1.933 kg = **19.33 kg**

Power Distribution Unit (PDU)

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

Table 21. *Power Distribution Unit Trade Studies*

Power Distribution Unit Trade Studies						
Criteria	**Explanation**	**Grade**	**Weight**	**Vicor PDU**	**Crane PDU**	**Custom PDU**
Scalability	Ability to scale with mission requirements	10 = high, 5 = medium 1 = low 0 = Fail	30%	8	7	10
Cost ($)	Total cost should be within budget	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	8	7
TRL	High TRL ensures reliability	10 = high, 5 = medium 1 = low 0 = Fail	20%	6	6	4
Reliability	High reliability for continuous operation	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	9	8
Size (cm^3)	Smaller size is beneficial for space-constrained applications	10 = high, 5 = medium 1 = low 0 = Fail	10.00%	7	8	7
		TOTALS:	**100%**	73.00%	76.00%	75.00%

The **Crane PDU** provides the best balance of cost, TRL, and reliability, making it an ideal choice for the Power Distribution Unit System (PDU). **Custom PDU** can also be a viable option, despite having a lot of things to deal with like the complexity integration and budget. **Vicor PDU** would stand out more to be an alternative for Crane PDU at a lower score in size and cost. Crane PDU has no history of space application, but a strong presence in the aerospace sector. This gives Crane PDU a TRL score of 6.

Crane PDU-20-250 will be used for the rover PDU.[16]

Number of Output Channels: 23

Average Power Distribution Unit Mass: 0.1 kg (typical mass for power distribution components)

The approximate mass of Crane PDU:

Total Mass = Mass per Channel x Number of Channels

= 0.1 kg/channel x 23 channels = **2.3 kg**

Thermal Management System

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

Table 22. *Thermal Management Trade Studies*

Thermal Management Trade Studies						
Criteria	**Explanation**	**Grade**	**Weight**	**Passive TMS**	**Active TMS**	**Hybrid TMS**
Power Draw (W)	Lower power draw is crucial for efficiency	10 = high, 5 = medium 1 = low 0 = Fail	35%	10	6	8
Mass (kg)	Lower mass is beneficial for overall system mass	10 = high, 5 = medium 1 = low 0 = Fail	30%	9	6	8
Cost ($)	Cost needs to be within budget constraints	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	5	7
Efficiency	High efficiency ensures effective thermal	10 = high, 5 = medium 1 = low 0 = Fail	10.00 %	7	9	9

	management					
		TOTALS:	**100%**	92.50%	61.50%	78.50%

In the trade study table, the **Passive TMS** offers the best overall score, making it an ideal choice for power draw, mass, cost and efficiency for the rover's mission. The **Hybrid TMS** is a good alternative if higher efficiency and moderate power draw are needed, but require more time and complexity to integrate. The **Active TMS,** despite providing the best thermal control, does not fit in a budget-constraint mission. Passive thermal management has been developed extensively on other lunar missions. This mission has different environmental factors, putting Passive TMS at a score of 6, and to be developed further according to the mission requirements in the future. Due to the small amount of space to implement the components like heat pipes and insulation, the total weight of Passive TMS is around **1kg**.

Health Monitoring System

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

Table 25. *Health Monitoring System Trade Studies*

Health Monitoring System Trade Studies (HMS)						
Criteria	**Explanation**	**Grade**	**Weight**	**Basic HMS**	**Advanced HMS**	**Custom HMS**
Sensor Coverage	Extensive sensor coverage for monitoring	10 = high, 5 = medium 1 = low 0 = Fail	35%	7	9	10
Cost ($)	Cost should be within budget constraints	10 = high, 5 = medium 1 = low 0 = Fail	30%	9	5	3
Reliability	High reliability is crucial for mission	10 = high, 5 = medium 1 = low	25%	8	10	9

	success	0 = Fail				
Ease of Integration	Ease of integration into the existing system	10 = high, 5 = medium 1 = low 0 = Fail	10.00 %	10	7	8
		TOTALS:	**100%**	81.50%	78.50%	74.50%

Basic HMS includes the basic sensors to monitor the voltage, current, and temperature data is sufficient for the rover mission. It also takes up less energy in the system, and easier to integrate at a lower cost. These reasons put Basic HMS as a first choice with a score of 81.50%. If the rover is required to execute more complex monitoring, advanced HMS can be a better choice due to the greater provided monitoring for the system. Custom HMS is helpful if there is a specific area that needs to be monitored carefully. Due to simplicity, lower cost, and previous usage on similar mission environments, the TRL score of Basic HMS is 7.

Voltage Sensors: Honeywell CSNA111 (29g)[13]
Current Sensors: Honeywell CSNF161 (20g)
Temperature Sensors: Honeywell T775A2009(300-400g)
Thermal Sensors: Honeywell ST3000 (100g)
Telemetry sensors: Honeywell HPM32322550 (700g)

Total Weight of the HMS:
Total Weight = 0.029 kg + 0.02 kg + 0.4 kg + 0.1 kg + 0.7 kg
= 1.249 kg

The approximate weight of the HMS is around **1.3 kg**.

The estimated total weight of the power system is:
Total Weight = Solar + Batteries + PDU + TMS + HMS
= 0.426 kg + 19.33 kg + 2.3 kg + 1 kg + 1.3 kg
= 24.356 kg

The total estimated weight of the power and associated subsystems for the CHILLY Rover is approximately **24.356 kg.** This met the mission mass requirements for under 30kg while having the system integrated with the most optimal components in quality.

The lowest score of the internal components determines the total TRL score of the rover's power subsystem. In this case, Crane PDU and Passive TMS provide the lowest scores at 6. Thus, giving the TRL score of the power subsystem at 6.

Lunar dust continues to be a challenging obstacle in the mission. Especially when it can get highly stuck on the solar cell panels and other electrical components. To overcome this, some mitigation strategies are suggested from Apollo missions and simulated testing environments. Dust-resistant coatings can be applied to solar panels and other power subsystem components to repel lunar dust and reduce adhesion. Some components like batteries and sensors can be sealed in enclosures to prevent dust and maintain longevity and efficiency.

Extreme temperature fluctuations of the lunar's PSRs are also causing a lot of trouble to the batteries' performance. By using advanced thermal insulation materials like Polypropylene film to cover batteries, PDU, and sensors, this method provides a way to maintain a suitable temperature. Implementing phase-change material around those components will also grant more layers of temperature protection.

Solar cells may experience long shadow periods that do not provide energy. Batteries are the recovery option, but they will not last long for an endurance mission. A possible strategy is to program the firmware of the rover so it can relocate itself to potential sunlit areas during the extended darkness period. Another idea is to have the rover deploy a solar array system at the sunlit area, acting as a charging station for the rover. Flywheel energy storage methods can also work well in the condition of a vacuum environment on the lunar surface. The momentum of the rover's wheels will convert mechanical energy into electricity to drive the rover to a deployed solar array station.

2.1.2.3. Power Subsystem Recovery and Redundancy Plans

Primary Power Source: Solar Cell Panels

Solar panels are a critical component of the rover, with the main task being to provide electrical resources to all systems in the rover. However, implementing an entire solar panel on the rover seems like a risky and high-cost method due to their large size, making it vulnerable to lunar dust damage. A plan has been developed to incorporate small solar cells in parallel to ensure continuous power generation if one panel or a section fails. The deployment and orientation mechanism are added to orient the solar cells for most sunlight absorption in case some solar cells are partially damaged.

Software controls of the rover will manage the deployment and orientation, while the health monitoring system ensures the solar cells' performance.

Energy Storage: Battery System

A battery system is valuable when there is not enough power generated from the solar cell panels. Similar to the solar cell panel, multiple independent battery packs will be connected together, creating a large battery system that can store more energy while reducing the risk of failing a whole system. The rover is implemented with a battery management system (BMS) to manage charge and discharge cycles, report the battery health data back to the main system, and send it back to the Earth once a day and first time landing.

Power Distribution Unit (PDU)

The PDU ensures reliable power distribution from the power source to other subcomponents. The PDU can help monitor these circuit lines. Due to the complexity and high cost of implementing a backup PDU, the risk of PDU failing is low and acceptable. The Health Monitoring System (HMS) sensors will monitor the PDU for safety. PDU should also be carefully checked before finalizing for the mission.

Thermal Management System

The thermal management system is using a passive method to maintain a suitable temperature for the power system, achieving redundancy through heat pipes and thermal coating. The health monitoring system will also be supporting monitoring the temperature of the rover overall. By this means, the thermal system is safe without a recovery method.

Health Monitoring System

The Health Monitoring System includes multiple sensors around the power system of the rover to monitor important parameters such as voltage, current, temperature, thermal, and telemetry. These sensors will monitor and send data back to the main board to form the health of the power system. The data will be sent back to the control team on Earth once every day to analyze and diagnose if any issues occur. There is a chance these sensors will face failure due to defection, so it is best to carefully verify the sensors before implementing and sending the rover on mission. Voltage sensors are the most important sensors, so it is best to have 2 of these in the system. At quantity of one, the other sensor functions fine.

2.1.2.4. Power Subsystem Manufacturing and Procurements Plans

Solar Cells:

- Spectrolab XTJ
- Solar Solutions | Rocket Lab (rocketlabusa.com)

CHILLY Rover will select Spectrolab as the main solar cell company to supply solar cells for the rover for power generation. Ideally, the Spectrolab XTJ solar cell is the best option due to efficiency, power output, cost, and availability in the trade study table previously from the System Review Requirements (SRR). Spectrolab can support the manufacturing of the solar cell and integration of cells on the CHILLY Rover can be done in house with Spectrolab's help in the best case. If Spectrolab is not available, an alternative supplier is SolAero with SolAero ZTJ due to their similar performance with Spectrolab XTJ but slightly underpriced in terms of availability. The third option would be AzurSpace for 3G30 or 3G28 solar cells, at lower performance at slightly higher cost. Typically, solar cells can have lead times from 12 to 24 weeks. This will also vary due to the complexity of the rover if customization is needed to fit the mission.

Battery: NANOeps-BMM-172wh - SkyLabs

CHILLY rover will utilize Lithium Iron Phosphate (LiFePO4) because it provides the best balance of performance, cycle life, cost, safety, and temperature range, making it a suitable choice for the battery system of the rover. The main supplier will be SkyLabs from Slovenia, providing the rover with SKY-NANOeps-BMM battery capable of high capacity, discharge rate, and availability of the technology. Berlin Space Technologies from Germany with BAT-110 Modular Battery is also considered a second option, with similar availability but score lower in terms of capacity and max discharge rate performance. The time lead for batteries will vary from 8 to 20 weeks and up to 25 weeks if the main supplier is unavailable, with extensions depending on type and customization if required.

Power Distribution Unit:

- DC DC Power Converters | Interpoint | Crane Aerospace & Electronics - SMHF4212S DC-DC
- High-efficiency DC-DCs for New Space Applications | Vicor (vicorpower.com) - DCM3623T36G31C2T00 DC-DC

SMHF4212S DC-DC converter from Crane Aerospace & Electronics proved to be the best option for the power distribution unit in the rover's electrical system. This converter meets the necessary voltage regulation, capable of inputting voltage up to 55 volts and output 12 volts of voltage, equal to 15 watts of power. It also has high efficiency at 80%, circuit safety, and operates from -55C to +125C, meeting the need for harsh conditions on Lunar Permanently Shadowed Regions (PSRs). An alternative option is the DCM3623T36G31C2T00 DC-DC converter module from Vicor with similar capabilities. The manufacturing process may take approximately up to 20 weeks and up to 25 weeks if the main supplier is unavailable.

Thermal Management System:
- Heat sinks
- Heat pipes
- Thermal interface materials
- Phase change materials
- Thermally conductive adhesives

Passive Thermal Management Solutions - Advanced Cooling Technologies (1-act.com)
NASA Selects Thermacore for Study of Spacecraft Thermal Control - Aerospace Manufacturing and Design

Passive thermal management proved to be the most suitable option for the electrical components of the CHILLY Rover. Key things of this passive system include heat sinks, heat pipes, thermal interface materials, and conductive adhesives. Thermacore can supply all of these key components, and offer a wider product range. They also have been in the industry for 50 years, with a proven track record of success in the aerospace and electronics industry with high standards. Advance Cooling Technologies is another viable option, similar in standards and success to Thermacore, but going for a dynamic solution with only 20 years of industry experience. Manufacturing lead times may consist around 15 weeks and up to 20 weeks if the main supplier is unavailable, while can extend further if a high-performance solution is needed.

Health Monitoring System:
- Voltage Sensors: Honeywell CSNA111 (29g)
- Current Sensors: Honeywell CSNF161 (20g)

- Temperature Sensors: Honeywell T775A2009(300-400g)
- Thermal Sensors: Honeywell ST3000 (100g)
- Telemetry sensors: Honeywell HPM32322550 (700g)

The Health Monitoring System of the CHILLY Rover includes important sensors that ensure the component's health level of the rover relating to voltage, current, temperature, thermal, and environmental. The selected components include voltage sensors (Honeywell CSNA111), current sensors (Honeywell CSNF161), temperature sensors (Honeywell T775A2009), thermal sensors (Honeywell ST3000), and telemetry sensors (Honeywell HPM32322550). Honeywell is the current leading manufacturer for the sensors due to their trustworthy reputation in the industry. Unless Honeywell is incapable of providing supplies, other reputable companies in the same industry like Sensirion, Texas Instruments can supply the needed sensors for the rover. Rough estimations of manufacturing lead times range from 6 to 12 weeks with extensive time for further customization and up to 17 weeks if the main supplier is unavailable.

2.1.2.5. Power Subsystem Verification Plans

Outlined below in table 26, is the Power subsystem's verification matrix.

Table 26. *Power Subsystem Verification Plans*

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
EPS-1	The power subsystem shall provide continuous power to all rover subsystems throughout the mission.	Analysis	Since the vehicle is a secondary payload, it must be ready for launch when the primary payload launches. An analysis is required for the electrical data from the rover to ensure it is operating smoothly	A detailed simulation model of the rover that includes all subsystem consumption will be created, and a mission simulation will contain all phases (launch, cruise, landing, and operations) to ensure continuous power supply. The electrical data from the simulation can then be analyzed and reviewed before entering a real mission. NASA Johnson Space Center (Houston, TX) can provide the simulation ground.
EPS-2	The power subsystem shall have a minimum power generation capacity of 200 watts.	Inspection	The method can be performed using a simple instrument such as a multimeter	Perform a solar panel test in a controlled low-sunlight condition of the lunar PSRs. Tests can be conducted at the at the NASA Glenn Research Center.
EPS-3	The power subsystem shall store a minimum of 1.5 kWh of energy for use during the lunar night.	Inspection	The method can be performed using a simple instrument such as a multimeter	Inspect the battery specification match the requirement. Peform capacity test to measure storage capacity. This can be done at the Battery Testing Facility such as Argonne National Laboratory (Lemont, IL)

EPS-4	The power subsystem shall have a total mass not exceeding 30 kg.	Inspection	The method can be performed using a simple scale	Weight and record each component of the power system. Add up and verify the total mass to make sure it does not exceed 30 kg following the requirements. Quality Control Lab at NASA Kennedy Space Center is a suitable location.
EPS-5	The power subsystem shall operate within the temperature range of -150°C to 100°C.	Analysis	Data from simulated condition like the lunar PSRs shalled be analyzed to further understand the capabilities of the rover power subsystem	A detailed thermal simulation model of the rover that includes all subsystem consumption will be created and go through an operational mission simulation to ensure the functionality under extreme temperatures. The thermal data from the simulation can then be analyzed and reviewed before entering a real mission. NASA Johnson Space Center (Houston, TX) can provide the simulation ground.
EPS-6	The power subsystem shall provide power at a regulated voltage of 28V ± 5%.	Inspection	The method can be performed using a simple instrument such as a multimeter	The Power Distribution Lab at NASA Glenn Research Center provides a good ground to test the voltage regulation. Different load conditions will also be applied to measure the voltage output. Component inspection can be done at NASA Kennedy Space Center.
EPS-7	The power subsystem shall have a reliability of at least 0.95 over the mission duration.	Analysis	Analysis is chosen because it allows for statistical modeling and prediction of the subsystem's reliability over the mission duration. This method can identify potential failure modes and ensure the subsystem meets the reliability requirement.	Failure analysis shall be done n the FMECA table. Simulation can also provide performance of the rover over time, predicting the mission successful. This can be done at NASA Johnson Space Center (Houston, TX)

EPS-8	The power subsystem shall include health monitoring systems to report power status and faults.	Inspection	Visual Inspection can be performed to check the report from health monitoring system	Test the health monitoring system to ensure it can accurately report power status and faults. Quality Control Lab at NASA Kennedy Space Center is a suitable location.
EPS-8.1	The health monitoring system shall have a data transmission capability to Earth.	Demonstration	This method ensures the data is sent back to Earth without malfunction in real time	Set up a demonstration where the health monitoring system transmits data from the rover to a ground station on Earth. Verify the accuracy and reliability of the data through computer calculation. Set up obstables that trigger EMI to test the operational scenario. Communication LAb at NASA Jet Propulsion Laboratory (Pasadena, CA) is a suitable location
EPS-9	The system shall not have a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof.	Inspection	Visual Inspection can be performed to ensure there is no RTG implemented on the rover	Visually inspect the blueprint design of the rover. Double check material history from supplier to confirm to RTG components are used. These inspection can be done at Component Inspection Lab at NASA Johnson Space Center
EPS-10	The power subsystem shall be designed to meet all electromagnetic compatibility (EMC) requirements.	Inspection	Ensure product does not generate EM energy that may interfere with other systems. Verify that the product is not susceptible to external EM energy	Radiated test: Sensitive receiver, anechoic chamber, antenna with known gain. Conduction susceptibility matched “box”. EMC Testing Chamber at NASA Glenn Research Center is a suitable location to forward the plan

EPS-11	The power subsystem shall be capable of withstanding transportation, including shocks and vibrations.	Analysis	Data from shock and vibration is needed to be analyzed for better understanding of the rover capability in transporting	Finite Element Analysis (FEA) simulation. Vibration testing, shock testing. FEA Lab: NASA Langley Research Center, Hampton, VA. Vibration Testing Facility: NASA Marshall Space Flight Center, Huntsville, AL. Environmental Test Lab: NASA Ames Research Center, Moffett Field, CA
EPS-12	The power system shall cost less than $30 million.	Inspection	Inspection is chosen because it provides a straightforward way to verify that the cost constraints are met.	Review budget reports and cost tracking documents. Conduct cost review, supplier cost analysis. Perform at Budget Office at NASA Headquarters, Washington, D.C. Milestone Review Center: NASA Kennedy Space Center, Merritt Island, FL Supplier Cost Analysis Office: NASA Johnson Space Center, Houston, TX

2.1.3. CDH Subsystem Overview

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

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

2.1.3.1. CDH Subsystem Requirements

Outlined below in table 27, are the CDH subsystem's requirements. These requirements outline what is expected of the CDH system in order to have a successful mission.

Table 27. *CDH Requirements Table*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH Subsystem Reqs							
CDH-1	The subsystem shall communicate with the primary mission orbiter for the duration of the mission lifetime of TBD.	The system needs to be able to communicate with the orbiter throughout the mission in order to communicate the information collected to accomplish the science objectives.	MR-7 MR-8	CDH-1.1 CDH-6 CDH-8 CDH-9	Demonstration	CDH Subsystem	Met
CDH-1.1	CDH system uses Ultra Hgih Frequency (UHF) for communication between rover and orbiter for a bandwidth of a few kilobits per second and S band and X band for a bandwidth of up to tens of mbps.	Communication with orbiter and mission control	CDH-1	N/A	Analysis	CDH Subsystem	Met
CDH-2	The subsystem shall cost a max amount of $TBD	The system needs to stay within the mission's assigned budget.	MR-6	CDH-2.1	Inspection	CDH Subsystem	Met
CDH-2.1	CDH System will not cost more than TBD to build and operate over the span of the TBD day mission.	Stay within budget of the mission	CDH-2	N/A	Inspection	CDH Subsystem	Met
CDH-3	The subsystem shall be able to operate in the lunar environment.	The system needs to remain operational throughout the	MR-2	CDH-3.1 CDH-3.2	Test	CDH Subsystem	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		mission in order to accomplish the mission objectives.					
CDH-3.1	CDH operations scheduled around temperatures ranging from -250°C to +120°C.	Remain operational in extreme temperature fluctuations	CDH-3	N/A	Analysis	CDH Subsystem	Met
CDH-3.2	CDH system shall withstand space radiation.	Remain operational while being bombarded by space radiation	CDH-3	CDH-3.2.1 CDH-3.2.2	Test	CDH Subsystem	Met
CDH-3.2.1	CDH System employs error detection and correction through voting logic to withstand up to 7 single event upsets per second.	Remain operational while being bombarded by space radiation	CDH-3.2	N/A	Test	CDH Subsystem	Met
CDH-3.2.2	CDH system display a total ionizing radiation dose tolerance of 300 mSv of radiation.	Remain operational while being bombarded by space radiation	CDH-3.2	N/A	Test	CDH Subsystem	Met
CDH-4	The subsystem shall have a max mass of TBD kg.	The system cannot exceed the mass allowance which is derived from the overall rover mass budget outlined in the Mission Task document. If the mass exceeds this amount, the mission could be subject to cancellation.	MR-4	N/A	Inspection	CDH Subsystem	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH-5	CDH system will not consume more than TBD watts per second during peak activity.	Limit the power usage of the CDH system	MR-3	N/A	Analysis	CDH Subsystem	Met
CDH-6	CDH employs a real time operating system with scheduling and the synchronization of multiple tasks	Operating system to manage CDH system	CDH-1	N/A	Demonstration	CDH Subsystem	Met
CDH-7	CDH employs telemetry monitoring system health and real-time capabilities.	Monitor system health and system capability	MR-3	N/A	Demonstration	CDH Subsystem	Met
CDH-8	CDH downlink scheduling system prioritizes data transmission based on crticality and optimizes use of available bandwidth for data transmission efficiency.	Organize data storage	CDH-1	N/A	Demonstration	CDH Subsystem	Met
CDH-9	CDH transmits and stores in a data format standardized by the Consultative Committee for Space Data Systems (CCSDS), which includes deployment of the Space Packet Protocol (SPP) and binary data.	Standardize data transformations and delivery	CDH-1	N/A	Demonstration	CDH Subsystem	Met

2.1.3.2. CDH Sub-Assembly Overview

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

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

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

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

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

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

Application Layer

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

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

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

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

Execution Layer

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

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

Processing Function

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

Sensors and Actuators

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

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

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

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

Data Storage

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

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

2.1.3.3. CDH Subsystem Recovery and Redundancy Plans

CPU - RAD 750
Redundant CPU
A backup CPU synchronized with the primary CPU makes sure that no data is lost.

Operating System - VxWorks
Multiple servers configured in a cluster. Redundant storage solutions that take advantage of RAID and distributed file systems.

Low Gain Antenna - Dipole antenna
Primary and secondary antenna to avoid a single point of failure

High gain Antenna - Parabolic Antenna

Non Volatile Storage - Leonardo DRS DDR3/NAND Flash Solid-State Drive

Volatile Storage - Texas Instruments Radiation Hardened SDRAM

RAID Abusing
RAID controllers
Hot swap bays

2.1.3.4. CDH Subsystem Manufacturing and Procurements Plan

CPU:

BAE Systems is the manufacturer of the space grade radiation hardened RAD750 CPU. The CPU has an order of magnitude more transistors than its predecessor, the RAD6000. It has an extended L2 cache to improve performance.The RAD750 has been used in Mars rovers and satellites, having been used in rovers such as the Curiosity and Perseverance Mars Rovers and satellites such as the James Webb Space Telescope.The RAD750 is available commercial off the shelf (COTS) with a price comparable to its predecessor, the RAD6000. The RAD750 meets industry standards for radiation hardness and performance. It can withstand a total ionizing dose of up to 200,000 rads and has built in features to mitigate the effects of single event upsets caused by heavy doses of radiation. The backup supplier chosen is SEAKR engineering, for their specialization in radiation hardened electronics for space applications.

OPERATING SYSTEM:

Wind River Systems develops and provides the VxWorks operating system. Wind River System specializes in real-time operating systems and they have a long history of supplying software solutions for aerospace and defense. VxWorks has been used in both the Perseverance and Curiosity Mars rovers. VxWorks is a commercial off-the-shelf product and it complies with industry standards, including DO-178B for avionics software. Green Hills Software is the choice of backup supplier. They are known for their high-reliability real-time operating system, INTEGRITY RTOS.

SSD and RAM:

Leonardo DRS is the choice for SSD and RAM because of their advanced electronic systems. They specialize in space proof drives. Texas Instruments is the choice for RAM.

2.1.3.5. CDH Subsystem Verification Plans

Verification methods for the CDH subsystem are unfortunately unavailable at this time.

2.1.4. Thermal Control Subsystem Overview

The thermal control system (TCS) is designed keeping in mind that it must endure the extremely cold temperatures in the PSRs of the chosen landing site in Leibnitz Beta Plateau, which can reach as low as -220°C. Thus, it needs good insulation and a heater to withstand the cold temperatures and keep it warm. At its warmest, it can get up to 40°C during the lunar day when the sun is out. The TCS consists of passive and active control. The overall TRL is 5.

Passive Thermal Control

The passive thermal control consists of: Multi-layer aerogel composite, Phase Change Material (PCM), Radiators, Louvers, Heat Pipes, and Thermal Coating. Multi-layer aerogel composite was chosen for the rover body, which consists of multi-layer insulation (MLI) combined with aerogel. The MLI will provide the primary insulation and aerogel will provide enhanced thermal protection along with enhanced durability. Another form of passive thermal control is the use of phase change materials to act as a thermal buffer for critical components. It will be particularly useful in case of a total power failure where the internal heat generation becomes 0 W, meaning the PCM alone must provide heat at a rate equal to the heat loss, in order to keep the rover at steady state (SS). Radiators will be useful during lunar day in the sun to prevent the rover from overheating, also in the PSR when the internal heat generation becomes high, such as when the rover is driving and components with high power draw are active. Thermal analysis of several scenarios both in the warm sun and cold PSR has been done to ensure the rover can reach an acceptable SS internal temperature 0-40°C in all scenarios. To ensure proper heat rejection, multiple Constant Conductance Heat Pipes (CCHPs) are connected between radiators and high power draw components. The heat pipes conduct heat from those components to the radiator so that the heat doesn't get trapped in the rover. To prevent the radiators from rejecting too much heat in the cold PSR, louvers cover the radiators. When the louvers are closed, the emissivity is reduced and thus heat rejection of the radiators is drastically reduced. When the louvers are open, the radiator can reject heat like normally, although the emissivity is somewhat reduced compared to an exposed radiator. To keep the rover cool when exposed to the sun, low absorptivity thermal coating is used on the radiators to lessen solar heating, the louvers are open in this case. The thermal coating also has high emissivity to enhance the heat rejection of the radiators. The MLI with low absorptivity will also prevent the temperature of the rover from climbing too much as well as the PCMs acting as a buffer.

Active Thermal Control

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

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

The electric heaters will heat the rover to the desired operating temperature to ensure the rover and its components do not get too cold. But they need thermostats and temperature sensors to function. The thermostat is the device that will trigger an electric heater to start a heating cycle whenever it drops below a certain threshold temperature. The thermostat will need accurate temperature readings which it will get from the temperature sensors placed throughout the rover, particularly near the critical components such as the battery, PDU, CDH, and science instruments.

Thermal Analysis and Heat Flow Maps

Known and Assumptions	
n radiating to space	1
SA top radiator face, m^2	0.1607824
n radiating to space/surface	4
n radiating to surface	1
SA side radiator face, m^2	0.4528988
n side radiator	2
space node temp, k	3
surface temp hot, k	313.15
surface temp cold, k	53.15
q_solar flux, W/m^2	1440
SA side faces, m^2	0.4528988
emissivity base, e	0.005
emissivity louver w/ radiator closed, e	0.09
emissivity louver w/ radiator open, e	0.71
emissivity radiator (deployed), e	0.88
abosportivity base, a	0.19
Stephan Boltzman Constant	0.0000000567

The following thermal scenarios were analyzed:

- Worst case cold scenario with 0 W internal heat generation

Cold Case	
Q_solar, W	0
Q_internal, W	0
Q_top-radiator, W	9.13
Q_side-radiator, W	7.31
Q_rad-space/surface, W	1.43
Q_rad-sruface, W	0.714
Q_in, W	0.00
Q_out, W	18.59
system temp, k	273.15
Q_net, W	**-18.59**
if positive system is heating, if negative system is cooling. If 0 assume ss stable	

SS is only reached at temperatures below 200 K, which is too cold for the rover, thus PCMs are used to provide heat.

- Cold case with 50 W internal heat generation from regenerative fuel cells

Cold Case	
Q_solar, W	0
Q_internal, W	50
Q_top-radiator, W	21.16
Q_side-radiator, W	24.25
Q_rad-space/surface, W	3.31
Q_rad-sruface, W	1.655
Q_in, W	50.00
Q_out, W	50.38
system temp, k	337
Q_net, W	**-0.38**
if positive system is heating, if negative system is cooling. If 0 assume ss stable	

SS is reached at 337 K which is too hot for the rover. Louvers can be opened to dissipate more heat, but since the internal heat generation is very low at only 50

W, the louvers should be halfway open to dissipate an appropriate amount of heat so the rover stays within 0-40C

- Cold case driving with 853 W internal heat generation

Cold Case	
Q_solar, W	0
Q_internal, W	853
Q_top-radiator, W	57.57
Q_side-radiator, W	783.85
Q_rad-space/surface, W	7.56
Q_rad-sruface, W	3.779
Q_in, W	853.00
Q_out, W	852.76
system temp, k	307.1
Q_net, W	**0.24**
if positive system is heating, if negative system is cooling. If 0 assume ss stable	

Louvers are open on both top and side radiators to dissipate heat

- Cold case stationary conducting science with 250 W internal heat generation

Cold Case	
Q_solar, W	0
Q_internal, W	250
Q_top-radiator, W	80.55
Q_side-radiator, W	153.71
Q_rad-space/surface, W	10.58
Q_rad-sruface, W	5.289
Q_in, W	250.00
Q_out, W	250.14
system temp, k	334
Q_net, W	**-0.14**
if positive system is heating, if negative system is cooling. If 0 assume ss stable	

SS is reached at 334 K with side radiator louvers closed and top radiator louver open, but this is a too high temperature so the side radiator louvers should be halfway open to dissipate an appropriate amount of heat so the rover stays within 0-40C

- Hot case driving with 853 W internal heat generation

Hot Case, with TCS	
Q_solar, W	410.4
Q_internal, W	853
Q_top-radiator, W	93.19
Q_side-radiator, W	868.81
Q_rad-space/surface, W	8.15
Q_rad-sruface, W	-0.008
Q_in, W	1263.41
Q_out, W	970.14
system temp, k	313
Q_net, W	**293.27**
if positive system is heating, if negative system is cooling. If 0 assume ss stable	

SS with all louvers open is reached at a too high temperature, thus PCM must absorb the extra 293.27 W of heat to stay below 40 C. This will allow the rover to drive for 11 minutes. If the rover overheats, it can also come to rest and turn off the high internal heat generating components to allow the rover to cool off before starting driving again.

- Hot case stationary conducting science with 250 W internal heat generation

Hot Case, with TCS	
Q_solar, W	410.4
Q_internal, W	321.5
Q_top-radiator, W	75.75
Q_side-radiator, W	651.89
Q_rad-space/surface, W	5.09
Q_rad-sruface, W	-0.772
Q_in, W	732.67
Q_out, W	732.73
system temp, k	297.2
Q_net, W	**-0.06**
if positive system is heating, if negative system is cooling. If 0 assume ss stable	

SS is reached at 297.2 K with all louvers open, which is within an acceptable range.

- Hot case with 0 W internal heat generation

Hot Case, with TCS	
Q_solar, W	410.4
Q_internal, W	0
Q_top-radiator, W	7.07
Q_side-radiator, W	403.38
Q_rad-space/surface, W	1.59
Q_rad-sruface, W	-1.647
Q_in, W	412.05
Q_out, W	412.04
system temp, k	275.3
Q_net, W	**0.00**
if positive system is heating, if negative system is cooling. If 0 assume ss stable	

SS is reached at 275.3 K with side radiator louvers open but top radiator louver closed. If the rover needs to warm up more, it can partially close the side louvers.

Table 28. *Thermal Control System Mass, Volume, and Max Power Draw*

Subassembly	Mass	Volume	Max Power Draw
Multi-Layer Aerogel Composite	0.01045451326 m^3 x 15 kg/m^3 = ~0.157 kg	2.7511877 m^2 x 3.8 mm thickness = ~0.01045451326 m^3	0 W
PCM+Container	1.585 + 0.308 = 1.893 kg	.0.001728 m^3	0 W
Radiators	3 kg	0.0036 m^3	0 W
Louvers	~10 kg	1.06658 m^2	0 W
Heat Pipes	500.66 g	0.00031556 m^3	0 W
Heater(s)	~500 g	small	40 W
Thermostat(s)	negligible	negligible	small
Temperature sensor(s)	negligible	negligible	small

Total	~ 12 kg		~50 W

2.1.4.1. Thermal Subsystem Requirements

Outlined below are the thermal subsystem requirements. These requirements are necessary in order for the CHILLY mission to be a success.

Table 29. *Thermal Subsystem Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Thermal Control System Reqs (TCS)							
TCS-1	The system shall operate in temperatures ranging from -233°C to 123°C.	The lunar environment presents extreme temperature variations, from the cold of permanently shadowed regions to the heat of lunar daytime and the system needs to be able to operate throughout the entire mission and be able to handle vast fluctuations.	SYS-2	TCS-1.1	Test	Thermal	Met
TCS-1.1	The thermal control system shall be capable of withstanding thermal cycles experienced between sunlit and shaded regions as well as day/night cycles, including PSRs.	Thermal cycles can cause significant stress on components; designing for these cycles ensures durability.	TCS-1	N/A	Test	Thermal	Met
TCS-2	The thermal control system shall keep other subsystems and instruments within the required operating range of -40°C to 40°C.	The temperature sensitive instruments and components in all of the subsystems need to be protected thermally to ensure they	MR-3	N/A	Analysis	Thermal	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		remain withing operating temperature throughout the entire mission.					
TCS-3	The thermal control system shall use 10-15% of the total rover's power.	The thermal subsystem cannot use more than the allotted power due to having a limited amount of power for the entire rover.	MR-3	N/A	Inspection	Thermal	Met
TCS-4	The thermal control system shall have a mass less than 20 kg.	The system cannot exceed the mass allowance which is derived from the overall rover mass budget outlined in the Mission Task document. If the mass exceeds this amount, the mission could be subject to cancellation.	MR-4	N/A	Inspection	Thermal	Met
TCS-5	The thermal control system shall cost less than $5 million.	The system needs to stay within the allotted amount based on the mission's assigned budget.	MR-6	N/A	Inspection	Thermal	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
TCS-6	The system shall maintain an internal temperature of -40 to 40 degrees Celcius for the duration of the mission.	Ensure systems are able to properly function.	MR-3	TCS-6.1 TCS-6.2	Test	Thermal	Met
TCS-6.1	The thermal control system shall include passive thermal insulation to minimize heat loss and gain.	Ensure temperature stability within the spacecraft and reduce need for active thermal control, reducing power needs.	TCS-6	N/A	Test	Thermal	Met
TCS-6.2	The thermal control system shall include active thermal control mechanisms to maintain the desired temperature range.	Due to the extreme temperatures, only thermal insulation will not be sufficient for keeping the internal temperature within operating range and thus active thermal control will be required.	TCS-6	N/A	Test	Thermal	Met
TCS-7	The thermal control system shall monitor and report the temperature in real-time.	Real-time data is essential for managing thermal conditions effectively and monitoring critical components.	MR-3	N/A	Test	Thermal	Met
TCS-8	The thermal control system shall have 0g of radioactive material.	The customer limited the amount of radioactive material the system	SYS-1	N/A	Inspection	Thermal	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		can use.					

2.1.4.2. Thermal Sub-Assembly Overview

Multi-layer Aerogel Composite TRL=5

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

To provide the best insulation, the MLI has an emissivity of $\varepsilon=0.005$, which requires ~30 layers of blankets. This is an approximation, the exact number of layers to reach $\varepsilon=0.005$ will have to be obtained from thermal testing, as each MLI will have varying emissivity and the aerogel composite will influence the emissivity as well. The multi-layer aerogel composite has TRL 5 because it has been tested in a lab as a component but full prototype testing in an operational space environment has not been done.

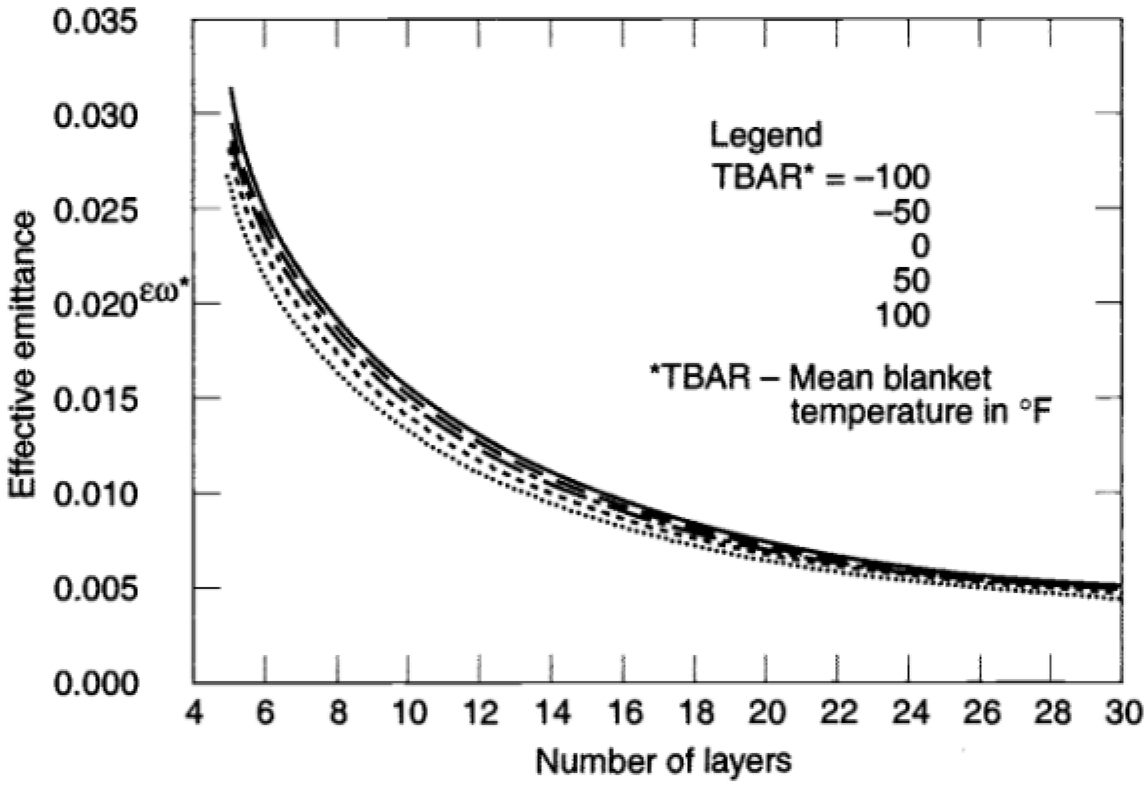


Fig. 5.5. MLI blanket effective emittance derived from the Spacelab thermal test data.

Figure #: Plot showing number of layers of blanket for MLI vs effective emittance (obtained from NASA Thermal Control Handbook)

Phase Change Material TRL=~6

The Phase Change Material (PCM) system serves as a critical thermal buffer for our lunar rover, addressing two key scenarios: extended driving time in direct sunlight and emergency thermal management during a total power failure.

Primary Design Case - Extended Driving: The PCM system is primarily sized to absorb excess heat during rover operations in the lunar daytime. Calculations show a net heat gain of 293.27 W during operation in sunlight. To allow for a 30-minute driving period, the PCM system is designed as follows:

- Heat to be absorbed: 293.27 W * 30 minutes * 60 seconds/minute = 527,886 J
- Mass of water required: 527,886 J / 333,000 J/kg = 1.585 kg
- Volume of water: 1.585 kg / 1000 kg/m³ = 1.585 L
- Container volume (including 9% for expansion): 1.585 L * 1.09 = 1.728 L

The aluminum container for this PCM has a mass of approximately 0.308 kg, bringing the total PCM system mass to 1.893 kg.

Secondary Function - Emergency Thermal Management: In the event of a total power failure where internal heat generation drops to 0 W, the PCM system will also act as a critical safeguard. With a Q_out of 18.59 W in this scenario, we can calculate the duration of thermal protection:

- Energy stored in PCM: 1.585 kg * 333,000 J/kg = 527,805 J
- Time until depletion: 527,805 J / 18.59 W = 28,392 seconds ≈ 7.89 hours

This means the PCM system can maintain the rover's internal temperature above 0°C for approximately 7.89 hours in a total power failure scenario, providing ample time for emergency procedures or potential recovery.

PCM Container Design: Water was chosen as the PCM due to its high heat of fusion and its melting point of 0°C, which aligns with the minimum allowable internal temperature of the rover. The container is designed to be leak-proof and accommodates the 9% volume expansion of water during freezing.

A trade study led to the selection of aluminum as the optimal material for the PCM container, offering an excellent balance of low mass, high thermal conductivity, good reliability, and extensive heritage in space applications.

This dual-purpose PCM system enhances the rover's operational capabilities in the challenging lunar environment while also providing a crucial safety margin in emergency situations, significantly improving the overall mission success probability.

Radiators TRL=7

Within our thermal subsystem, having radiators is crucial for being able to properly control the temperature of our rover. For our mission, we decided to go with the HPS manufactured, Metal Radiator. This radiator from HPS is built specifically for spacecraft purposes and the unforgiving space elements. The material is Aluminum alloy and weighs roughly 3 kgs, and will utilize a negligible amount of power (>1W). Operating temperature for this radiator is -30°C to 120°C. The size of this component is 40 cm in length, 30 cm in width and 3 cm in height. With these specifications, this metal radiator will be able to withstand the conditions of this mission and fulfill its purpose.

Louvers TRL=~5

For the thermal analysis, louvers having emissivity ε=0.09 when closed and ε=0.71 when opened showed favorable results. Moreover, the louver should have be adjustable such that it can be half open and not only fully closed or fully open, this is to provide an emissivity value in between the closed and open positions, which is beneficial for certain scenarios as shown by the thermal analysis. Off-the-market louvers were not large enough to cover the entire radiator surfaces, thus a custom louver will have to be made, which lowers the TRL.

Thermal Coating TRL=7

The white paint that we decided to use is Aztechnology manufactured, AZ-93 White Thermal Control, Inorganic Paint. This paint was developed specifically for spacecraft use. With the appliance of this paint, this protection layer will only allow 13-17% of solar radiation while emitting 89-93% of the internal heat to the vacuum of space. This paint has previously been utilized by NASA on numerous missions and it has proven to be the best. Therefore, CHILLY has decided to use it on their rover.

Heat Pipes TRL=7

Heat pipes are a critical component of our rover's thermal management system, providing efficient heat transfer from key heat-generating components to the radiators. For our design, we have selected Advanced Cooling Technologies (ACT) Constant Conductance Heat Pipes (CCHPs). ACT has had a very accomplished history in relation to building the best thermal control system components for spacecraft of any sort. These exact heat pipes were utilized on the recent VIPER’s thermal control system. The reason we chose to go with ACT’s heat pipes is simply because of how well they are able to perform under rigorous space conditions, and for our mission, they should be over qualified to do the job they need to.

Our heat pipe configuration has been customized to address the specific thermal challenges of our rover design and lunar environment. All calculations and performance estimates are based on ACT's heat pipe calculator, ensuring accuracy and reliability in our thermal management predictions.

Motor Heat Pipes:

Each of the four wheel motors, located at the center of each wheel, requires significant cooling due to their high heat generation (150W each). We have designed a heat pipe system with the following specifications:

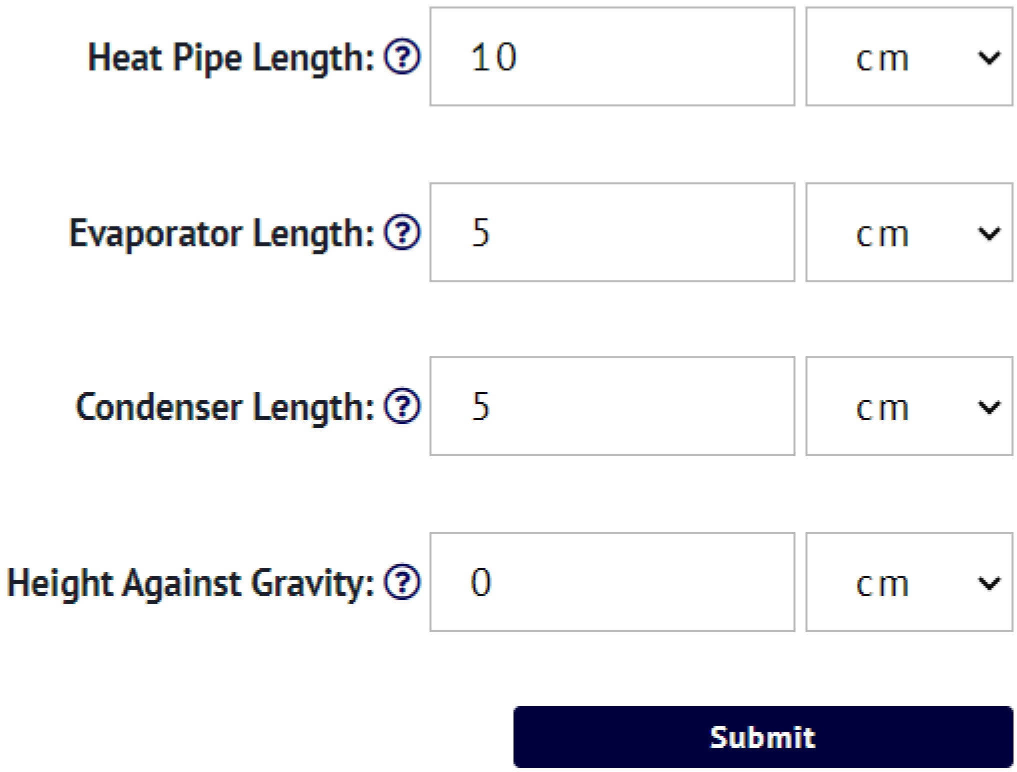
- Quantity: 3 heat pipes per motor, 12 total
- Length: 20 cm
- Diameter: 0.5 inch (12.7 mm)
- Material: Copper/water
- Heat dissipation capacity: ~50W per pipe at 40°C
- Mass per pipe: 40.22g
- Volume per pipe: 25.45 cm^3
- Total mass (12 pipes): 482.64g
- Total volume (12 pipes): 305.40 cm^3

These heat pipes will transfer heat from the motors to radiators on the side of the rover. The length is optimized to span from the wheel center to the radiator, minimizing thermal resistance while accommodating the rover's structure. Note that the fluid in these heat pipes will have to travel up from the wheel to the side radiators, meaning they will work against gravity which reduces their heat dissipation capacity, which is why so many heat pipes are required.

Additional Heat Pipes:

We have also designed heat pipes for other critical components:

1. Solar Panel Heat Pipe:



- Quantity: 1
- Length: 10 cm
- Diameter: 8 mm
- Mass: 7.83g
- Volume: 5.03 cm^3
- Heat dissipation: 150W

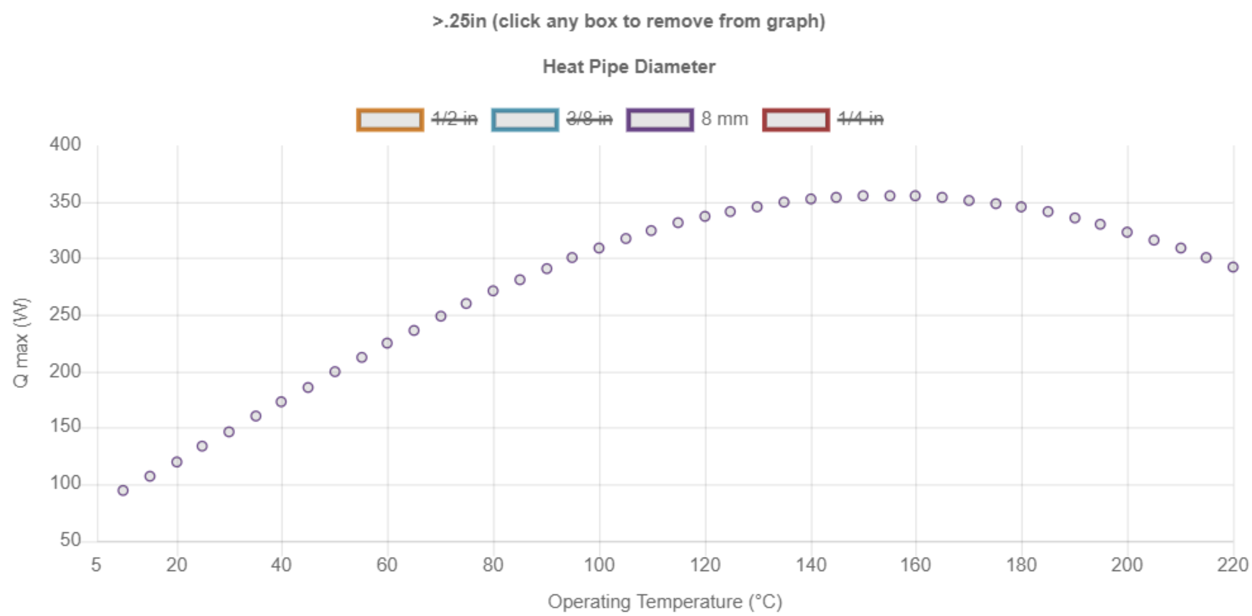
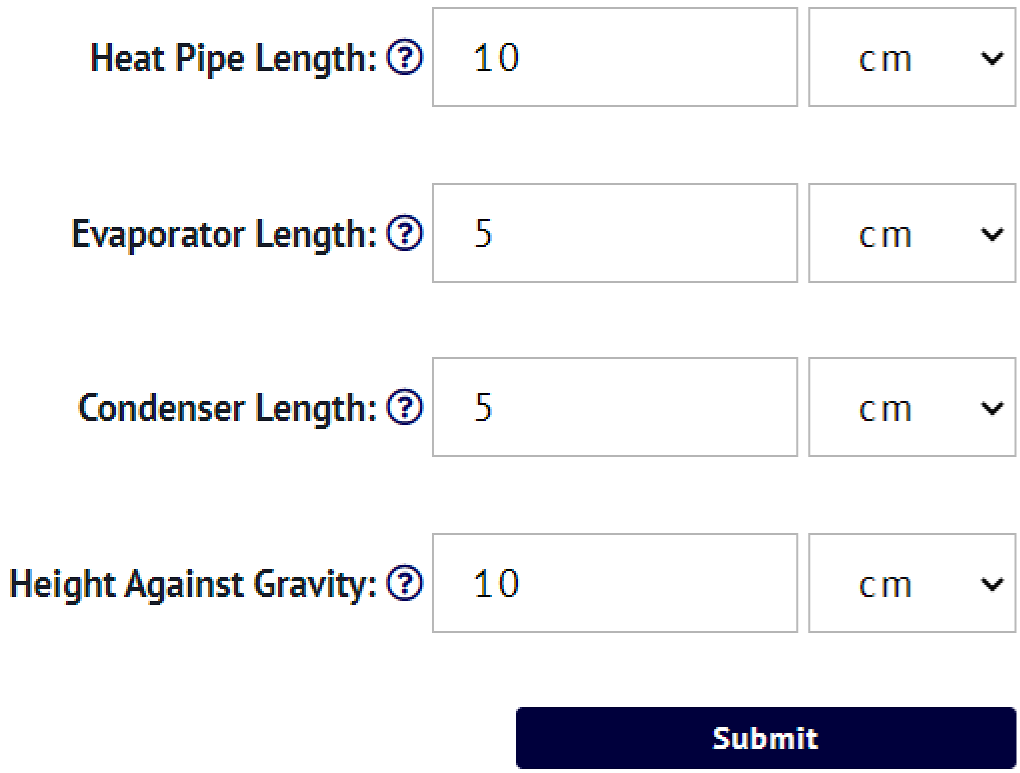


Figure #: Plot showing heat dissipation vs temperature for the 10 cm heat pipe used for the solar panel. At 40C, a 8 mm heat pipe provides a little over 150 W of heat dissipation.

2. Battery System Heat Pipe:



- Quantity: 1
- Length: 10 cm
- Diameter: 8 mm
- Mass: 7.83g
- Volume: 5.03 cm³
- Heat dissipation: 100W

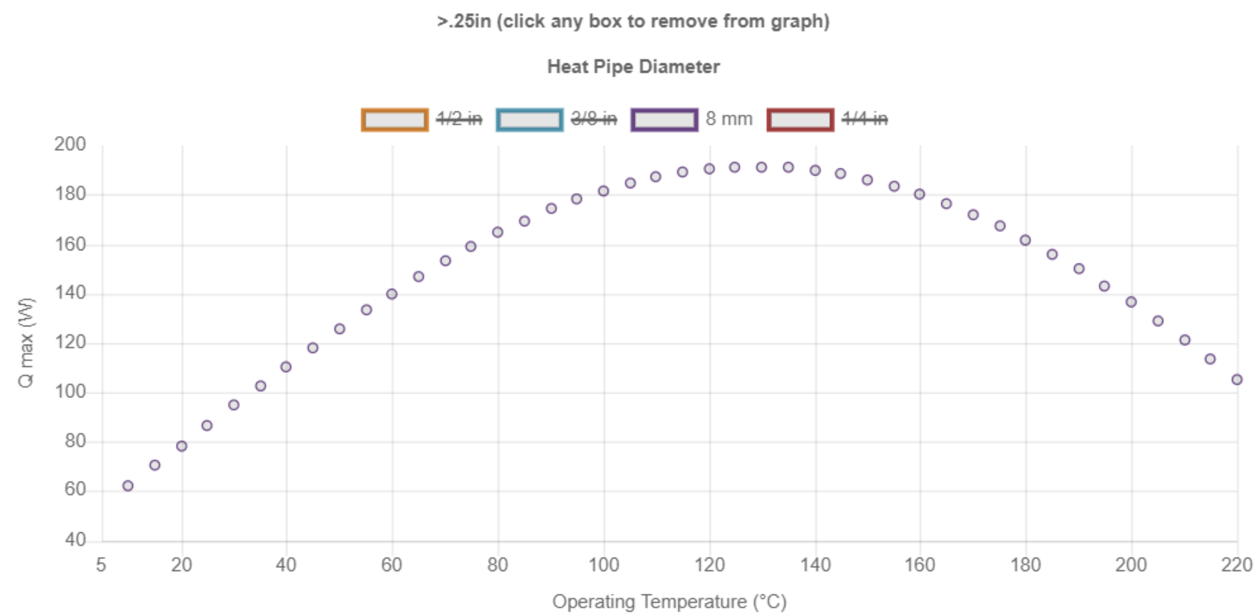
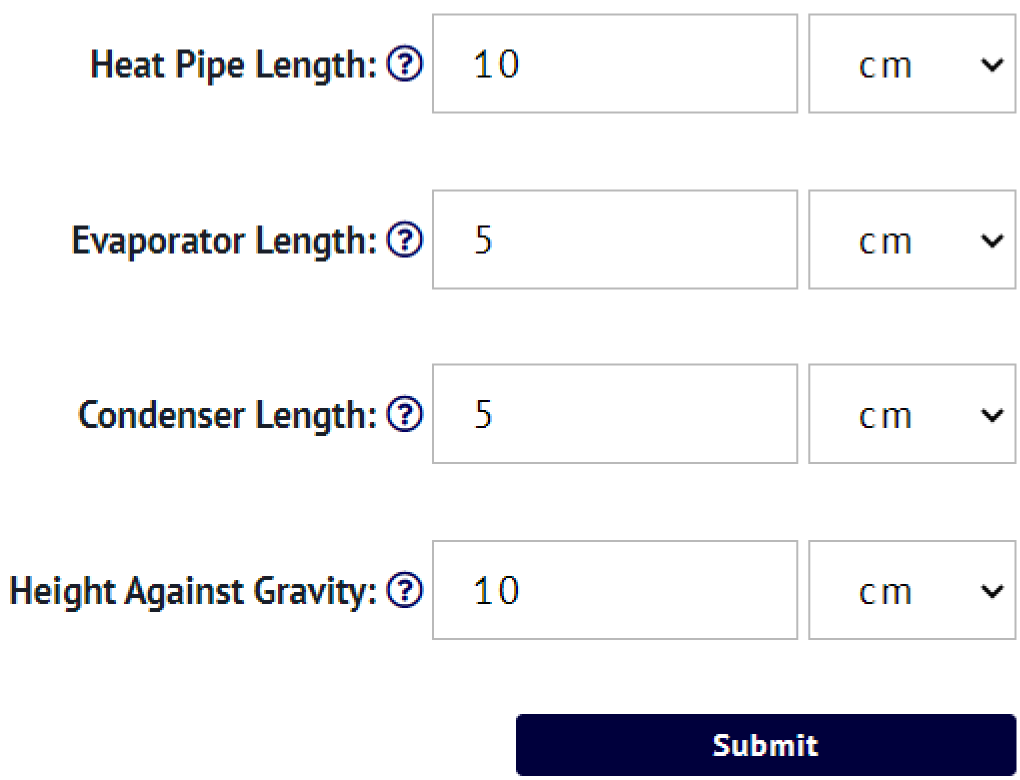


Figure #: Plot showing heat dissipation vs temperature for the 10 cm heat pipe used for the solar panel. At 40C, a 8 mm heat pipe provides a little over 100 W of heat dissipation.

3. Regenerative Fuel Cell Heat Pipe:



- Quantity: 1

- Length: 10 cm

- Diameter: 5 mm

- Mass: 4.23g

- Volume: 1.96 cm^3

- Heat dissipation: 50W

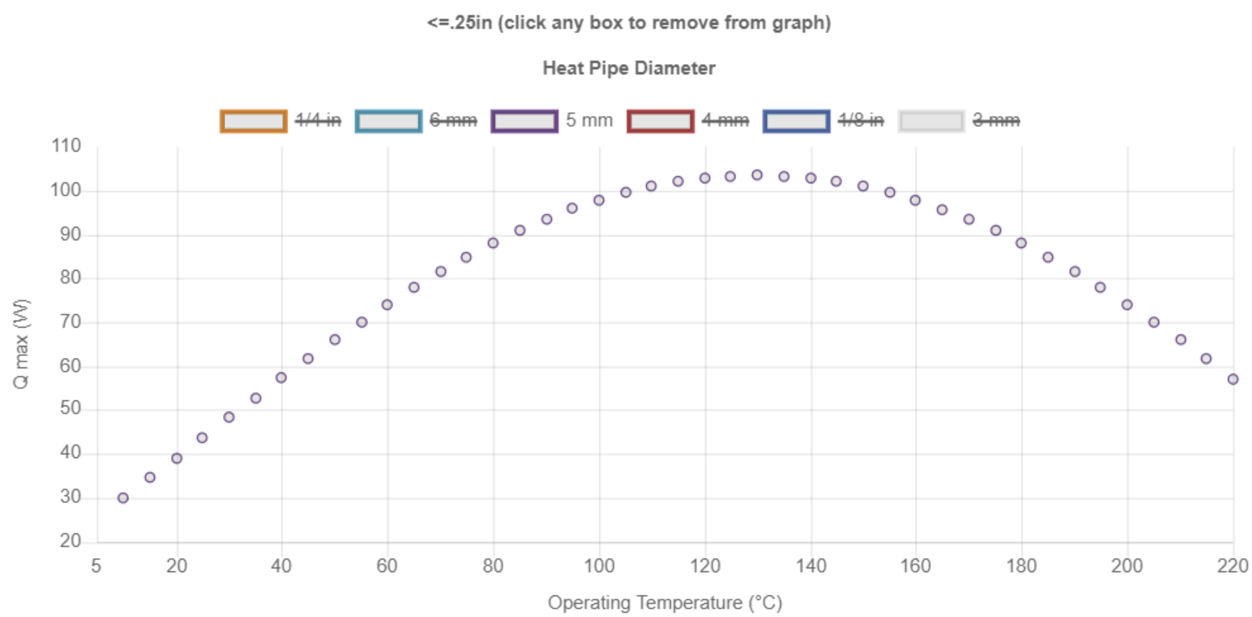


Figure #: Plot showing heat dissipation vs temperature for the 10 cm heat pipe used for the regenerative fuel cell. At 40C, a 5 mm heat pipe provides a little over 50 W of heat dissipation.

These additional heat pipes are designed to efficiently transfer heat from their respective components to the top radiator with as short travel as possible, which can be achieved by placing the batteries and regenerative fuel cells closer to the top of the rover. The solar panel heat pipe is designed with zero height against gravity because the solar panel will be on top of the rover, so naturally the heat pipe fluid will flow down to the radiator.

Total Heat Pipe System:

- Total Quantity: 15 heat pipes

- Total Mass: 500.66g

- Total Volume: 315.56 cm³

The heat pipe system has been carefully designed to manage the thermal loads of our rover's critical components while minimizing mass and volume. This system will ensure that all components remain within their operational temperature ranges throughout the mission, even in the extreme lunar environment.

Technology Readiness Level (TRL): The ACT Constant Conductance Heat Pipes (CCHPs) have a high TRL due to their extensive flight heritage in space applications. ACT's website states that their CCHPs have accumulated significant space flight hours, indicating a TRL of 9 for the basic CCHP technology. However, the specific configuration for our rover design brings the overall heat pipe system TRL to 7, as it will require some additional testing in simulated lunar conditions to fully verify performance in our unique application.

ACT manufactures these CCHPs to exact aerospace requirements under their ISO 9001:2015 and AS9100D certified Quality System. This high level of quality control and space heritage provides confidence in the reliability of these components for our mission.

In the next phase of development, we will conduct detailed thermal simulations and physical tests to validate the performance of this CCHP system under expected mission conditions. This will include verifying its ability to handle the extreme temperature variations between lunar day and night, as well as its performance in permanently shadowed regions (PSRs).

In the next phase of development, we will conduct detailed thermal simulations and physical tests to validate the performance of this heat pipe system under expected mission conditions. This will include verifying its ability to handle the extreme temperature variations between lunar day and night, as well as its performance in permanently shadowed regions (PSRs).

Heater, Thermostat & Temperature Sensor TRL=7

Some of the main components that will be utilized within our thermal subsystem is the heater, thermostat, and temperature sensor.

For our heater, we chose to go with the KHLVA PLM - Series, which is manufactured by Omega. This heater uses 0.4 - 1.56 (W/cm²) of power, has temperature limits ranging from -40 °C to 149 °C, is made out of Kapton (polyimide) and comes in various sizes. For our purposes, the size that we chose has 1 inch in width, 4 inches in length, and an area of 10 W/in². Our heater would only utilize less that 25 Watts, and weights an almost negligible mass of less than 1 kg, which makes this heater extremely viable for our mission.

For our thermostat, we went with the Sierra Nevada manufactured, passive thermal control heat switch. This thermostat was originally designed for Martian surface ops. Its mass comes in at roughply 0.110kg. Its maximum conductance is 1 W/K and its minimum conductance is .015 W/K. This thermostat is more than capable of being in the conditions that our rover will face, and it will be able to do its job with very little difficulty.

Lastly, for our temperature sensor, we decided to go with the IR20, which is manufactured by Hukseflux. This is a space-grade temperature sensor with a sensitivity (nominal) 17 x 10^-6 V/(W/m²). It's field of view angle is 180°, and it's rated operating temperature range is -40 - +80°C. The mass is less than 0.1 kg and will be paired with other thermal control components to do its job adequately.

2.1.4.3. Thermal Subsystem Recovery and Redundancy Plans

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

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

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

2.1.4.4. Thermal Subsystem Manufacturing and Procurements Plans

Passive thermal management proved to be the most suitable option for the electrical components of the CHILLY Rover. Key things of this passive system include heat sinks, heat pipes, thermal interface materials, and conductive adhesives [23]. Thermacore can supply all of these key components, and offer a wider product range. They also have been in the industry for 50 years, with a proven track record of success in the aerospace and electronics industry with high standards [24]. Advance Cooling Technologies is another viable option, similar in standards and success to Thermacore, but going for a dynamic solution with only 20 years of industry experience. Manufacturing lead times may consist around 15 weeks and up to 20 weeks if the main supplier is unavailable, while can extend further if a high-performance solution is needed.

2.1.4.5. Thermal Subsystem Verification Plans

Outlined below in table 30, is the thermal subsystem's preliminary verification plans. These plans provide further explanation to the various verification methods chosen for the thermal requirements. Verification plans are important in reducing the risks and demonstrating the reliability of the thermal subsystem.

Table 30. *Thermal Verification Plans*

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
TCS-1	Operate in Temperatures Ranging from -223°C to 123°C	Test	Testing ensures the subsystem operates under expected space conditions.	Perform thermal vacuum testing, cycling temperatures from -23°C to 123°C. Monitor and ensure subsystem functions within operational parameters.
TCS-1.1	Withstand Thermal Cycles and Damping Effects	Test	Validates the system's durability under repetitive thermal stress.	Subject the subsystem to multiple thermal cycles, simulating the expected transitions between sunlit and shaded regions for the mission duration, including day/night cycles. Verify no degradation occurs in system performance or structure.
TCS-2	Maintain Operating Range for Other Subsystems (-40°C to 40°C)	Analysis	Analytical simulations predict thermal behavior under various conditions.	Use thermal modeling software to simulate mission conditions. Verify that all subsystems maintain temperatures within the required range.

TCS-3	Use 10-15% of the Total Rover’s Power	Inspection	Ensures power usage stays within the allocated budget, critical for mission planning.	Review and measure power consumption during operation. Ensure it remains within the 10-15% range of the total rover power budget.
TCS-4	Mass Less Than 20 kg	Inspection	Direct measurement verifies compliance with mass constraints.	Weigh the fully assembled thermal control subsystem and confirm it does not exceed the 20 kg limit.
TCS-5	Cost Less Than $5 Million	Inspection	Regular cost audits ensure financial constraints are met.	Audit procurement, manufacturing, and labor costs to ensure total expenditure remains under $5 million.
TCS-6	Maintain Internal Temperature of -40°C to 40°C for Mission Duration	Test	Testing over mission duration validates temperature stability in long-term operations.	Conduct extended thermal vacuum testing under simulated mission profiles to ensure internal temperatures stay within the specified range for the full expected mission duration.

TCS-6.1	Include Passive Thermal Insulation	Demonstration	Demonstration in controlled conditions verifies insulation effectiveness.	Test passive insulation performance in a thermal vacuum chamber. Demonstrate that the insulation performance matches the thermal analysis predictions within an acceptable margin of error.
TCS-6.2	Include Active Thermal Control Mechanisms	Demonstration	Active thermal control systems must be validated in simulated operational environments.	Demonstrate the active thermal control system in a thermal vacuum chamber. Verify that the system maintains internal temperatures between -40°C to 40°C, with temperature adjustment rates matching the thermal analysis predictions.
TCS-7	Monitor and Report Temperature in Real-Time	Demonstration	Real-time monitoring and reporting are essential for mission success. Testing ensures accuracy and reliability of the temperature data system.	Operate the subsystem and verify the accuracy (within ±0.1°C) and frequency (at least once per second) of real-time temperature data monitoring and reporting under simulated operational scenarios lasting 24 hours. Include temperature variations covering the full expected range.
TCS-8	0g of Radioactive Material	Inspection	Ensure compliance with SYS-1. Inspection will confirm that the subsystem adheres to this requirement.	Review material certificates, supplier documentation, and manufacturing records for all components of the thermal control system. Verify that no radioactive materials are listed in any bill of materials. Conduct a physical inspection using a calibrated Geiger counter to confirm absence of radioactivity above background levels in the fully assembled thermal control system.

2.1.5. Payload Subsystem Overview

The CHILLY mission rover will consist of two main science instruments, a Strata Ground Penetrating Radar (GPR) and a Near Infrared Volatile Spectrometer System (NIRVSS). The GPR is a significant and necessary tool for this mission as it is the primary instrument that will fulfill the customer given criteria (2a) of measuring the water ice abundance in the top 1 meter of the lunar regolith with an accuracy of at least +/- 5%. The GPR measures water ice abundance by measuring permittivity, an electromagnetic property that indicates the presence of water ice as well as other structures in the lunar regolith [14]. Electromagnetic waves are a crucial indicator of composition of the lunar regolith as waves reflect or refract when coming into contact with different materials. Analyzing the behavior of the electromagnetic waves provides data about the composition of the lunar surface and subsurface. Frequency of the permittivity bands in particular will give insight into not only the presence of water ice, but its abundance far below the lunar surface as well [27]. When specifically looking at high frequencies, the GPR is capable of mapping accurate water ice structures 10 meters below the surface, demonstrating that the goal of identifying water ice in the top 1 meter of the regolith will be easily fulfilled [28]. As previously stated, the electromagnetic capabilities of the GPR extend to the other materials present in the regolith. This will help to fulfill science objective 6n which includes analyzing the sedimentation of the lunar regolith. Specifically, the GPR has been shown to find the chemical and mineral composition of the lunar surface which will help when discerning different sediment particles that have settled under the lunar surface.

The primary physical characteristics that were researched in conjunction with functionality included the mass, volume, and maximum power draw of the GPR. It was found that the mass of the GPR models tends to be around 4 kg while the volume is only .01 m^3 (see Table 31). This compact size was a significant consideration which is outlined in the Payload Trade Studies. Additionally, the maximum power draw of the GPR can vary from 7 to 10 W depending on the modifications and time it is used (see Table 21). The functionality of the GPR, its physical qualities, and test runs are vital factors when determining its Technology Readiness Level (TRL) which indicates how mature the technology is. The GPR has not only been developed and used here on Earth but also has been successfully used on lunar rovers on both the Chang'E-3 mission and the Chang'E-4 mission [14] [#].

The NIRVSS instrumentation will be used to identify lunar surface composition, morphology, and thermophysical properties. The primary scientific objectives to be fulfilled by this instrument will include the identification of hydrogen and oxygen concentrations (6n). This instrument has two main components: a bracket assembly and a spectrometer box. The spectrometer box contains two spectrometers with distinctive capabilities to account for ice and mineral and organic compounds [62]. The bracket assembly includes a CMOS sensor that distinguishes wavelengths between 340-940 nm, a long wave calibration sensor for monitoring surface temperatures, thermopile sensors, and an infrared lamp for illumination. This optimal wavelength range provides higher sensitivity to detecting atmospheric gasses, surface minerals and volatiles. The identification of elemental compositions on the moon surface is crucial for determining lunar water distribution while high resolution imaging capabilities will help capture lunar surface morphology. Additionally, the NIRVSS will further help measure the lunar surface's thermophysical responses to characterize surface materials and their behavior under microgravity. Observations obtained from the NIRVSS will ultimately provide insight into lunar surface composition, variation in volatiles including water, hydrogen, and oxygen.

Some of the metrics pertaining the NIRVSS instrumentation include a mass of 3.6 kg, a volume of 0.0025 m^3, and a maximum power draw of 30 W (Table 31). Lower metrics are desirable and are met by the two chosen instruments. A max power draw of 30 W is appropriate given it is a multi-system-based instrument— and one that will overlap the criteria of two science objectives.

Table 31. *Physical Characteristics of Science Instrumentation*

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

2.1.5.1. Science Instrumentation Requirements

Table 32. *Science Instrumentation Requirements*

Science Instruments Req							
PAY-1	The science instruments must be able to measure the spectral resolution of a sample with a resolution of at least 20 nm	The science instruments must be able to differentiate between common materials in the lunar environment complete mission	MR-8	N/A	Test	Payload Subsystem	met

		objective 6n					
PAY-2	The science instrument must be able to resolve temperature differences of a sample from 0°C to 100°C	The science instrument must be able to identify the conditions of water-ice at and above its melting point	MR-8	N/A	Test	Thermal	met
PAY-3	The science instrument must be able to resolve the distance between objects in a sample with an accuracy of 5cm or less	The science instrument must be able to locate the particulates in suspension of a liquid during the sedimentation process	MR-8	N/A	Test	Payload Subsystem	met
PAY-4	The science instrument must be able to produce radiation within the range of 100 - 1000MHz	The science instrument must be able to produce radiation that is able to penetrate lunar regolith while still be affected by water-ice and other volatiles	MR-7	N/A	Demonstration	Payload Subsystem	met
PAY-5	The science instrument must be able to resolve the location of underground water-ice and other volatiles within 5cm	The science instrument must be able to determine the water-ice abundance within the top 1m of regolith within 5%	MR-7	SCI-5.1 SCI-5.2	Test	Payload Subsystem	met
PAY-5.1	The instrument must be able to resolve the distance of water-ice within 5 cm	The science instrument must be able to determine the water-ice abundance within the top 1m of regolith within 5%	SCI-5	N/A	Test	Payload Subsystem	met
PAY-5.2	The instrument must be able to resolve the lateral distance of sample measurements within 5 cm	The science instrument must be able to determine the water-ice abundance within the top 1m of regolith within 5%	SCI-5	N/A	Test	Payload Subsystem	met

PAY-6	The science instruments must be able to operate with 40 W or less for extended periods	The subsystem must be able to operate on battery power over extended periods	MR-3 PAY-3	N/A	Demonstration	Thermal	met
PAY-7	The science instrument must be able to operate within the acceptable temperature ranges provided by the thermal module	The minimum operating temperature of the NIRVSS spectrometers is 289 K	MR-3	N/A	Demonstration	Thermal	met
PAY-8	The science instrument must have the ability to measure lunar surface activity	The science instruments must be able to take measurements of the surface to complete science objectives	MR-3	N/A	Test	Payload Subsystem	met

2.1.5.2. Payload Subsystem Recovery and Redundancy Plans

Due to the mission size of the CHILLY mission and the budget, it is unreasonable to have any backup science instruments. It would be far too expensive and there would be no room on the rover to house them. If any of the science instruments fail, the science goals associated with that instrument will not be met, or will have to be satisfied with limited scientific data.

2.1.5.3. Payload Subsystem Manufacturing and Procurement Plans

One of the primary instruments in the payload subsystem that will be aboard the CHILLY rover is a Ground Penetrating Radar (GPR). The primary supplier that will be used to manufacture the GPR for this mission will be Astrobotic Technology Inc [53]. This supplier has been chosen as they are a United States based aerospace technology company which has a well established relationship with NASA. In fact, they developed technology aboard a mission that ended successfully in early 2024 which was specifically geared towards experimentation utilizing multiple scientific instruments [46]. In 2020, Astrobotic received multiple grants from NASA, one of which is a contract to develop a non-contact GPR for lunar experimentation. The lead time to manufacture the GPR can only be estimated since the manufacturing of the GPR is not complete. The research to raise the GPR to a Technology Readiness Level (TRL) of two was completed in seven months by Astrobotic and predictions to raise this TRL to be flight ready is anywhere from 12 months to 30 months in total [45]. A possible backup supplier could be Geophysical Survey Systems Inc. (GSSI) which is the leading manufacturer of personalized GPRs in the United States [21]. While GPRs are readily available from this company, they are not specialized in lunar uses which will increase the manufacturing time to 30 months or more for additional testing and adaptations through NASA.

For the NIRVSS subsystem, NASA will utilize the same suppliers as the Resource Prospector (RP) Mission to ensure reliability and consistency in quality and performance. Accordingly, the RP mission was intended to advance lunar exploration by utilizing NIRVSS as one of its key instruments. However, NASA’s cancellation of the RP mission in 2018 disrupted these plans. As a result, NIRVSS has not been tested on a lunar surface but has been previously tested in a rover subsystem on Earth to confirm component functionality [62]. The two identified suppliers are ThermoFisher Scientific, which provides the spectrometer optical engines, and Kennedy Space Center, responsible for the payload management. NASA’s Ames Research Center has collaborated with these suppliers to develop NIRVSS for the RP mission through a rapid-development process that includes quick iterations on the design cycle, and building and testing high-fidelity engineering units. For CHILLY’s rover mission, ThermoFisher's NIR analyzers will be used for their wavelength accuracy and precision, high spectral resolution, and dynamic alignment for stability in production environments [41]. ThermoFisher Scientific is an adequate supplier for the NIR subsystem due to its proven track record in delivering high-quality optical instruments and its established relationship with NASA.

ThermoFisher Antaris MX FT-NIR Process Analyzer meets factory requirements and is suited to meet challenging conditions. As part of ThermoFisher Scientific, Unity Lab Services ensures regulatory compliance to ensure correct instrument installment, operation, and performance according to user requirements. Specifically, Unity Lab Services complies to GLP/GMP, GxP, 21 CFR Part 11, ISO, and other key regulations [12]. Compliance services include but are not limited to analytical instruments, laboratory equipment, and calibration. These services ensure highly documented processes and procedures to produce reports and documentation adherence to regulatory requirements. The qualification services are conducted on-site by factory-trained technicians. Instrument qualification ensures support to major guidelines (FDA, GMP, ISO, and pharmacopoeial), including certification, traceability, and monitoring [11].

To estimate ThermoFisher’s FT-NIR’s manufacturing lead time, general purpose IR spectrometers were researched, providing insight into lead times according to their corresponding complexity and capabilities (Table 33). Option one meets the temperature requirements needed for the mission's scientific objectives but does not satisfy the wavelength requirements. The estimated lead time provided by the manufacturer is 11 weeks. With option two, an optical sensor with an IR of 5000nm does not meet either of the mission wavelength and temperature requirements but does provide a larger range of wavelengths to be detected. The estimated manufacturer lead time for the second option is 24 weeks, which corresponds with the increasing complexity and capability of the device. Option three is a small-scale NIR spectrometer that would most closely resemble the needed technology for the mission. However, the supply has been discontinued and no longer available for manufacturing. The estimated lead time provided for this option is 16 weeks. Given these estimates, it is predicted that ThermoFisher's FT-NIR Process Analyzer will have a lead time greater than 24 weeks and not less than 16 weeks. Given NIRVSS' dimensions, extensive requirements to meet scientific objectives, and being a two main component system, a complete flight-ready instrumentation is ensured to have an estimated manufacturing lead time greater than 12 months.

Table 33. *NIRS Science Instrumentation Component Manufacturer Comparison Table*

NIRS Component	Option 1	Option 2	Option 3	ThermoFisher FT-NIR Process Analyzer (Bracket Assembly Not Incl.)
Supply Description	Optical Sensor IR 720nm I2C 8-WFQFN Exposed Pad, Module	Optical Sensor IR 5000nm ~ 20000nm I2C, SPI 10-LFDFN	Mini Spectrometer NIR: Light, Infrared (IR) Sensor Evaluation Board	Antaris MX FT-NIR Process Analyzer
Manufacturer	Vishay Semiconductor Opto Division	STMicroelectronics	ams-OSRAM USA INC.	ThermoFisher Scientific
Wavelength Requirements Satisfied	No (720nm)	No (5000nm ~ 20000nm)	Unknown	No (833 to 2500 nm)
Temperature Requirements Satisfied (0°C to 100°C)	Yes (-40°C ~ 105°C)	No (-40°C to +85°C)	Unknown	No (15°C to 35°C)

Complexity	General Purpose - applications in entrances, elevators, and escalators	General Purpose - high-sensitivity	Unknown	Advanced (In-process liquid analysis, laboratory liquid analysis supported)
Size	Dimensions (L x W x H in mm): 4.0 x 2.36 x 0.75	Dimensions (L x W x H in mm): 4.2 x 3.2 x 1.455	Unknown	Dimensions (L x W x H in inches):18.97 x 15.98 x 9.72
Manufacturer Standard Lead Time	11 Weeks	24 Weeks	16 Weeks	Estimated: >32 weeks for NIR component only >12 months for full NIRVSS component

2.1.5.4. Payload Subsystem Verification Plans

The plans for verifying the Payload Subsystem can be found in the verification matrix below:

Table 34. *Payload Verification Matrix*

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
PAY-1	The payload subsystem shall not exceed a cost of $TBD	Inspection	In order to verify this requirement, the cost of each part on the payload subsystem must be recorded and their sum must be compared to the allocated budget of the subsystem	The budget must be updated regularly with the true costs of each part and compared to the proposed budget to ensure that the cost limitations are considered.
PAY-2	The payload subsystem shall not exceed a mass of 10 kg	Inspection	In order to verify this requirement, the weight of each part must be recorded and their sum must be compared to the allotted weight of the subsystem	Weight/mass must be updated regularly and compared to the proposed weight of the payload to ensure that the maximum allotted weight is not exceeded.
PAY-3	The payload instruments shall not exceed a maximum power draw of 40 watts	Demonstration	In order to verify this requirement, the subsystem must run and demonstrate that its max power draw is less than 40 W	The payload instruments will be run on Earth with their full capabilities (conducting the same experiments as will be done on the lunar surface) and power draw will be recorded over the course of the run to ensure that it doesn't exceed the maximum power draw.
PAY-4	The payload instruments shall be able to measure the water content of the first meter of lunar regolith	Test	In order to verify the payload can measure water content in lunar regolith, the instruments must be tested in similar environments and made to perform to at least a minimum requirement	The instruments will have a test run in a simulated environment that replicates the lunar water-ice. Known amounts of water ice will be present and the data produced by the instruments will be compared to the true data to ensure accuracy. Lab with lunar regolith will be needed.
PAY-4.1	The Ground Penetration Radar shall be able to measure water-ice presence within at least 1 meter of surface regolith within 5 centimeters	Test	In order to verify the GPR can measure water-ice content within 1 meter of the surface, it can be tested on a known sample of water and simulation lunar regolith.	A lab or testing center with simulated lunar regolith will be needed to ensure that the GPR data for water ice content is similar to the known water ice content of the simulated surface.

PAY-5	The Near-Infrared Volatile Spectrometer System(NIRVSS) shall complete science objective 6n	Test	In order to verify the NIRVSS system can perform objective 6n, the instrument must undergo tests to ensure the measurements taken meet the requirements of specific requirements	A facility where NIRVSS can be tested will be needed, such as a lab that can simulate the volatiles present in the water ice and lunar regolith as a whole.
PAY-5.1	The NIRVSS shall be able to measure the physical conditions of hydrogen, oxygen, and water condensation	Test	In order to verify this requirement, the NIRVSS instrument must be tested on a known sample of water-ice and be able to measure the temperature, composition, and particulate density	A temperature controlled lab or testing center that can create different samples of the lunar surface with varying compositions will be needed to test if NIRVSS can accurately identify the features of each sample (such as density and temperature)
PAY-5.1.1	The NIRVSS shall differentiate between liquid water and gaseous hydrogen, oxygen and water vapor	Demonstration	In order to verify the NIRVSS can differentiate between liquid and gaseous, the system can be used to determine the phase of given samples and demonstrate the accuracy of its measurements	Known amounts of different gasses (such as hydrogen, oxygen, and pure water vapor) will be present in ice samples that NIRVSS will test. The collected data will be compared to the true amounts of each to ensure that the accurate amounts and types of volatiles are recorded.
PAY-5.1.2	The NIRVSS shall be able to measure temperatures of various gasses and liquids	Test	In order to verify the NIRVSS can measure temperatures of gasses and liquids, samples of different materials and temperatures can be measured and the data obtained be compared to known results	A temperature controlled lab will be needed to alter the temperature of the environment and liquid samples to extremely cold temperatures, replicating the conditions of the lunar south pole (especially for permanently shadowed regions)
PAY-5.1.3	The NIRVSS shall be able to differentiate between gaseous hydrogen and oxygen	Demonstration	In order to verify the NIRVSS can differentiate between gaseous hydrogen and oxygen, the system can be used on liquid and gaseous hydrogen and oxygen and demonstrate it can differentiate between the two	NIRVSS will demonstrate that it can identify the hydrogen and oxygen in their gaseous states by testing contained samples of each and a mix of both. The data NIRVSS collects will then be compared to the true contents of the samples.

PAY-5.2	The NIRVSS shall be able to measure the composition of water and suspense regolith during the sedimentation process	Test	In order to verify the NIRVSS can measure the composition of water and suspended particulates, a test can be administered against a known sample and compared against known results	A lab with access to tensiometers or photometers will be needed to identify the sediments and compare it to the data that NIRVSS outputs.
PAY-5.2.1	The NIRVSS shall be able to differentiate between water and regolith suspended in liquid water using a spectral resolution of at least 50 nm	Test	In order to verify the NIRVSS can differentiate between water and regolith, the instrument must be used to measure a known sample and compared against known results	A testing center where both water ice and regolith can be displayed for NIRVSS to analyze will be needed to ensure that it can differentiate the two and deliver accurate data.
PAY-5.2.2	The NIRVSS shall be able to determine the temperature of a given sample around the liquefaction temperature of water	Test	In order to verify the NIRVSS can determine the temperature of a given sample, it can be tested on materials of differing temperature including solid and liquid water	A lab that can have water ice reaching temperatures of 150K will be needed to test if NIRVSS can accurately record these temperatures.
PAY-5.2.3	The NIRVSS shall be able to determine the location of suspended particles in liquid water within TBD cm	Test	In order to verify the NIRVSS can measure the location of suspended particles, it can be tested on a sample with suspended particles of known location and compare measured locations against known results	A lab with access to suspension liquid will be needed in which sediment particles can be inserted and location can be identified with a tensiometer or photometer. NIRVSS location data will be compared to these to ensure that location of the sediments is accurately being displayed.

2.2. Interface Control

Outlined below in figure 15, is the N^2 Chart. This chart outlines the interfacing relationships between each of the different subsystems.

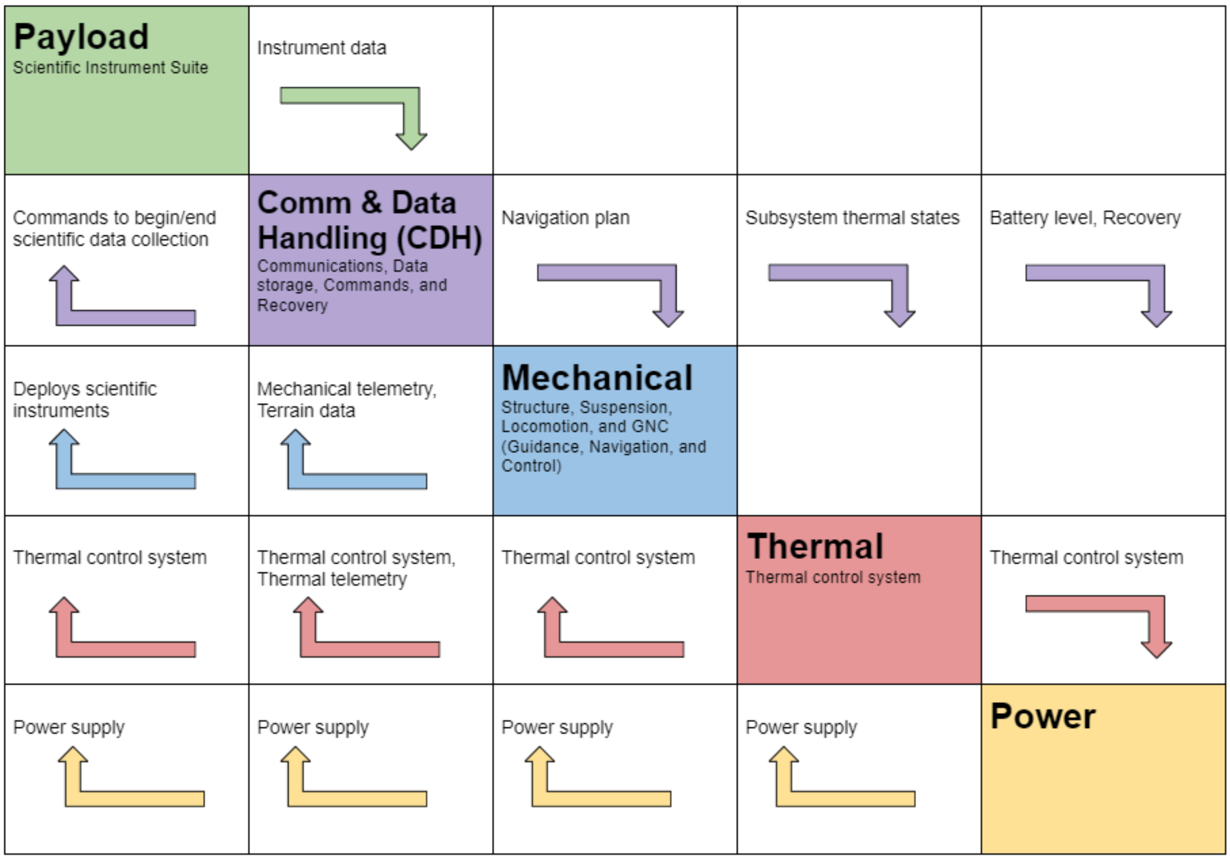


Figure 15. *N^2 Diagram*

The mechanical subsystem is responsible for deploying the instruments from the payload subsystem and relies on the CDH subsystem for navigation commands and telemetry data. The power system supplies the power to all of the other subsystems. The components are kept within operating temperatures by the thermal subsystem. The thermal subsystem is in charge of regulating the temperatures of all of the subsystems. The CDH subsystem is in charge of all communication and gives commands to all of the other subsystems. Additionally, the CDH subsystem also keeps track of the health of each subsystem. The payload system is in charge of using its scientific instruments to accomplish the science goals and sends the instrument data to the CDH subsystem to be sent to the primary mission orbiter.

Additionally, the block diagram is shown below in figure 16. This further outlines the interfacing relationships between all of the subsystems.

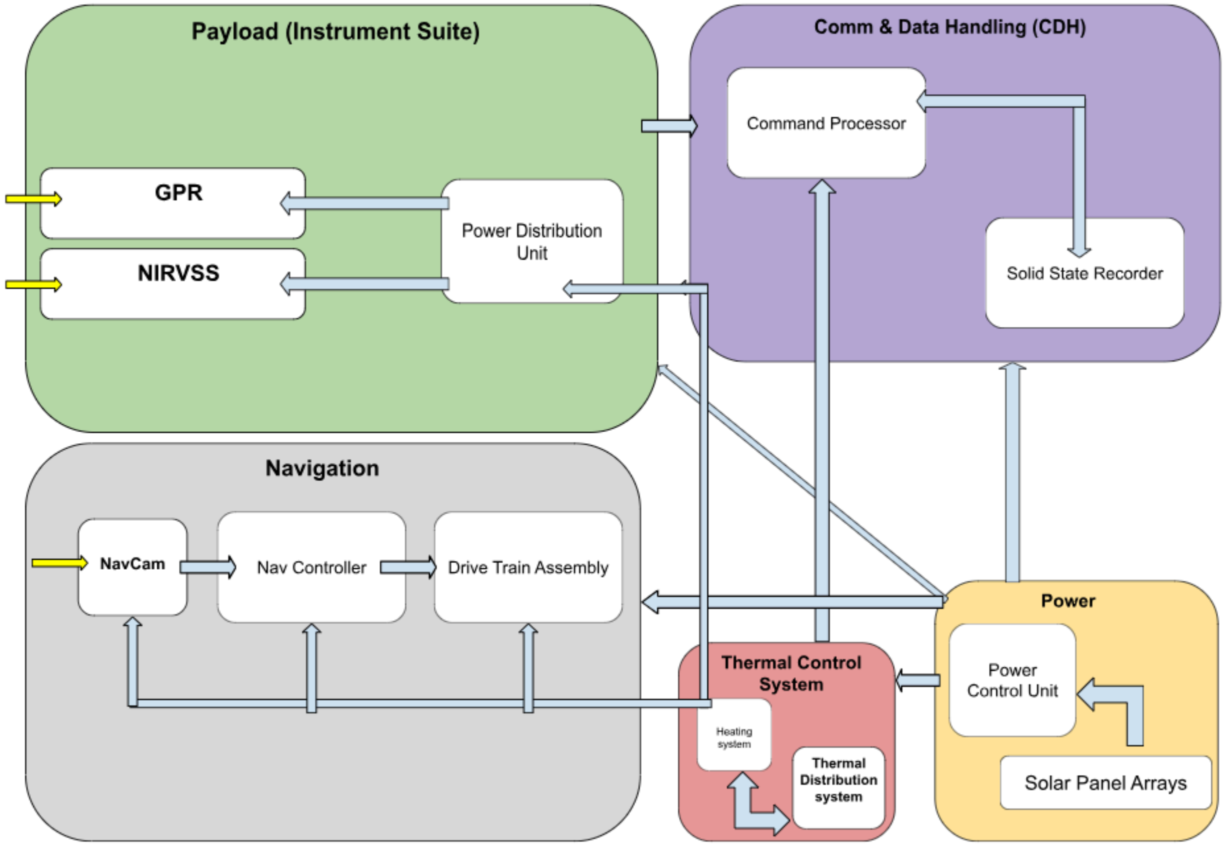


Figure 16. *Block Diagram*

The interface between the mechanical and payload is shown in figure 16. This basic sketch shows how the mechanical subsystem supports the payload in accomplishing the science goals.

3. Science Mission Plan

3.1. Science Objectives

As stated in section 1.2 (*Table 1*), the CHILLY mission comprises three main objectives. The first two objectives are to see how condensation of hydrogen, water, and oxygen is impacted by conditions on the moon as well as analyzing the effects of gravity on solid-liquid phase change and composition of the water ice. The NIRVSS instrument will fulfill the first objective by measuring physical parameters for the condensation. Similarly, NIRVSS and GPR will both help to identify temperatures and change in composition during the phase change in the second objectives. Completing these two objectives will help to achieve the Artemis science goal 6n, which aims to examine conversion of water ice to gaseous hydrogen and oxygen, thus demonstrating the effects that lunar conditions have on water ice movement and phases [#]. The third objective is to determine the water ice abundance within the top 1 meter of the lunar regolith in a PSR region which will help to fulfill the customer given Artemis science goal 2a regarding the distribution of volatiles and water ice in the lunar South Pole. Both NIRVSS and GPR will work together to measure temperature and presence of the water ice within the PSR of the Leibnitz Beta Plateau. This will produce data indicating the amount of water ice in this PSR and if it could be used for future missions depending on its volatile composition.

3.2. Experimental Logic, Approach and Method of Investigation

Strata Ground-Penetration Radar -
The Strata ground-penetrating radar, or GPR, is a device consisting of two antennas. The first is a transmitting antenna responsible for producing high frequency radio waves that can penetrate the ground. This allows for radio waves to go through the ground and interact with the regolith. Since there are different materials in the regolith, the radio waves will behave differently depending on what is in the vicinity of the GRP. The second part is what allows the instruments to make measurements of what is underground. A receiver antenna catches the radio waves and measures the difference between the output radiation and the input radiation. By measuring attenuation and time after emission of the waves, the onboard computer can make calculations as two what is below the surface as well as what material it is. If multiple frequencies are used as well as multiple passes for a specific area are made, a high resolution 3D map of the regolith can be made to varying depths. Since the Chilly mission only requires a depth of 1 meter, the transmitter antenna will be expected to produce between 25 and 1500 MHz radio waves to take measurements below the surface. Using the data collected by the receiving antenna, after it has been processed by the onboard computer, it can be analyzed and a ratio of ground water-ice to regolith within the top meter of lunar regolith can be collected. This will allow the mission objective, 2a, to be achieved. Using the same technique, the composition of solid and liquid water-ice can be known fulfilling objective 6n. From this, the Chilly mission will be able to find information on water-ice abundance, its condensation patterns, as well as sedimentation patterns of regolith.

Near Infrared Volatiles Spectrometer System -
The Near Infrared Volatiles Spectrometer System, or NIRVSS, is an instrument made of two parts. The first is a bracket assembly containing a four megapixel CMOS sensor which has seven LEDs that allow it to discern several wavelengths, a longwave

calibration sensor allowing for surface temperature measurements, an infrared lamp allowing illumination of measurement surface, and four thermopiles with filters of varying sizes. The second portion is a spectrometer box containing both a short and long wave spectrometer. With all of these combined, the NIRVSS is able to discern between materials, tell the temperature, and take pictures of the surface of the lunar south pole. This, in conjunction with the GPR system will allow the Chilly mission to make measurements concerning objective 6n and provide supplementary data for said objective.

Experimental Plan-

The Chilly mission is based on a rover designed to traverse a PSR on the lunar south pole. The two science instruments would be placed facing the bottom of the rover for access to take measurements. The GRP would send and receive radio waves to and from the regolith at regular intervals. This will happen on multiple passes of the same area to build a better picture of the top meter of the regolith. On certain sections of the PSR, the NIRVSS will take temperature measurements as well as spectrometer readings of the ground to determine the sedimentation and temperature of the water-ice and other volatiles in that location.

3.3. Payload Success Criteria

The Strata Ground-Penetration Radar (GPR) should be able to meet three main payload objectives: (1) measure ground water content, (2) measure location of particles, and (3) determine the phase of measured materials. To meet these objectives, minimum and optimum success criteria has been identified, including a stretch goal (Table 1). To meet minimum success for the first payload objective, GPR must measure ground content in 15 different locations at least 2 km apart, have a minimum accuracy of 95% for optimum success, and additional five locations with 90% minimum accuracy for stretch goal. Understanding ground water content in the lunar environment is important for resource identification, especially in identifying potential landing sites by mapping water distributions across the locations explored. This data would also provide an assessment of the hydration of the lunar regolith and variations across locations. To meet minimum success for the second payload objective, measurements of particle locations from 15 samples obtained at least 2 km apart must be obtained, a minimum accuracy of 95% must be met for optimum success, and an additional five locations with a 98% minimum accuracy must be achieved for the stretch goal criteria. Identifying location of particulates is important for understanding lunar regolith composition, erosion, and deposition. It is also a strategy for assessing lunar surface hazards, particularly lunar dust which can pose a threat to the equipment. To meet minimum success for the third payload objective, phase of materials from 15 samples collected at least 2 km apart must be obtained, have a minimum accuracy of 95% for optimum success, and have an additional five samples with a minimum accuracy of 98% for stretch goal. Determining the phase of the measured materials is important for resource utilization, including fuel generation and material process needed for the equipment.

The Near-Infrared Volatile Spectrometer System (NIRVSS) should be able to meet three main payload objectives: (1) measure temperature readings, (2) determine material composition, and (3) locate particulates in a sample. To meet these objectives, minimum and optimum success criteria has been identified, including a stretch goal (Table 1). To meet minimum success for the first payload objective, NIRVSS must measure temperatures in 15 locations at least 2 km apart, have a minimum accuracy of 95% for optimum success, and an additional five locations for a 98% minimum accuracy for stretch goal. Temperature data-logs of lunar surface locations are important for understanding thermal properties of lunar materials, such as regolith, roc, and ice formation. This also supports the data that will be collected for material phase determination. To meet minimum success for the second payload objective, NIRVSS must determine material composition in 15 samples obtained from different locations at least 2 km apart, a minimum accuracy of 95% must be obtained for optimum success, and an additional five locations must measured with a minimum accuracy of 98% for stretch goal criteria. The determination of material composition also supports previous objectives, including the detection of hydrogen, ice, and other volatiles. Additionally, global maps of lunar surface composition could be developed and existing models of lunar geology refined. To meet minimum success for the third payload objective, phase of materials from 15 samples collected at least 2 km apart must be obtained, have a minimum accuracy of 95% for optimum success, and have an additional five samples with a minimum accuracy of 98% for stretch goal. As previously mentioned, determining the phase of the measured materials is essential for future resource utilization and in optimizing the design and equipment to accommodate lunar materials. Thermal and mechanical properties of lunar materials, and how these factors influence surface processes, such as regolith formation, potential seismic activity, and its interaction with the lunar environment would also be better understood as a result.

Overall, the payload objectives identified in both instruments have the potential to improve the scientific understanding of lunar geology, surface and subsurface interactions, and additional lunar processes. This also affords an improved understanding of mission landing site selections, resource utilization, exploration strategies, hazards identification, and technology development for future missions.

Table 35. Payload Success Criteria and Associated Failure Modes for Science Instrumentation

Payload Objectives	Minimum Success	Optimum Success	Stretch Goal
Strata Ground-Penetration Radar (GPR)			
Should be able to measure ground water content	Measure ground water content in 15 different locations at least 2 km apart	Measure ground water content in 15 different locations at least 2 km apart with a minimum accuracy of 95%	Measure ground water content in 20 different locations at least 2 km apart with a minimum accuracy of 98%
Should be able to measure the location of particulates	Measure the location of particulates from 15 different samples obtained at least 2 km apart	Measure the location of particulates from 15 different samples obtained at least 2 km apart with a minimum accuracy of 95%	Measure the location of particulates from 20 different samples obtained at least 2 km apart with a minimum accuracy of 98%
Should be able to determine the phase of measured materials	Determine the phase of materials in 15 samples obtained from different locations at least 2 km apart	Determine the phase of materials in 15 samples obtained from different locations at least 2 km apart with a minimum accuracy of 95%	Determine the phase of materials in 20 samples obtained from different locations at least 2 km apart with a minimum accuracy of 98%
Near-Infrared Volatile Spectrometer System (NIRVSS)			
Should be able to take temperature readings	Measure temperature in 15 different locations at least 2 km apart	Measure temperature in 15 different locations at least 2 km apart with a minimum accuracy of 95%	Measure temperature in 20 different locations at least 2 km apart with a minimum accuracy of 98%
Should be able to determine material composition	Determine material composition in 15 samples obtained from different locations at least 2 km apart	Determine material composition in 15 samples obtained from different locations at least 2 km apart with a minimum accuracy of 95%	Determine material composition in 15 samples obtained from different locations at least 2 km apart with a minimum accuracy of 98%
Should be able to locate particulates in sample	Measure the location of particulates from 15 different samples obtained 2 km apart	Measure the location of particulates from 15 different samples obtained 2 km apart with a minimum accuracy of 95%	Measure the location of particulates from 20 different samples obtained 2 km apart with a minimum accuracy of 98%

3.4. Testing and Calibration Measurements

In addition to laboratory and field tests, both GPR and NIRVSS scientific instrumentation will undergo preliminary testing procedures once at the desired location to ensure proper equipment function and accurate data collection. Previous laboratory data will be collected through several hardware iterations using lunar regolith stimulants. Individual component testing in thermal and vacuum environments will also be conducted according to lunar observed conditions. This data will then be compared against the data obtained once at the desired location.

It is critical to select the appropriate GPR equipment, including the antenna frequency and system type based on the required depth and resolution. Site assessment includes the understanding of properties of the materials to be surveyed and one that considers environmental conditions like soil moisture and temperature, which can influence GPR performance. The survey design will include a systematic layout with relevant spacing and transect lines oriented to maximize data accuracy. During data collection, variables such as antenna orientation, survey speed, and regular calibration must be managed to ensure consistent data quality. Post-collection, data processing includes the filtering to remove noise and enhance signal clarity, followed by thorough interpretation to identify and map subsurface features. Comprehensive documentation and description of survey parameters, equipment settings, and environmental conditions are necessary for a detailed summary of findings, including spatial maps or cross-sections of the surveyed area. This organized approach increases predictability and allows the GPR to make modifications as needed.

The next step will be to select the proper GPR equipment antenna frequency as per the required depth and resolution. Lower frequencies penetrate deeper but offer lower resolution, while higher frequencies provide better resolution but shallower penetration. The decision is between single-frequency or multi-frequency systems depending on the complexity of the assessment including the site assessment, which will focus on material properties in addition to its dielectrics. This affects the radar velocity and the strength of reflections. Similarly, environmental conditions such as soil moisture, temperature, and surface conditions can also impact GPR performance.

Transect Lines play an important role as well to determine orientation. To control this, data will be collected in multiple directions to improve the accuracy. Data collection variables will adjust the antenna orientation to optimize data collection.

Data analysis filtering will be applied to remove noise and enhance signal clarity.

NIRVSS has two main component assemblies— a bracket assembly and a spectrometer box. Accurate surface temperatures and spectral measurements will be collected for analysis. To measure for accuracy, a photometric linearity test will be conducted to measure Y-axis reproducibility. There are various NIST photometric standards at nominal transmission levels that are acceptable on the FT-NIR Analyzer. In addition to this, Fourier transform technology has allowed for internal NIR HeNe laser for X-axis (frequency) calibration. Specifically, the Antaris FT-NIR analyzer uses this to achieve a higher frequency accuracy. One of the main key features of the FT-NIR analyzer is its long-term stability which affords its ability to transfer chemometric methods from one instrument to another without the need for re-calibration [58]. Previous tests have revealed absorbance values of the NIST standards at three wavelengths that demonstrate long-term stability with a percent standard deviation between 0.11% and 0.73% (Table **36**). With this information, a higher accuracy percentage is to be expected once at the target body even after preliminary testing.

Table 36. NIR Standard Results of Three Wavelengths

	2% NIST STANDARD ($8333\ cm^{-1}$)	2% NIST STANDARD ($6250\ cm^{-1}$)	2% NIST STANDARD ($5000\ cm^{-1}$)
Average	1.7380	1.4737	1.3457
St. Dev.	0.0020	0.0020	0.0016
% St. Dev.	0.11	0.13	0.12

	10% NIST STANDARD ($8333\ cm^{-1}$)	10% NIST STANDARD ($6250\ cm^{-1}$)	10% NIST STANDARD ($5000\ cm^{-1}$)
Average	1.1217	1.0520	1.0185
St. Dev.	0.0017	0.0017	0.0016
% St. Dev.	0.15	0.16	0.16

	20% NIST STANDARD ($8333\ cm^{-1}$)	20% NIST STANDARD ($6250\ cm^{-1}$)	20% NIST STANDARD ($5000\ cm^{-1}$)
Average	0.6522	0.5935	0.6005
St. Dev.	0.0027	0.0026	0.0026
% St. Dev.	0.42	0.44	0.43

	40% NIST STANDARD ($8333\ cm^{-1}$)	40% NIST STANDARD ($6250\ cm^{-1}$)	40% NIST STANDARD ($5000\ cm^{-1}$)
Average	0.4389	0.3918	0.3666
St. Dev.	0.0018	0.0018	0.0017
% St. Dev.	0.42	0.45	0.47

	80% NIST STANDARD ($8333\ cm^{-1}$)	80% NIST STANDARD ($6250\ cm^{-1}$)	80% NIST STANDARD ($5000\ cm^{-1}$)
Average	0.1344	0.1122	0.0991
St. Dev.	0.0008	0.0008	0.0007
% St. Dev.	0.60	0.67	0.73

A thermal sensibility test will also be conducted to ensure that the spectrometer box is within the optimal temperature range. Control variables for NIRVSS will include spectral resolution, laser communication, and detector sensitivity controls. Accuracy testing will again involve comparing the experimental variables against the baseline data. Taking NASA's Volatiles Investigating Polar Exploration Rover (VIPER) as an example, similar performance operation procedures will be performed on NIRVSS after landing. Surface operations will include continuous data collection of imaging, spectral, and surface temperature measurements during traverses [61]. After and during each site drilling, NIRVSS will also collect full site spectral, LSC, and LED observations. As a result, these observations will document the temperature, morphology, and compositional behavior of the subsurface materials as it is exposed at the surface [61].

3.5. Precision and Accuracy of Instrumentation

The GPR precision and accuracy numbers can vary depending on the modifications made to the instrument and whether the instrument is damaged during spaceflight and landing. Both simulated images and field images have been used to determine the precision of GPRs, which is calculated by dividing the number of correctly detected rebars by all detected rebars. Studies show that the highest precision rate reported for a GPR that could be adapted for lunar use is 95.9%, but the average precision rate of 84.9% is a more accurate representation of the ground penetrating radar's capabilities [64]. Accuracy of the GPR is more difficult to determine due to the unpredictable lunar environment and limited testing of the instrument in space. Tests have shown that accuracy of the GPR in space can be as high as precision rates if the instrument is calibrated on Earth. Limited research is available in this area but it can be assumed that an average accuracy rate of 60%-70% is reasonable considering the overall similarity of field test images with simulated images [6].

The second science instrument aboard the rover is the NIRVSS. Since this instrument has not been tested on the lunar surface, precision and accuracy of the device can only be predicted by tests conducted on Earth and in space. The device has been shown to be fairly accurate as it can detect radiance to <25%, which will help to analyze the composition of the lunar surface and water-ice. However, the accuracy rate of NIRVSS may vary after reaching the lunar surface due to harsh temperatures. The inaccuracies caused by temperature variations can be mitigated by making prediction models before launch and using these data points as a model for that may be scanned on the lunar surface. When specifically looking at the spectrometer within NIRVSS, there are two channels that have different spectral resolutions, one from 10-20 nm and the other from 20-40 nm. The spectrometer can only analyze wavelengths that fall within this range and therefore can only accurately detect and record volatiles that fall within this spectral range [64].

3.6. Expected Data & Analysis

Strata Ground-Penetration Radar -

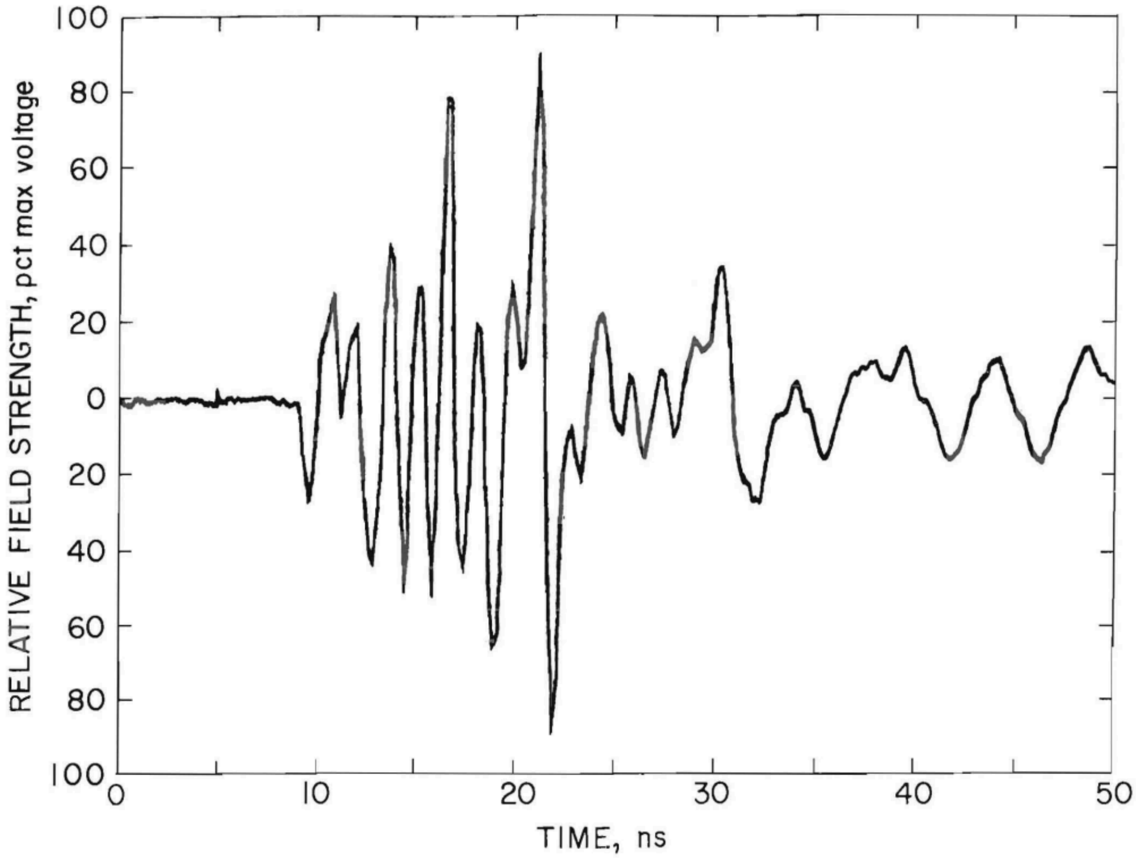


Figure 17. Radio wave measurements of GPR

The data collected from the Chilly mission will likely resemble that from Figure #. Using this data, the different materials in the path of the radio can be obtained using the max voltage measured at that time. Using the speed of the rover and its position, the location of the underground deposits of water or other volatiles can be measured and noted. This can all be done electronically with software or manually. From the data derived from this, the abundance of water-ice can be measured with high accuracy. Using this same method, measurements of a sample can be made and particulates within that sample can be located and differentiated from the surrounding material. The accuracy for this instrument depends on the frequency of the output radio waves. Since the GPR can emit a variety of waves and multiple passes will be done, the accuracy of the measurements should be very high. Laterally, the GPR can measure roughly 1.8 centimeters and for distance, it is less than 1 centimeter. Outside interference coming from space or bodies other than the instrument may introduce some noise to the data but that should be minimal as the rover should shield from most of it. For the rest, it can be ignored as a constant to be removed from the data.

Near-Infrared Volatile Spectrometer System -

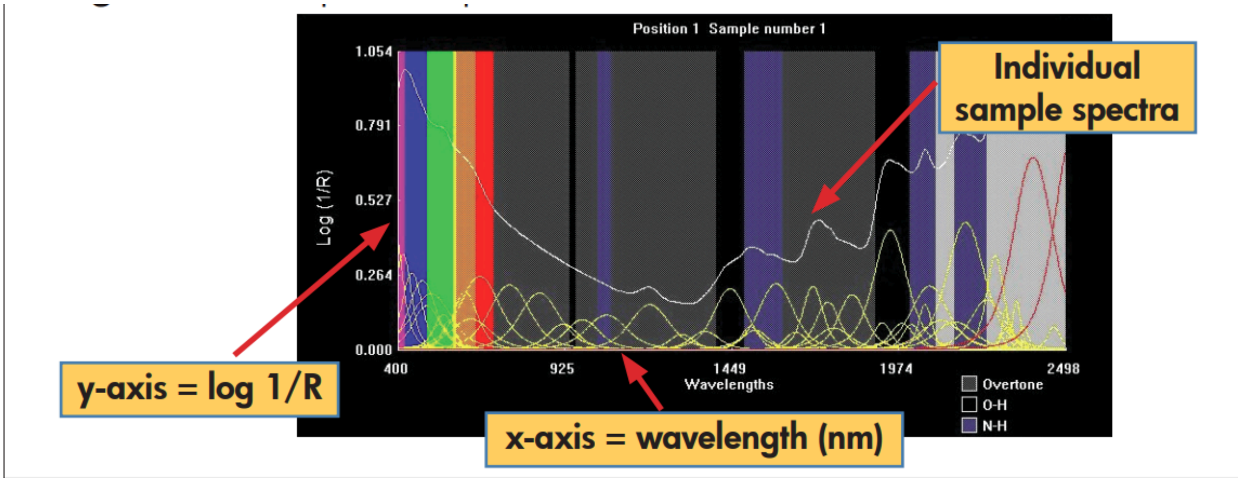


Figure 18. Example spectrometer data

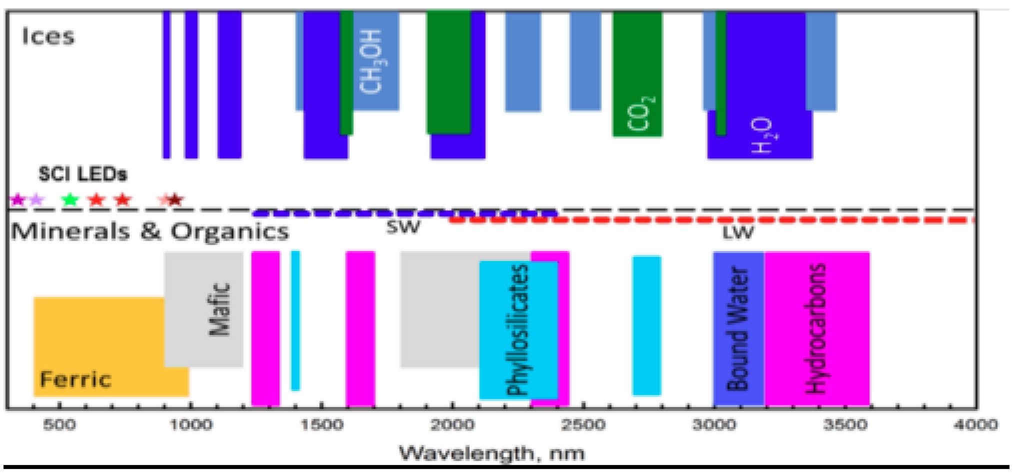


Figure 19. Example spectra of varying materials

For the NIRVSS instrument, the data will be spectral readings, temperature and pictures of the surface. Using the spectral readings, the material being focused on can be determined by comparing to the known spectra of materials. This, combined with temperature readings and visual pictures will allow the Chilly mission to determine the nature of sedimentation in the lunar PSR's. The visuals provided by the NIRVSS can be enhanced with further temperature and spectral data to identify different materials on the surface. This will allow scientists to gain knowledge on the surface composition as well as the sedimentation patterns of water-ice. If used on a sample during a phase change, it would also allow for the analysis of the condensation of the volatiles mentioned in objective 6n. The NIRVSS system comes with redundancy in the spectrometer in the form of overlapping spectral wavelengths from the two spectrometers as well as several lighting options for the camera and several sizes of filters for the thermopiles. This will allow for very accurate information to be obtained at any given time from the instrument. As for outside interference, there is little that could influence the measurements being made from the instrument. Since the machine will be housed and isolated on the rover, temperature fluctuations and anything that would make the spectrometer less accurate would be kept to a minimum.

4. Mission Risk Management

4.1. Safety and Hazard Overview

In order to identify, analyze, and mitigate risks in the mission as a whole, Team 9 has formulated a variety of methods that allow for a comprehensive approach to risk management. These methods are designed to ensure the early recognition of risks as well as the thorough analysis of risk in order to implement effective mitigation strategies to maintain mission success and safety. By employing these strategies, Team 9 can address risks across all phases of the mission, from manufacturing and integration to testing and operational deployment.

Risk Identification/Assessment Strategies

The first aspect to Team 9's approach to understanding risks and hazards during the mission duration is the identification of risks. This identification of risks starts with a systematic process starting at the trade studies for potential materials where all potential risks are clearly identified and weighed to determine if this risk is necessary to the success of the mission. Additionally, risks are also identified through systematic documentation such as Risk Matrices and Failure Mode and Effects Analysis (FMEA) which allow the entire team to have a comprehensive overview of the mission's current risks and potential hazards.

Risk Mitigation Strategies

Once risks are clearly identified and assessed using the strategies above, Team 9 then will move to the implementation of mitigation strategies. These mitigation strategies are clearly outlined both in the Risk Matrices and FMEA as well as in the narrative for each subsystem in order to provide both the members of the team and the shareholders of the mission with absolute confidence in the mission's safety and transparency. The mitigation strategies are designed to reduce the likelihood of risks occurring or to minimize their impact if they do, thereby ensuring that the mission remains on track and that all critical systems are protected.

Concerns and Communication

In order to properly manage major concerns of our mission such as the planetary impact, Team 9 emphasizes the importance of transparent and ongoing dialogue between all stakeholders. This includes regular updates on risk status, potential emerging threats, and the effectiveness of implemented mitigation strategies. Additionally, in order to mitigate the planetary impact of the mission on the lunar surface, Team 9 is also focused on the upholding of planetary protection protocols that ensure that the scientific experiments that include drilling and other physical impacts to the surface.

4.1.1. Risk Analysis

Table 37. *Risk Analysis*

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
Mechanical Subsystem Risks							
1	Terrain Navigation Obstacle	1	3	↓	W	The wheels fail to go over a max of 15 degree slope	Active
2	Entrapped Regolith	3	5	→	W	Regolith is captured in the nooks and crannies of the rover	Active
3	Deployment Malfunction	2	5	→	M	Due to mechanical malfunction, the mechanical arm, solar panels, antennas, or science instruments do not deploy	Active
4	Exposure to Micrometeoroids	1	4	↓	R	Micrometeoroids can hit the surface of the moon with an impact due to lack of atmosphere where it can damage the rover's outside mechanical instruments and body.	Active
5	Malfunction from Thermal Cycling	3	5	→	M	Due to severe heat fluctuations, temperatures on the surface of the rover cause fatigue or cracking	Active
6	Manufacturing Delays	3	4	→	W	Delays in the manufacturing or shipping of materials/parts	Active
Power Subsystem Risks							
1	Power Generation Failure	4	5	**NEW**	M	Dust or damage to the primary power source may cause failure in the rover's mission. The solar cells instead of solar panels are used to mitigate large damage and must be	Active

						built in high quality to reduce lunar dust.	
2	Battery Malfunction	3	4	**NEW**	M	Extreme temperature fluctuations can degrade batteries' performance. A thermal system management has been added specifically for the power system in order to maintain an ideal temperature.	Active
3	Inadequate Power Resource	4	4	**NEW**	W	Solar cells may experience long shadow periods that do not provide energy. Batteries are the recovery option, but they will not last long for an endurance mission.	Active
Thermal Risks							
1	Louver Malfunction	3	5	NEW	M	Louvers failing to open or close correctly, leading to improper thermal regulation.	Active
2	Deployable Radiator Malfunction	3	5	NEW	M	Deployable radiators failing to deploy or retract properly, leading to improper thermal regulation.	Active
3	Material Degradation Over Time	3	3	NEW	M	Long-term exposure degrades MLI and aerogel, reducing effectiveness.	Active
4	Debre Interference	2	4	NEW	W	Debris from unknown sources interfering with mechanical function of components within thermal subsystem	Active
5	All Power Loss	3	4	NEW	M	In the case of an all power loss of the rover, this would lead to the temperatures within the hot and cold case heavily interfering with the functionality of the thermal subsystem	Active
Payload Risks							
1	Payload: GPR & NIRVSS	4	3	New	M	Lunar dust reduces signal accuracy	Active
2	Payload: GPR	3	3	New	A	Excess sedimentary particles cluttering image	Active
3	Payload: NIRVSS	2	4	New	W	Temperature fluctuations affecting capabilities	Active

4	Planetary Protection	2	4	New	M	Contaminating lunar regolith with Earth's organic materials	Active
5	Payload: GPR & NIRVSS	3	4	New	W	Wear on wheel treads due to abrasive lunar regolith reduces mobility	Active
Programmatics Risks							
1	Component Shipping Delay	4	3	↓	W	Supply chain issues lingering from global conflicts (tariffs, bans, etc.) and the COVID-19 pandemic can have potential negative effects on the availability and shipping of necessary components from suppliers	Active
2	Cost Escalation	2	5	→	W	Issues in inflation rates that stray too far from the estimated 2.6% per year causing increased costs and budget overruns	Active
3	Regulatory Certification Delay	2	4	↓	W	Delays in safety certifications necessary for facilities from organizations such as OSHA can lead to schedule delays in testing and manufacturing	Active
4	Decreased Availability of Personnel	2	3	→	M	Due to uncontrollable/unforeseen issues, staff could have potentially lower amounts than initially projected leading to potential project delays	Active

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4.1.2. Failure Mode and Effect Analysis (FMEA)

Table 38. *FMEA*

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Power System	Damaged Solar Cell Panels	Reduce Power Generation	7	Lunar dust	6	Apply dust-resistant coatings, Utilizing high-efficiency solar cells	8	336	Change main power source, Research and Test on dust-resistant material for solar cell
	Inadequate Power Source	Increase risk of running out of power	10	Rover goes into areas that provide no sunlight	7	Apply flywheel to store energy mechanically, Program Rover to relocate to sunlit areas	9	630	Deploy solar array as a charging station at sunlit areas, Add backup power source

4.1.3. Personnel Hazards and Mitigations

Identifying the potential hazards during the manufacturing, integration, and testing phases of the mission is crucial for maintaining a safe working environment. To ensure the safety of team members various types of hazards will be identified and mitigation solutions will be provided to address each risk effectively. During machining and manufacturing phases, potential hazards that could threaten the safety of team members include mechanical hazards, electrical hazards, and chemical hazards. To mitigate these risks, preventative measures will be put in place, including the integration of safety guards on machines, emergency stops, machine-specific training, safety protocol response training, and strict regulations on personal protective equipment (PPE). To prevent chemical and hazardous materials spills and leaks, materials will be properly contained, sealed, and marked with the appropriate safety labels, including laboratory, chemical, GHS, and hazardous materials [66]. To avoid potential electrical hazards, equipment management guidelines will be enforced to ensure that all electrical equipment is properly insulated and marked with electrical labels. Furthermore, to comply with OSHA's regulation 29 CFR 1910.333(a), which mandates safety-related work practices to prevent electrical injuries, the NFPA 70E Standard for Electrical Safety in the Workplace will be followed. The latest edition of these regulations will include employee training, an actionable written safety program, PPE availability, use of insulated tools, arc flash hazard degrees calculations, and properly labeled equipment. Additional safety measures will be imposed to account for human error, including encouraging communication across the company, posting safety checklists, displaying warning signage, and abiding by all local and national guidelines and regulations. All equipment will be properly maintained and frequently assessed to ensure that it operates safely and efficiently, minimizing the risk of failure or injury. Regular maintenance helps identify potential issues before they become hazards, ensuring that equipment remains in good working condition and adheres to safety standards. Failure to maintain manufacturing equipment can lead to increased risk of malfunctions and injuries. Worn-out parts or substandard assembly heighten the chances of accidents. Regular servicing and timely replacement of equipment are crucial. Additionally, inspection and repair label printers will be used to document maintenance history and upcoming service dates, while reminders about the importance of proper equipment maintenance will also be prominently posted. When replicating similar lunar conditions for testing, it is still crucial to consider potential hazards for personnel conducting the tests. The pre-launch testing environment must be representative of the lunar surface. During this phase of the mission, mishandling of the equipment and exposure to simulated extreme conditions can pose risks such as thermal stress and pressure-related issues. Ensuring that proper safety protocols and protective measures are in place is essential to mitigate these risks and safeguard the health and safety of the testing personnel. Furthermore, the most common type of hazards during such testing often comes in the form of slips, trips, and falls. These hazards are prevalent because they can arise from a variety of sources, making nearly anyone involved in the testing susceptible. Slips, trips, and falls can result from wet or uneven surfaces, poorly marked walkways, or improper use of equipment. To prevent these incidents, it is crucial to implement effective prevention practices. Maintaining a dry and clutter-free workplace, clearly marking all walkways and passages, providing proper training for equipment use, and installing safety railings along elevated walkways are key measures. By identifying and addressing these common safety hazards, employee safety can be significantly improved while reducing the risk of injuries.

5. Activity Plan

5.1. Project Management Approach

Aside from the personnel already assigned roles in Team 9, the C.H.I.L.L.Y mission requires a team of approximately 26-31 personnel at any given point in the mission timeline. This theorized team includes 7 Science Personnel, 7-10 Engineering Personnel, 7-10 Technicians, 2-4 Administration Personnel, and 2 Management Personnel. To better delegate tasks in the broader team for the C.H.I.L.L.Y mission, Team 9 has decided to utilize the existing subteams of Science, Programmatics, and Engineering as well as the role of the project manager and expand on the roles outlined within the subteams to ensure the work each team member is responsible for is clearly outlined. The delegation of the new roles for each sub-team can be found below:

1. Project Manager - The role of the project manager in the expanded mission team is relatively the same. This role includes overseeing the entire mission, coordinating with stakeholders and sub-teams, and managing schedules and budgets within the scope of the mission.
2. Science - Responsible for the research and analysis tasks. Responsibilities include researching mission requirements, selecting necessary instruments, and analyzing related data. All science personnel report to the Chief Scientist. The expanded mission team will include the following roles within the sub-team
    a. Chief Scientist - Leads the research efforts of the science team and is responsible for the definition of scientific goals necessary for the mission. Reports to the project manager in order to ensure alignment of the sub-team with the overall mission objectives.

    b. Research Analysts - Conduct in-depth studies during mission duration and are responsible for data collection and insight on collected materials.
    c. Instrument Selection Experts - Responsible for maintenance and calibration of selected science instrumentation (GPR and NIRVSS). Also responsible for testing pertaining to science instrumentation.
    d. Data Scientists - Responsible for the processing and interpretation of collected data. This team reports to the Chief Scientist.
3. Programmatics - Responsible for overseeing the schedule, cost, and outreach of the mission. Handles tasks related to the mission's timeline and budget. The primary method of communication between the Project Manager and the other sub-teams. All members of the Programmatics team report to the Deputy Project Manager of Resources.
    a. Deputy Project Manager of Resources - Responsible for the confirmation of all tasks relating to the schedule, cost, and outreach of the mission. The deputy project manager reports directly to the project manager with any updates on the mission and also is heavily involved with the process of communication with stakeholders and sub-team leads.
    b. Outreach Specialists - Responsible for the coordination of the team's outreach plan including, but not limited to, travel, merchandise, guest speakers, and other important aspects of the outreach program.
    c. Finance Managers - Handles the financial aspects of the mission. Responsible for coordinating with manufacturers and contractors to create cost estimates and manage purchases made within the scope of the mission.
    d. Scheduling Coordinator - Handles the updating of the mission schedule as well as the verification of deadlines and other critical dates with sub-team leads and stakeholders. Also responsible for team communication about deadlines and availability as well as record keeping and documentation.
4. Engineering - In charge of mission design, problem-solving, and documenting the design process. Engineering tasks include conducting first-order analysis to meet technical requirements, developing solution plans based on research, designing prototypes for science instruments, creating CAD models, and tracking budgets and milestones. All Engineering members report to the Lead Systems Engineer.
    a. Lead Systems Engineer - Responsible for the coordination of subsystems and ensuring the seamless integration of each subsystem and model into the overall design of the mission vehicle. Responsible for communication with each specialization lead.
    b. Mission Design Engineers (MDE) - Responsible for the definition of the overall mission architecture and the verification of the technical feasibility

of the mission. Each engineering specialization will have a mission design engineer as its lead as listed below.

   i. Mechanical MDE - Responsible for overseeing the mechanical subsystem and the implementation of the necessary technology required to align with the mission objectives.
   ii. Electrical MDE - Responsible for overseeing the Power Subsystem and the implementation of the necessary technology required to align with the mission objectives.
   iii. Thermal MDE - Responsible for overseeing the Thermal Control Subsystem and the implementation of the necessary technology required to align with the mission objectives.
   iv. Computer Hardware MDE - Responsible for overseeing the Comms and Nav Subsystems and the implementation of the necessary technology required to align with the mission objectives.

c. Systems Engineers - Serve as the subteam of specialized engineers under the mission of Design Engineers that focus on the manufacturing and validation of subsystems. Each category of MDE has its own subteam of system engineers.
d. CAD Modelers - Serves as the primary design team for the engineering team. Design the initial fabrications of necessary machinery and the overall mission vehicle for prototyping.

Budget Handling within this reorganized mission team will be dedicated primarily to the Programmatics team with the Deputy Project Manager of Resources handling the allocation of the budget to each subteam. After the budget is allocated all responsibility of management within sub-teams falls to the sub-team lead. The following chart depicts the Organizational chart of the full mission team.

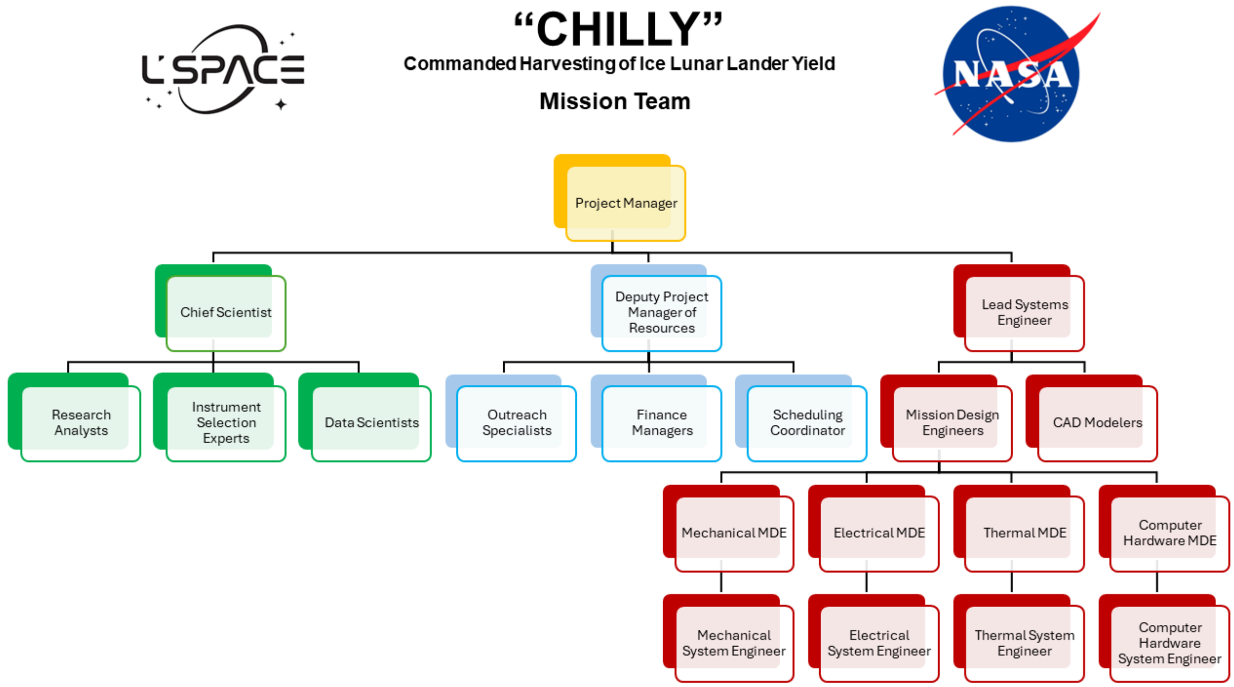

Figure 20. *Full Mission Team Organizational Chart*

5.2. Mission Schedule

5.2.1. Schedule Basis of Estimate

When creating the schedule for Team 9's mission, data was compiled from various sources to make tasks that best aligned with the mission's goals and the critical tasks that needed to be accomplished within the mission's lifespan. When viewing the schedule and understanding the reasoning behind the choices made for the task description and duration, three main fundamental aspects of the schedule need to be considered:

1. Ground Rules
   a. This schedule begins after the presentation of Team 9's PDR on August 25, 2024. Immediately after the completion of the PDR the first phase of the schedule is assumed to start and all given time frames are expected to be followed.
   b. This schedule follows the standard year calendar year (January 1 to December 31) as opposed to the fiscal year. This calendar format better

aligns with the set dates the schedule needs to adhere to and is based on the operational and logistical needs of the project.

c. This schedule utilizes NASA's VIPER mission timeline as an analog for many of its major phases and tasks. VIPER was chosen due to its striking similarities to Team 9's current mission giving the schedule a similar modern mission to base itself on.[54]
d. Initial fabrication and construction of many of the mission vehicle subsystems will be started as soon as the schedule begins with margins being placed in the schedule to align with any sudden changes or important documentation that must be completed.

2. Assumptions
    a. This schedule is assumed to include any additional or necessary testing for a required subsystem or component to meet the desired TRL. This assumption is based on previous mission data and test results that indicate that TRL levels that require testing are allocated in the mission schedule.[48][59] This is seen during Phase D of the mission where all testing is prioritized per subsystem and based on the desired TRL levels specified by the Engineering and Science teams.
    b. This schedule assumes that all necessary resources (personnel, materials, and facilities) will be available by the required times. This assumption is based on Team 9's trade studies which outline the estimated duration of manufacturing for many of the components as well as the data of previous NASA missions.[29] This is seen in the delegation of tasks to subteams as well as the full team org chart for Team 9.
3. Constraints
    a. All key dates listed in the schedule must align with the necessary hard deadlines of the mission required by stakeholders and management.

5.2.2. Mission Schedule

Following the completion of Phases A-B, Team 9's focus will shift to the completion of the mission vehicle for its scheduled launch on September 1st, 2028 from Cape Canaveral adjacent to the Kennedy Space Center. To meet this requirement and have the vehicle fully tested and prepared by the desired time, the schedule overview found in Table # consists of concrete phases and subtasks based on historical mission data that need to be ideally completed in the given period for the entire mission to go as smoothly as possible. [54]

The description of each phase following Phases A-B and what it entails for each subsystem of the mission vehicle can be found below in order of ID #:

1. Phase C: Final Design and Fabrication - This phase begins after the presentation of the team's PDR on the date of August 25, 2024. This task is divided into subtasks pertaining to the completion of each subsystem and concludes with the finalization of construction/software development and the writing of the CDR. Each subsystem is allocated an approximately 70-day period for tasks pertaining to construction to be completed.
    a. Mechanical Subsystem: This phase includes the total construction of the mechanical subsystem including the 7050 Aluminum Alloy chassis as a frame for the vehicle, the multi-layer aerogel insulation found within the chassis for passive thermal insulation, the Maxon wheel motors, the sheet metal wheels, and the drill and mechanical arm found on the body of the mission vehicle. Phase C of this design also includes initial testing and verification of the vehicle body and its mass and dimensions to ensure it aligns with the specifications.
    b. Power Subsystem: This phase also includes the construction and verification of the power subsystem starting with the primary power system of the solar panels and solar cells and concluding with the backup power system of battery cells. Phase C also includes the integration of the Power Distribution Unit (PDU) of the subsystem in order to accurately power the rest of the vehicle.
    c. Thermal Control Subsystem: Phase C includes the construction of both the passive and active thermal control systems of the mission vehicle. This schedule allocates time to each important aspect of the thermal system with time being dedicated to the aerogel and PCMs, Alumunized Multi-Layer Insulation, Electric Heaters, and Thermally Actuate Louvers for heat release.
    d. Communication and Navigation Subsystems: Phase C includes the construction and validation of all necessary high-gain and low-gain antennas for the communication system as well as the integration of the main operating system and CPU through driver communication and software.
    e. Science Instrumentation: Phase C includes the integration of both selected science instrumentation needed to achieve the science goals of the mission with time being allocated to the assembly, validation, and calibration of the Strata Ground Penetrating Radar and NIRVSS.
2. Phase D: System Assembly, Integration, and Test - This phase is designed to test the mission vehicle against the simulated harsh conditions of the lunar landing sight to ensure stability and implement any needed improvements to the vehicle with each subsystem getting specialized testing environments at the Ames

Research Center allocated with an approximate 10 day setup time and 140 day execution time.

    a. Mechanical Subsystem: Time is allocated to the testing of the mechanical subsystem in an environment set up with the lunar terrain of the Leibnitz Beta Plateau to ensure the stability of the vehicle in harsh conditions.
    b. Power Subsystem: The power subsystem is scheduled to be tested in a simulated PSR to evaluate the functionality of the solar panels and the battery system even in environments with little to no sunlight to ensure vehicle operation even when conditions are not optimal.
    c. Thermal Control Subsystem: The thermal control subsystem is scheduled to be tested in simulated harsh weather conditions similar to temperatures found in the Leibnitz Beta Plateau to test the ability of the mission vehicle to stay at operational temperature levels despite harsh conditions.
    d. Communication and Navigation Subsystem: The communication and navigation subsystems are scheduled to be tested with long-range communication to ensure that the mission vehicle can be operated even from the surface of the moon.
    e. Science Instrumentation: Science instrumentation is scheduled to be tested using simulated experiments that are necessary to confirm the accuracy of the instrumentation for the required data.

3. Phase D: Test Launch - This phase is designed to test a simulated launch day experiment to analyze how the mission vehicle handles the launch and weather conditions of Cape Canaveral and validate its upcoming final launch.
4. Phase D: Launch Preparation and Travel - This phase prepares the mission vehicle for launch in Cape Canaveral and includes the transport of important materials and personnel to the landing sight for validation and later launch viewing.
5. Phase D: Launch - This phase includes the final launch of the vehicle from Cape Canaveral on September 1, 2028, and the analysis of the mission as it departs to the Moon after launch. The mission vehicle is expected to land in the Leibnitz Beta Plateau approximately 4-5 days after launch by September 6, 2028.
6. Phase E: Operations and Sustainment - This phase monitors the mission vehicle while it is performing its mission task on the surface of the moon while also ensuring proper operation and sustainment of the vehicle for the duration of the mission period. The vehicle is expected to conclude its research by January 24, 2029, completing the desired 20-week period by the team.
7. Phase F: Closeout - This phase includes the return and retrieval of data from the mission for the team to analyze and draw conclusions from. The mission is expected to be completed 40 weeks after return and will conclude with the final mission report.

Table 38. *Schedule Overview*

ID#	PHASE	ASSIGNED TO	START	END	DAYS
1	**Phase C: Final Design and Fabrication**		8/25/24	7/26/26	701
1.1	Finalize Vehicle Design and obtain approval	Admin/Engineering	8/25/24	9/29/24	36
1.2	Construction of Subsystems	Mechanical/Engineering	11/4/24	2/1/26	455
1.90	Schedule Margin		2/2/26	2/9/26	8
1.10	Finalize Construction and Software Development	All Teams	2/10/26	5/24/26	104
1.11	◆Conduct and Present CDR	All Teams	5/25/26	7/26/26	63
2	**Phase D:System Assembly, Integration and Test**		7/27/26	6/22/27	331
2.3	Conduct Environmental Testing	All Teams	7/27/26	3/4/27	221
2.4	Schedule Margin		3/4/27	3/11/27	8
2.5	Analyze Test Results	All Teams	3/12/27	4/11/27	31
2.6	◆Implement Improvements and Prepare for Test Launch	All Teams	4/12/27	6/22/27	72
3	**Phase D: Test Launch**		4/12/27	8/20/28	497
3.1	Coordinate Logistics	Admin	4/12/27	4/19/27	8
3.2	Final Vehicle Verification	All Teams	4/20/27	6/9/27	51
3.3	Schedule Margin		6/9/27	6/16/27	8
3.4	Transport to Launch Site	All Teams	6/17/27	6/30/27	14
3.5	Initial Test Launch	All Teams	7/1/27	7/15/27	15
3.6	◆ Perform Final Modifications and Prepare for Launch Day	All Teams	7/15/27	8/20/28	403

4	**Phase D: Launch Preparation and Travel**		8/21/28	9/1/28	12
4.1	Travel to Cape Canaveral	Science, Engineering	8/21/28	8/28/28	8
4.2	◆Launch Day	Science, Engineering	8/28/28	9/1/28	5
5	**Phase D: Launch**		9/1/28	9/6/28	6
5.1	Initial Launch	All Teams	9/1/28	9/1/28	1
5.2	Monitor Flight Path	All Teams	9/1/28	9/4/28	4
5.3	◆Estimated Landing on Selected Site	All Teams	9/5/28	9/6/28	2
6	**Phase E: Operations and Sustainment**		9/6/28	1/24/29	141
6.1	Monitor Landing and Vehicle Stability	Mechanical, Software	9/6/28	9/13/28	8
6.2	Conduct Lunar Surface Explorations	Science, Engineering	9/13/28	1/20/29	130
6.3	Monitor Vehicle Health	Mechanical, Software	9/13/28	1/20/29	130
6.4	◆Conduct water-ice experiments on Lunar Surface	Science, Engineering, Software	9/13/28	1/20/29	130
6.5	Schedule Margin		1/20/29	1/24/29	5
7	**Phase F: Closeout**		1/25/29	11/1/29	281
7.1	Prepare Vehicle for return journey	All Teams	1/25/29	2/19/29	26
7.4	Schedule Margin		2/19/29	2/25/29	7
7.6	Analyze Mission Data	All Teams	2/26/29	8/27/29	183
7.7	◆Prepare and Present detailed mission report	All Teams	8/28/29	11/1/29	66

Additionally, the detailed schedule found in Table 39 (see page below) provides a detailed description of not only the concrete phases and subtasks but also the breakdown of the tasks within each subtask in the form of a complete Gantt Chart for presentation:

Table 39. *Detailed Schedule*

ID#	PHASE	ASSIGNED TO	START	END	DAYS	Margin
1	**Phase C: Final Design and Fabrication**		8/25/24	7/26/26	701	8
1.1	Finalize Vehicle Design and obtain approval	Admin/Engineering	8/25/24	9/29/24	36	
1.2	Construction of Mechanical Subsystem	Mechanical/Engineering	11/4/24	1/13/25	71	
1.2.1	Fabrication and Design of 7050 Aluminum Alloy Chassis	Mechanical/Engineering	11/4/24	11/17/24	14	
1.2.2	Verify Structural Stability of Chassis	Mechanical/Engineering	11/18/24	11/25/24	8	
1.2.3	Fabrication of multi-layer aerogel composites for rover body	Science/Engineering	11/25/24	12/8/24	14	
1.2.4	Fabrication of Maxon EC-4pole 30 in-wheel motors and sheet metal wheels	Mechanical/Engineering	12/8/24	12/21/24	14	
1.2.5	Verify wheel specifications and motor power	Mechanical/Engineering	12/22/24	12/29/24	8	

1.2.6	Fabrication of Honeybee Robotics Nano Drill	Mechanical/Engineering	12/30/24	1/6/25	8	
1.2.7	Verification of Drill mass and dimensions	Mechanical/Engineering	1/6/25	1/8/25	3	
1.2.8	Fabrication of Maxar Space Systems Mechanical Arm	Mechanical/Engineering	1/8/25	1/13/25	6	
1.3	Construction of Power Subsystem	Electrical/Engineering	1/14/25	3/24/25	70	
1.3.1	Fabrication of Solar Cells and Anti-Reflective Coating	Electrical/Engineering	1/14/25	1/27/25	14	
1.3.2	Fabrication of Solar Panel Structure and Deployable Mechanism	Electrical/Engineering	1/27/25	2/9/25	14	
1.3.3	Verification of Solar Panel Integration	Electrical/Engineering	2/9/25	2/11/25	3	
1.3.4	Development of Battery Cells and Battery Management System (BMS)	Electrical/Engineering	2/11/25	3/2/25	20	
1.3.5	Construction of Power Distribution Unit (PDU)	Electrical/Engineering	3/3/25	3/16/25	14	

1.3.6	Integration of PDU into the mission vehicle	Electrical/Engineering	3/16/25	3/24/25	9	
1.4	Construction of Thermal Control Subsystem	Science/Engineering	3/25/25	6/2/25	70	
1.4.1	Development of Aerogel and Phase Change Materials(PCMs)	Science/Engineering	3/25/25	4/2/25	9	
1.4.2	Integration of PCMs and Low Absopritivty Paint	Science/Engineering	4/2/25	4/17/25	16	
1.4.3	Development of Outer and Interior Aluminized Multi-Layer Insulation (MLI)	Science/Engineering	4/18/25	5/1/25	14	
1.4.4	Development of Laminated Inner Cover and Netted separators	Science/Engineering	5/2/25	5/17/25	16	
1.4.5	Development of Active Thermal Control Electric Heaters	Science/Engineering	5/18/25	5/28/25	11	
1.4.6	Integration of Thermally Actuated Louvers	Science/Engineering	5/29/25	6/2/25	5	
1.5	Construction of Comms & Nav Subsystems	Software/Engineering	6/3/25	8/10/25	69	

1.5.1	Telemetry Software Integration and Hardware Setup	Software/Engineering	6/3/25	6/17/25	15	
1.5.2	Development of Low Gain and High Gain Antennas	Software/Engineering	6/18/25	7/3/25	16	
1.5.3	Integration of Onboard CPU and Operating System	Software/Engineering	7/3/25	7/19/25	17	
1.5.4	Integration of Non-Volatile and Volatile Storage	Software/Engineering	7/20/25	8/4/25	16	
1.5.5	Application and Execution Layer Software Installation	Software/Engineering	8/5/25	8/10/25	6	
1.6	Construction of Science Instrumentation	Science	8/11/25	10/18/25	69	
1.6.1	Assembly of Strata Ground Penetrating Radar (GPR)	Science	8/11/25	8/27/25	17	
1.6.2	Calibration of Strata GPR	Science	8/28/25	9/2/25	6	
1.6.3	Integration of Strata GPR with Rover Software	Science	9/2/25	9/9/25	8	
1.6.4	Assembly of Near Infrared Volatile Spectrometer System (NIRVSS)	Science	9/10/25	9/25/25	16	

1.6.5	Calibration of NIRVSS and Verification of Infrared Lamp	Science	9/26/25	10/9/25	14	
1.6.6	Integration of NIRVSS with Rover Software	Science	10/10/25	10/18/25	9	
1.80	Complete Hardware + Software Verification of Subsystems	All Teams	10/19/25	2/1/26	106	
1.90	Schedule Margin		2/2/26	2/9/26	8	
1.10	Finalize Construction and Software Development	All Teams	2/10/26	5/24/26	104	
1.11	◆Conduct and Present CDR	All Teams	5/25/26	7/26/26	63	
2	**Phase D:System Assembly, Integration and Test**		7/27/26	6/22/27	331	8
2.1	Develop Testing Protocols	Admin	7/27/26	8/26/26	32	
2.1.1	Flight and Analysis of Testing Facilities at Ames Research Center	Admin	7/26/26	8/12/26	18	
2.1.2	Transportation of Materials to Testing Facilities	Admin	8/13/26	8/26/26	14	
2.2	Prepare Testing Environment	Science/Engineering	8/27/26	10/14/26	49	

2.2.1	Prepare PSR Testing for Solar Panels and Battery System	Electrical/Engineering	8/27/26	9/5/26	10	
2.2.2	Prepare Leibnitz Beta Plateau Weather Testing for Thermal Subsystem	Science/Engineering	9/6/26	9/15/26	10	
2.2.3	Prepare Lunar Terrain Testing for Mechanical Subsystem	Mechanical/Engineering	9/16/26	9/25/26	10	
2.2.4	Prepare Experimental Testing for accuracy of Science Instrumentation	Science	9/26/26	10/5/26	10	
2.2.5	Prepare Long Range Communication Testing for Comms and Data Handling Subsystem	Softwatre/Engineering	10/6/26	10/14/26	9	
2.3	Conduct Environmental Testing	All Teams	10/15/26	3/4/27	141	
2.4	Schedule Margin		3/4/27	3/11/27	8	
2.5	Analyze Test Results	All Teams	3/12/27	4/11/27	31	
2.6	◆Implement Improvements and Prepare for Test Launch	All Teams	4/12/27	6/22/27	72	
3	**Phase D: Test Launch**		4/12/27	8/20/28	497	8

3.1	Coordinate Logistics	Admin	4/12/27	4/19/27	8	
3.1.1	Analyze Launch Site	Admin	4/12/27	4/15/27	4	
3.1.2	Confirm Weather Conditons in Cape Canaveral	Admin	4/16/27	4/19/27	4	
3.2	Final Vehicle Verification	All Teams	4/20/27	6/9/27	51	
3.3	Schedule Margin		6/9/27	6/16/27	8	
3.4	Transport to Launch Site	All Teams	6/17/27	6/30/27	14	
3.4.1	Personnel Travel to Cape Canaveral	All Teams	6/17/27	6/24/27	8	
3.4.2	Material Transportation to Cape Canaveral	All Teams	6/24/27	6/30/27	7	
3.5	Initial Test Launch	All Teams	7/1/27	7/15/27	15	
3.6	◆ Perform Final Modifications and Prepare for Launch Day	All Teams	7/15/27	8/20/28	403	
4	**Phase D: Launch Preparation and Travel**		8/21/28	9/1/28	12	0
4.1	Travel to Cape Canaveral	Science, Engineering	8/21/28	8/28/28	8	
4.1.1	Personnel Travel to Cape Canaveral	All Teams	8/21/28	8/23/28	3	

4.1.2	Material Transportation to Cape Canaveral	All Teams	8/24/28	8/28/28	5	
4.2	◆Launch Day	Science, Engineering	8/28/28	9/1/28	5	
5	**Phase D: Launch**		9/1/28	9/6/28	6	0
5.1	Initial Launch	All Teams	9/1/28	9/1/28	1	
5.2	Monitor Flight Path	All Teams	9/1/28	9/4/28	4	
5.2.1	Ensure Landing in Leibnitz Beta Plateau	All Teams	9/1/28	9/4/28	4	
5.3	◆Estimated Landing on Selected Site	All Teams	9/5/28	9/6/28	2	
6	**Phase E: Operations and Sustainment**		9/6/28	1/24/29	141	5
6.1	Monitor Landing and Vehicle Stability	Mechanical, Software	9/6/28	9/13/28	8	
6.1.1	Ensure operation of vehicle motors and instrumentation	Mechanical, Software	9/6/28	9/10/28	5	
6.1.2	Verify Structural Stability of Chasis	Mechanical, Software	9/10/28	9/13/28	4	
6.2	Conduct Lunar Surface Explorations	Science, Engineering	9/13/28	1/20/29	130	
6.2.1	Deploy GPR and NIRVSS	Science, Engineering	9/13/28	9/20/28	8	

6.2.2	Begin Data Collection using Science Instrumentation	Science, Engineering	9/20/28	10/1/28	12	
6.2.3	Perform Intial Data Analysis to confirm functionality and accuracy	Science, Engineering, Software	10/2/28	10/15/28	14	
6.2.4	Continue Exploration/Data Colelction	Science, Engineering	10/16/28	1/20/29	97	
6.3	Monitor Vehicle Health	Mechanical, Software	9/13/28	1/20/29	130	
6.4	◆Conduct water-ice experiments on Lunar Surface	Science, Engineering, Software	9/13/28	1/20/29	130	
6.5	Schedule Margin		1/20/29	1/24/29	5	
7	**Phase F: Closeout**		1/25/29	11/1/29	281	7
7.1	Prepare Vehicle for return journey	All Teams	1/25/29	2/8/29	15	
7.1.1	Ensure Full Vehicle Operation	All Teams	1/25/29	1/31/29	7	
7.1.2	Verify Data Collection and Communication	All Teams	2/1/29	2/8/29	8	
7.2	Monitor Return to Earth	All Teams	2/8/29	2/18/29	11	
7.3	Ensure Safe Re-entry	All Teams	2/18/29	2/19/29	2	

7.4	Schedule Margin		2/19/29	2/25/29	7	
7.5	Retrieve Data from Mission Vehicle	All Teams	2/26/29	4/8/29	43	
7.6	Analyze Mission Data	All Teams	4/9/29	8/27/29	141	
7.7	◆Prepare and Present detailed mission report	All Teams	8/28/29	11/1/29	66	

5.3. Budget

5.3.1. Budget Basis of Estimate

When arriving at the total cost of $173,727,456 for the mission, data from previous missions as well as real-world travel, materials, and inflation data was compiled to create the most accurate calculation of Team 9’s mission budget following the budget cut. When viewing the mission budget and understanding the reasoning behind the choices made for certain aspects of the cost and its subsections, three fundamental aspects of our budget need to be considered:

1. Ground Rules
    a. The budget begins at phase C of the NASA Mission Life Cycle Timeline and aligns with Team 9’s mission schedule of starting after the presentation of the team’s PDR on the date of August 25, 2024. This alignment is crucial as it ensures that the budget directly corresponds to the mission's active development stages, allowing for accurate forecasting of costs associated with design finalization, hardware development, and early testing phases.
    b. This budget follows 5 years of the mission starting in 2024 with Phase C of the NASA Mission Life Cycle Timeline and ending in 2029 with Phase F of the NASA Mission Life Cycle Timeline as required. Using this set time frame following the completion of the PDR allows the mission budget to have a clear structure for financial planning.
    c. The total project cost of $173,727,456 was calculated using the sum of each major field of the mission budget including personnel costs, travel costs, outreach costs, direct costs, and facilities and administrative costs. Using this holistic approach to calculating the cost of this mission ensures all aspects are properly covered and all possible expenses can be efficiently managed and monitored.
    d. All costs for subsystems were derived from the Team 9 subsystems outlined in the MDR, SRR, and MCR allowing for a consistent estimate of all subsystem costs as the mission evolves and the technical requirements are met.
    e. The total amount of personnel on the team is recalculated every fiscal year of the mission as opposed to the calendar year to better align with budget reports and other government-level economic reports ensuring that the budget reflects actual economic conditions and trends.
2. Assumptions

a. An inflation rate of 2.6% per year was assumed based on the NASA standard as found in the NASA New Start Inflation Index.[38] Using this inflation rate increase per year allowed the costs estimated to accurately reflect the projected amount in 2024 USD by the end of the mission.
b. All travel accommodation costs for team members we based on the Per Diem rates provided by the United States General Services Administration and were integrated into the budget per traveling team member.[20] Using this estimation allowed for a set rate to be allocated to the travel of team members based on actual government estimations.
c. Outreach costs were calculated using a blend of data from large-scale missions such as Artemis and costs of facilities and venues in areas close to the launch site in Cape Canaveral and other areas of interest allowing for a more accurate approximation of how much money should be accommodated to outreach.[10]
d. All flight costs were calculated using business-class flights from the nearest airport to Pasadena, California, the city of the NASA Jet Propulsion Laboratory which is the furthest NASA facility from Cape Canaveral in the continental United States. This allows for the most extreme travel costs to be considered in the budget allowing for possible leeway in actual mission execution.
e. Testing and Manufacturing Facility costs were estimated using a combination of parametric estimations sourced from the NICM Version 9c as well as data on existing NASA testing facilities and their costs of maintenance/upkeep.[27][35] This allowed for the mission to not only rely on the construction of new facilities for testing but also save time by utilizing already constructed facilities that met the needs of the mission significantly reducing costs.
f. Team size throughout the mission will range from 26-31 members depending on the requirements of the mission at the time as outlined by the NASA Mission Life Cycle Timeline and Team 9's schedule. This varying team size will not only allow for a more flexible budget at certain stages of the mission but also allow for "effective team composition" as researched by NASA psychologists from DePaul University.[8]

3. Constraints
    a. The total mission cost shall not exceed the given budget cap of $175,000,000.
    b. Travel costs during the time of launch must include the transport of the entire team and necessary materials.
    c. The total mission cost must encompass all years of the mission after the beginning of Phase C of the NASA Mission Life Cycle Timeline.

d. Salary costs are set at constant values as outlined by the Mission Task document.

5.3.2. Total Mission Cost

The mission cost of Team 9’s C.H.I.L.L.Y mission totals a final cost of $173,727,456. This total cost includes all significant factors in the mission budget including:

1. Personnel Costs: $15,272,146
2. Travel Costs: $1,378,129
3. Outreach Costs: $3,109,350
4. Direct Costs: $146,675,213
5. Facilities and Administrative Costs: $7,292,619

To properly present this cost per mission phase and include all relevant expenses in one table, Team 9 has organized the budget into a comprehensive breakdown by phase. The following table provides a detailed summary of the total mission costs, categorized by the specific phases of the NASA Mission Life Cycle:

Table 40. *Full Budget Table*

NASA L'SPACE Mission Concept Academy Budget - *C.H.I.L.L.Y.*						
Mission Phase	**Phase C**	**Phase C-D**	**Phase D**	**Phase E-F**	**Phase F**	
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Cumulative Total**
PERSONNEL						
Science Personnel	$ 560,000	$ 589,120	$ 603,680	$ 618,240	$ 632,800	$ 3,003,840
Engineering Personnel	$ 800,000	$ 841,600	$ 603,680	$ 618,240	$ 632,800	$ 3,496,320
Technicians	$ 420,000	$ 631,200	$ 452,760	$ 463,680	$ 474,600	$ 2,442,240
Administration Personnel	$ 120,000	$ 126,240	$ 194,040	$ 264,960	$ 271,200	$ 976,440
Project Management	$ 240,000	$ 252,480	$ 258,720	$ 264,960	$ 271,200	$ 1,287,360
Total Salaries	$ 2,140,000	$ 2,440,640	$ 2,112,880	$ 2,230,080	$ 2,282,600	**$ 11,206,200**
Total ERE	$ 597,274	$ 681,183	$ 589,705	$ 622,415	$ 637,074	**$ 3,127,650**
Personnel Margin	$ 179,182	$ 204,355	$ 176,911	$ 186,725	$ 191,122	**$ 938,295**
TOTAL PERSONNEL	$ 2,916,456	$ 3,326,177	$ 2,879,496	$ 3,039,220	$ 3,110,796	**$ 15,272,146**
TRAVEL						
Total Flights Cost	$ -	$ 22,800	$ 148,200	$ 153,900	$ 153,900	**$ 478,800**

Total Hotel Cost	$ -	$ 19,400	$ 126,100	$ 130,950	$ 130,950	**$ 407,400**
Total Transportation Cost	$ -	$ 13,000	$ 84,500	$ 87,750	$ 87,750	**$ 273,000**
Total Per Diem Cost	$ -	$ 4,360	$ 28,340	$ 29,430	$ 29,430	**$ 91,560**
Travel Margin	$ -	$ 9,399	$ 62,601	$ 66,576	$ 68,144	**$ 206,719**
Total Travel Costs	$ -	$ 62,657	$ 417,337	$ 443,841	$ 454,294	**$ 1,378,129**
OUTREACH						
Total Outreach Materials	$ -	$ -	$ 300,000	$ 300,000	$ -	**$ 600,000**
Total Outreach Venue Costs	$ -	$ -	$ 150,000	$ 150,000	$ -	**$ 300,000**
Total Outreach Travel Costs	$ -	$ -	$ 250,000	$ 250,000	$ -	**$ 500,000**
Total Outreach Services Costs	$ -	$ -	$ 75,000	$ 75,000	$ -	**$ 150,000**
Total Outreach Personnel Costs	$ -	$ -	$ 500,000	$ 500,000	$ -	**$ 1,000,000**
Outreach Margin	$ -	$ -	$ 150,000	$ 150,000	$ -	**$ 300,000**
Total Outreach Costs	$ -	$ -	$ 1,536,150	$ 1,573,200	$ -	**$ 3,109,350**
DIRECT COSTS						
Mechanical Subsystem	$ 5,016,000	$ 1,482,000	$ 1,482,000	$ 620,000	$ 330,000	**$ 8,930,000**
Power Subsystem	$ 13,200,200	$ 3,390,000	$ 1,150,000	$ 1,800,000	$ 1,480,000	**$ 21,020,200**
Thermal Control Subsystem	$ 1,900,000	$ 200,000	$ 200,000	$ 260,000	$ 80,000	**$ 2,640,000**
Comms & Data Handling Subsystem	$ 7,700,000	$ 2,300,000	$ 2,300,000	$ 1,060,000	$ 290,000	**$ 13,650,000**
Guidance, Nav, & Control Subsystem	$ 600,000	$ 114,000	$ 114,000	$ 160,000	$ 20,000	**$ 1,008,000**
Science Instrumentation	$ 15,400,000	$ 2,840,000	$ 2,840,000	$ 800,000	$ 740,000	**$ 22,620,000**
Spacecraft Cost Margin	$ 21,908,100	$ 5,163,000	$ 4,043,000	$ 2,350,000	$ 1,470,000	**$ 34,934,100**
Total Spacecraft Direct Costs	$ 65,724,300	$ 16,294,428	$ 13,075,062	$ 7,783,200	$ 4,983,300	**$ 107,860,290**
Manufacturing Facility Cost	$ 11,600,000	$ 3,480,000	$ 696,000	$ -	$ -	**$ 15,776,000**

Test Facility Cost	$ 584,000	$ 7,322,000	$ 1,464,400	$ -	$ -	**$ 9,370,400**
Facility Cost Margin	$ 6,092,000	$ 5,401,000	$ 1,080,200	$ -	$ -	**$ 12,573,200**
Total Facilities Costs	$ 18,276,000	$ 17,045,556	$ 3,493,367	$ -	$ -	**$ 38,814,923**
Total Direct Costs	$ 84,000,300	$ 33,339,984	$ 16,568,429	$ 7,783,200	$ 4,983,300	**$ 146,675,213**
Total MTDC	$ 65,724,300	$ 16,294,428	$ 13,075,062	$ 7,783,200	$ 4,983,300	**$ 107,860,290**
FINAL COST CALCULATIONS						
Total F&A	$ 4,381,620	$ 1,113,143	$ 903,206	$ 543,320	$ 351,330	**$ 7,292,619**
Total Projected Cost	$ 91,298,376	$ 37,841,961	$ 22,304,618	$ 13,382,781	$ 8,899,720	**$ 173,727,456**
Total Cost Margin	$ 28,179,282	$ 10,777,753	$ 5,512,712	$ 2,753,301	$ 1,729,266	**$ 48,952,314**
	30.9%	28.5%	24.7%	20.6%	19.4%	
Total Project Cost	$ 91,298,376	$ 37,841,961	$ 22,304,618	$ 13,382,781	$ 8,899,720	**$ 173,727,456**

5.3.3. Personnel Budget

Team 9's Personnel Budget encompasses the salaries and benefits of the 26-31 members found on the mission team at any given phase of the mission. The breakdown of the specific type of personnel in each phase as well as the total number of personnel per phase and the explanation behind the selection can be found below:

Table 41. *Number of Personnel per Phase*

	Phase C	**Phase C-D**	**Phase D**	**Phase E-F**	**Phase F**
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5
Science Personnel:	7	7	7	7	7
Engineering Personnel:	10	10	7	7	7
Technicians:	7	10	7	7	7
Administration Personnel:	2	2	3	4	4
Management Personnel:	2	2	2	2	2
Total Personnel:	28	31	26	27	27

- Phase C: This phase is comprised of 28 total members with a heavy emphasis on engineering personnel given the focus on final design and fabrication being done within Phase C of the NASA Mission Life Cycle Timeline.
    - Science Personnel (7 members): Science personnel will focus on the final fabrication of the science instrumentation (Strata GPR and NIRVSS). Science personnel will also be expected to collaborate with engineers to ensure scientific instruments meet the required specifications and conduct preliminary tests on instrumentation to ensure functionality.
    - Engineering Personnel (10 members): Responsible for finalizing the design and fabrication of the mission chassis. The team will be focusing on every relevant subsystem as per the schedule plan while also overseeing the fabrication process to ensure all components are built to the specifications desired through CAD and other technical diagrams.
    - Technicians (7 members): Assist in the fabrication of subsystems and instrumentations and perform hands-on work with the hardware and assembly of components and subsystems.
    - Administration/Management (4 members): Oversees the design process of the mission vehicle and ensure the project's alignment with the schedule. Primarily focused on finalizing the CDR.
- Phase C-D: This phase is the largest phase of the mission in terms of personnel quantity with 31 total members. This phase focuses on the transition from the completion of the CDR to the final design/fabrication to the actual assembly and integration of the subsystems into the final mission vehicle.
    - Science Personnel (7 members): Science personnel will continue to support the integration of science instruments into the mission vehicle and focus on the development of operation procedures for integrated instruments.
    - Engineering Personnel (10 members): Engineering personnel with continue to oversee the final designs and fabrications while also focusing on the assembly and development of drivers and integration necessary for the vehicle subsystems to communicate.
    - Technicians (10 members): Technicians will have an increase in personnel from 7 to 10 members to handle the assembly and initial testing of the rover as well as many of the software aspects needed to make the rover functional and able to communicate.
    - Administration/Management (4 members): Focused primarily on coordinating the transition from the design to the assembly process and managing resource allocation and budgeting to ensure the mission stays within the designated scope.

- Phase D: This phase focuses on the integration and testing of the assembled mission vehicle, which is comprised of 26 members. This phase cuts back on the total amount of engineers and technicians on the team as the focus will be on the verification and testing of the machine with changes only being implemented to the mission vehicle if absolutely necessary.
    - Science Personnel (7 members): Focused on validating the integration of scientific instruments integration into the mission vehicle as well as focusing on the instrumentation accuracy and calibration for testing in the landing site.
    - Engineering Personnel (7 members): Reduced engineering personnel will transition focus from hands-on fabrication and designing to system-level testing to verify the integration of subsystems.
    - Technicians (7 members): Technicians will be reduced from 10 members to 7 as the primary focus will shift to conducting environmental testing for condition simulation as opposed to physical designing and fabrication.
    - Administration/Management (5 members): Administration personnel will see an increase in members in order to begin coordination of launch logistics as well as the management of testing facilities and other resources.
- Phase E: Phase E of the mission focuses on the Operation and Sustainment of the mission vehicle once it launches and reaches the Leibnitz Beta Plateau. This phase increases the administration personnel from 3 to 4 to handle any critical errors or issues that arise during the mission. This phase is also heavily reliant on technicians and science personnel to operate the vehicle and accomplish the desired science objectives of the mission.
    - Science Personnel (7 members): Science personnel will primarily focus on the operation of the vehicle's science instrumentation remotely and ensure property accuracy and calibration when observing water-ice samples.
    - Engineering Personnel (7 members): Engineering personnel will be responsible for monitoring of the vehicle systems to ensure continued functionality throughout the duration of the entire trip as well as troubleshooting any technical issues that arise during the mission and implementing quick fixes.
    - Technicians (7 members): Technicians will provide support to the daily operations of the mission vehicle and perform daily system checks and maintenance remotely and assist with any necessary software updates needed for continued functionality.
    - Administration/Management (6 members): The administration personnel is once again increased to handle critical error management and issue

resolution while reporting to officials and stakeholders while also managing mission documentation and reporting.

- Phase F: Phase F maintains the same amount of personnel as Phase E and focuses on the closeout of the mission with the priority being the retrieval of data from the mission vehicle and the organization of a final mission statement document.
  - Science Personnel (7 members): Science personnel will focus on the retrieval and analysis of final data from the mission vehicles collection tools and begin preparing reports.
  - Engineering Personnel (7 members): Engineering personnel will support the decommissioning of the mission vehicle and its related systems as well as assist in preparing the final technical report.
  - Technicians (7 members): Technicians will begin archiving software and hardware configurations from the mission vehicle and assist in the decommissioning process ensuring all systems are safely shut down.
  - Administration/Management (6 members): The administration personnel is responsible for overseeing the closeout process to ensure all tasks are completed according to schedule as well as the finalization of all mission-related documentation with collaboration from all teams to prepare the final mission report.

The cost estimation of the aforementioned personnel numbers can be found below:

Table 42. *Personnel Budget*

PERSONNEL						
	Phase C	**Phase C-D**	**Phase D**	**Phase E-F**	**Phase F**	**Cumulative Total**
Science Personnel	$ 560,000	$ 589,120	$ 603,680	$ 618,240	$ 632,800	$ 3,003,840
Engineering Personnel	$ 800,000	$ 841,600	$ 603,680	$ 618,240	$ 632,800	$ 3,496,320
Technicians	$ 420,000	$ 631,200	$ 452,760	$ 463,680	$ 474,600	$ 2,442,240
Administration Personnel	$ 120,000	$ 126,240	$ 194,040	$ 264,960	$ 271,200	$ 976,440
Project Management	$ 240,000	$ 252,480	$ 258,720	$ 264,960	$ 271,200	$ 1,287,360
Total Salaries	$ 2,140,000	$ 2,440,640	$ 2,112,880	$ 2,230,080	$ 2,282,600	**$ 11,206,200**
Total ERE	$ 597,274	$ 681,183	$ 589,705	$ 622,415	$ 637,074	**$ 3,127,650**
Personnel Margin	$ 179,182	$ 204,355	$ 176,911	$ 186,725	$ 191,122	**$ 938,295**
TOTAL PERSONNEL	$ 2,916,456	$ 3,326,177	$ 2,879,496	$ 3,039,220	$ 3,110,796	**$ 15,272,146**

These estimations were based on the given salaries and ERE numbers outlined in the Mission Task document which can be found below:

- Salaries
  - Science Personnel: $80,000/yr
  - Engineering Personnel: $80,000/yr
  - Technicians: $60,000/yr
  - Administration Personnel: $60,000/yr
  - Project Management: $120,000/yr
- ERE
  - 28% of total salaries

The inflation rate increase of 2.6% per year was also used to calculate these results.

5.3.4. Travel Budget

Team 9's Travel Budget outlines personnel travel for various reasons travel is necessary throughout the mission duration. The travel breakdown per phase and an explanation of the costs and the reasoning behind them can be found below:

Table 43. *Travel Budget*

TRAVEL						
	Phase C	**Phase C-D**	**Phase D**	**Phase E-F**	**Phase F**	**Cumulative Total**
Total Flights Cost	$ -	$ 22,800	$ 148,200	$ 153,900	$ 153,900	**$ 478,800**
Total Hotel Cost	$ -	$ 19,400	$ 126,100	$ 130,950	$ 130,950	**$ 407,400**
Total Transportation Cost	$ -	$ 13,000	$ 84,500	$ 87,750	$ 87,750	**$ 273,000**
Total Per Diem Cost	$ -	$ 4,360	$ 28,340	$ 29,430	$ 29,430	**$ 91,560**
Travel Margin	$ -	$ 9,399	$ 62,601	$ 66,576	$ 68,144	**$ 206,719**
Total Travel Costs	$ -	$ 62,657	$ 417,337	$ 443,841	$ 454,294	**$ 1,378,129**

- Phase C: With Phase C focusing on the final design and fabrication of the mission vehicle along with the completion of the CDR, no travel is considered necessary in this phase as all work will mostly be done digitally and in-house. The need for no travel is mostly accomplished by the use of remote collaboration and digital tools that allow teamwork and management of the nature of the work in Phase C without the need for physical presence.[50]

- Phase C-D: With the transition from final design and CDR completion to the assembly of subsystems and initial testing happening in this phase, travel costs are included for administration and management personnel to travel to possible manufacturing and testing facilities to validate their usage and check on the progress of the mission vehicle. This cost was calculated using the per diem and business class flight costs for possible facility locations such as the NASA Ames Research Center in Moffett Field, California that could assist with the production of necessary materials such as multi-layer aerogel composites for the thermal system and Aluminum 7050 Alloy for the chassis.[19][18]
- Phase D: Given that Phase D concludes with the final launch of the mission vehicle and also includes the test launch of the system, travel costs for Phase D include the cost of transportation of the entire 26-member team and the mission vehicle and necessary materials to ensure a successful launch which includes the entire mission team.
- Phase E-F: Due to the focus on operations and sustainment along with the return of the vehicle at the conclusion of Phases E-F, travel costs are included to account for the travel and transport of administration personnel to theorized centers of operation for the vehicle such as Ames Research Center (based on analog missions such as VIPER) during its mission duration as well as team travel to Cape Canaveral for the return of the mission vehicle.[19][3]
- Phase F: With Phase F encompassing the closeout of the mission and the necessary documentation and analysis that comes with it, travel costs are included for the entire team to travel to necessary research centers for data analysis as well as travel of administration/management personnel to locations such as NASA Headquarters in Washington, DC to present the findings of the mission.[5]

5.3.5. Outreach Budget

Given the tight budget of this mission and the importance of the science objectives to the understanding of space exploration as a whole, Team 9 decided to allocate the majority of the budget to the mission vehicle and its maintenance and reserve the community outreach for the later phases of the mission as depicted in Table # below:

Table 44. *Outreach Budget*

OUTREACH						
	Phase C	**Phase C-D**	**Phase D**	**Phase E-F**	**Phase F**	**Cumulative Total**
Total Outreach	$ -	$ -	$ 300,000	$ 300,000	$ -	**$ 600,000**

Materials						
Total Outreach Venue Costs	$ -	$ -	$ 150,000	$ 150,000	$ -	**$ 300,000**
Total Outreach Travel Costs	$ -	$ -	$ 250,000	$ 250,000	$ -	**$ 500,000**
Total Outreach Services Costs	$ -	$ -	$ 75,000	$ 75,000	$ -	**$ 150,000**
Total Outreach Personnel Costs	$ -	$ -	$ 500,000	$ 500,000	$ -	**$ 1,000,000**
Outreach Margin	$ -	$ -	$ 150,000	$ 150,000	$ -	**$ 300,000**
Total Outreach Costs	$ -	$ -	$ 1,536,150	$ 1,573,200	$ -	**$ 3,109,350**

Starting in Phase D of the mission, Team 9 plans to begin outreach efforts to areas with high interest in STEM education such as California, Texas, Massachusetts, Washington, and Colorado and educate individuals of all ages on the mission and its goals. [65] This large goal led to a significant amount of funds being allocated to outreach programs for the mission in its later phases as most of the outreach work will be performed by personnel who will discuss details of the mission and the science objectives it attempts to cover following a format similar to prior NASA missions.[2] A breakdown of each category and its cost estimates can be found below:

- Materials: Given that the outreach program will attempt to cater to all age groups and audiences, a variety of items are expected to be printed and handed out to attendees. These items include flyers and brochures that must be manufactured, designed, and printed, posters to be hung up in event spaces, educational books and pamphlets that explain the mission, and other items such as shirts and stickers that can raise public awareness of the mission and increase youth interest. These items are expected to cost around $300,000 for the entire year including all costs associated with manufacturing, distribution, and designing of the items. This cost was estimated using data from prior NASA missions and offices that specialize in outreach.[55]
- Venue Costs: Given the selection of a high-interest STEM education state as the target for Team 9's outreach program, venues in each of the states such as the Moscone Center in San Fransisco, California, or the George R. Brown Convention Center in Houston, Texas were researched as potential locations to hold the events in each of the selected states. These convention centers, as well as smaller institutions such as local schools, were then researched using comptroller data to find out daily rental costs to estimate the costs needed to properly acquire venues for the events.[30][1] The cost was then taken with

additional added overhead to account for any additional events or costs that may be associated with venues.

- Travel Costs: With the states selected being in varying areas of the United States, travel costs include the travel of any needed personnel and materials (an estimated team of 10-15 per event) on business class flights that ensure the arrival and safety of team members who participate in outreach events. These costs were estimated using the average domestic airline itinerary fares for each of the relevant states' major airports sources from the United States Department of Transportation.[#]
- Services Costs: Relevant services costs for the outreach plan of Team 9 include the compensation of any guest/panel speakers who appear at any of the promotional events as well as any additional contracting with external agencies that intend to speak or support the event. These costs were estimated based on prior NASA missions and offices that specialize in outreach.[55]
- Personnel Costs: Outreach personnel includes any staff on-site at the event along with the payment of local organizers or others who helped make the events possible. These costs are assumed to cover a team of approximately 10 members who will receive an estimated salary of $50,000.

5.3.6. Direct Costs

Team 9's Direct Costs encompass the majority of the project's budget and consist of the costs of all the mission vehicle subsystems and all testing and manufacturing facilities costs associated with them. The total cost of all direct costs across the span of the project sums to $146,675,213. A breakdown of the cost of each subsystem and facility can be found below:

Table 45. *Direct Costs*

DIRECT COSTS						
	Phase C	**Phase C-D**	**Phase D**	**Phase E-F**	**Phase F**	**Cumulative Total**
Mechanical Subsystem	$ 5,016,000	$ 1,482,000	$ 1,482,000	$ 620,000	$ 330,000	**$ 8,930,000**
Power Subsystem	$ 13,200,200	$ 3,390,000	$ 1,150,000	$ 1,800,000	$ 1,480,000	**$ 21,020,200**
Thermal Control Subsystem	$ 1,900,000	$ 200,000	$ 200,000	$ 260,000	$ 80,000	**$ 2,640,000**
Comms & Data	$ 7,700,000	$ 2,300,000	$ 2,300,000	$ 1,060,000	$ 290,000	**$ 13,650,000**

Handling Subsystem						
Guidance, Nav, & Control Subsystem	$ 600,000	$ 114,000	$ 114,000	$ 160,000	$ 20,000	**$ 1,008,000**
Science Instrumentation	$ 15,400,000	$ 2,840,000	$ 2,840,000	$ 800,000	$ 740,000	**$ 22,620,000**
Spacecraft Cost Margin	$ 21,908,100	$ 5,163,000	$ 4,043,000	$ 2,350,000	$ 1,470,000	**$ 34,934,100**
Total Spacecraft Direct Costs	$ 65,724,300	$ 16,294,428	$ 13,075,062	$ 7,783,200	$ 4,983,300	**$ 107,860,290**
Manufacturing Facility Cost	$ 11,600,000	$ 3,480,000	$ 696,000	$ -	$ -	**$ 15,776,000**
Test Facility Cost	$ 584,000	$ 7,322,000	$ 1,464,400	$ -	$ -	**$ 9,370,400**
Facility Cost Margin	$ 6,092,000	$ 5,401,000	$ 1,080,200	$ -	$ -	**$ 12,573,200**
Total Facilities Costs	$ 18,276,000	$ 17,045,556	$ 3,493,367	$ -	$ -	**$ 38,814,923**
Total Direct Costs	$ 84,000,300	$ 33,339,984	$ 16,568,429	$ 7,783,200	$ 4,983,300	**$ 146,675,213**
Total MTDC	$ 65,724,300	$ 16,294,428	$ 13,075,062	$ 7,783,200	$ 4,983,300	**$ 107,860,290**

1. Mechanical Subsystem - The costs of the mechanical subsystem totals $8,390,000. This total cost was initially calculated parametrically using the Mechanical/Structures Subsystem Model CER found in NCIM Version 9c.[26] This cost was estimated by finding the total mass of the Mechanical subsystem (Approx. 10 kg) and the max power draw of the mechanical subsystem (Approx. 45 W) from Team 9's specified system. After making this initial cost estimation, the real-world cost of known components from manufacturers such as the Maxon Ec-4pole wheel motors (~ $1000 per unit) and the price of components found in analog missions such as VIPER were factored into the estimation to create the final value.[15][49] This cost was then broken into components and assigned to the relevant phases of the mission where the portion of the cost was relevant. A description of each phase and the reasoning behind the cost allocation is described below.
    a. Phase C ($5,016,000) - Contains the approximate costs of all the instruments and manufacturing costs of the materials used in the mechanical subsystem such as 7050 Aluminium Alloy and Multi-Layer Aerogel found in the chassis of the mission vehicle. This phase encompasses 56% of the total cost of the subsystem as it includes the

majority of the necessary costs for the production of the subsystem as seen in the schedule estimate for phase C.

   b. Phase C-D ($1,482,000) - Contains the Integration and testing costs of the subsystem. This cost encompasses all costs associated with any repairs or software costs needed to integrate the mechanical instruments and technology with the rest of the machine. This was approximated using the breakdown of the CER cost found in the Mission Concept Cost Estimate Tool (MCCET) and is about 17% of the total cost of the subsystem.
   c. Phase D ($1,482,000) - Phase D contains a continuation of the Integration and Testing costs of the subsystem. This cost encompasses all costs associated with any repairs or software costs needed to integrate the mechanical instruments and technology with the rest of the machine. This was approximated using the breakdown of the CER cost found in the Mission Concept Cost Estimate Tool (MCCET) and is about 17% of the total cost of the subsystem.
   d. Phase E ($620,000) - Phase E contains the Product Assurance and Management Costs of the subsystem. These costs were derived parametrically from the aforementioned CER and describe the total costs needed for maintenance and operation of the mechanical subsystem during its operation on the lunar surface. This cost is approximately 7% of the total subsystem cost.
   e. Phase F ($330,000) - Phase F contains the Management costs of the subsystem needed for the retrieval and recollection of data from the mechanical subsystem in the close-out of the mission. This cost is approximately 3% of the total subsystem cost.

2. Power Subsystem - The costs of the power subsystem totals $21,020,200. This cost was estimated similarly to the Mechanical subsystem initially starting with a parametric estimation starting from the Electronics Subsystem Model CER found in NCIM Version 9c.[26] This cost was found using the mass of the power subsystem (~15 kg) and applying it to the CER formula above. To increase the accuracy of this estimation, the cost of analog missions which also utilized solar panels and battery cells were used to create the final estimation.[57] This use of parametric and analogous estimations allowed the total cost to be approximated at $21 million for the costs of manufacturing, testing, and maintaining solar panels and battery cells within our mission vehicle. The cost breakdown per phase for this total cost is described below.
   a. Phase C ($13,200,200) - This phase contains the costs of both the acquisition of solar panels and battery cells from manufacturers and also the in-house manufacturing of to-spec solar panels/battery cells that fit the dimensions of the mission vehicle. This phase accounts for approximately

63% of the total subsystem cost due to the high cost of materials necessary such as lithium-ion and silicon.

b. Phase C-D ($3,390,000) - This phase includes the integration and testing of the power subsystem against climate changes and low-light regions such as the PSRs found on the Lunar Surface. This category accounts for approximately 16% of the costs to account for integration into the mission vehicle.
c. Phase D ($1,150,000) - This phase includes the finalization of integration of the power subsystem into the vehicle focusing on components such as the Power Distribution Unit (PDU) needed to push power across the entire mission vehicle. This represents approximately 5% of the total subsystem costs.
d. Phase E ($1,800,000) - This phase includes product assurance and maintenance costs during the mission's operation phase in order to ensure the vehicle continuously has the power to perform its needed goals. This accounts for approximately 9% of the total cost of the subsystem.
e. Phase F ($1,480,000) - This phase encompasses necessary management costs for data retrieval and close-out procedures needed to ensure the proper disposal and deconstruction of the power subsystem. This represents approximately 7% of the total mission costs.

3. Thermal Control Subsystem - The costs of the thermal control subsystem total $2,640,000. This cost was estimated parametrically using the Thermal/Fluids Subsystem Model CER found in NCIM Version 9c. [26] This cost was found using the mass of both the Passive and Active Thermal Control Systems (~2.5 kg) which included the Multi-Layer Aerogel, Electric Heater (Minco Polyimide Thermofoil HK series, and Phase Change Materials (PCMs) found in the subsystem.[36] Given the low overall weight of this subsystem costs were estimated to be minimal as the majority of the work would be done passively by the required materials. The cost breakdown per phase can be found below.
    a. Phase C ($1,900,000) - Includes the cost of manufacturing Multi-Layer Aerogel, acquiring the Electric Heater from Minco, and implementing PCMs into the mission vehicle. This cost represents approximately 72% of the total cost.
    b. Phase C-D ($200,000) - Covers the integration of the Multi-Layer Aerogel and PCMs into the chassis of the rover along with the temperature testing necessary for the verification of the thermal subsystem. Accounts for 8% of the total cost.
    c. Phase D ($200,000) - Covers the integration of the Electric Heater into the subsystem along with any necessary software needed to control the

electric heater from the rest of the system. Accounts for 8% of the total cost.

d. Phase E ($260,000)- Includes the costs of product assurance and maintenance costs during the mission duration for heating in the PSRs and regions of the lunar surface. Accounts for 9% of the total cost.
e. Phase F ($80,000)- Management costs for the retrieval and disposal of the thermal subsystem during the closeout of the mission, accounts for 3% of total subsystem cost.

4. Comms & Data Handling Subsystem - The costs of the comms and data handling subsystem total to a cost of $13,650,000. This cost was initially calculated parametrically using both the Electronics and Software Subsystem Models CER found in NCIM Version 9c. [1] This cost was later adjusted using the prices of real-world components that fit the requirements of the mission vehicle such as the RAD 750 CPU, VxWorks Operating System, Dipole Antenna, Parabolic Antenna, Leonard DDR3 Solid-State Drive, and Texas Instruments Radiation Hardened SDRAM. By combining the estimated costs of these materials found through the Comms and Data Handling Subsystem trade studies, the final cost of $13,650,000 was found. A breakdown of how this cost was distributed per phase can be found below.
    a. Phase C ($7,700,000) - Accounts for the acquisition and manufacturing of all necessary communication equipment as well as the software and hardware manufacturing of the CPU, operating system, and drivers necessary for the communication materials. Totals to 56% of the total subsystem cost.
    b. Phase C-D ($2,300,000) - Includes the integration and testing costs of the communication system given the need for the operating system to communicate with all components found in the mission vehicle accurately. Accounts for 17% of the total subsystem cost.
    c. Phase D ($2,300,000) - Continuation of integration and testing costs necessary for the communication system. Includes the cost of testing the long-range capabilities of the communication system for lunar exploration. Accounts for 17% of the total subsystem cost.
    d. Phase E ($1,060,000) - Product Assurance and maintenance costs for the communication of the mission vehicle back to base during the entire duration of the mission. Accounts for 8% of the total subsystem costs.
    e. Phase F ($290,000) - Management costs for data retrieval from the subsystem as well as the maintenance of non-volatile storage and other necessary data storing components after the duration of the mission for further analysis. Makes up 2% of the total subsystem cost.

5. Guidance, Nav, & Control Subsystem - The cost for the Guidance, Nav, & Control subsystem totals to $1,008,000. This cost was estimated parametrically using the Software Subsystem Model CER found in NCIM Version 9c. [26] Due to the low mass of this subsystem given the cost is the majority of software licenses necessary for calibration and control of the mechanical subsystem as well as necessary camera equipment source from analog missions such as VIPER like the Intel D435i RealSense Depth Camera, the overall cost of this subsystem was relatively low. [4] The breakdown of the costs per phase can be found below.
    a. Phase C ($600,000) - Accounts for the manufacturing and acquisition of Guidance and navigation software and hardware necessary for the mission vehicle as well as their initial integration into the vehicle. Represents 60% of the total cost.
    b. Phase C-D ($114,000) - Accounts for the integration and testing costs necessary to allow the Guidance and Navigation equipment to work seamlessly with the operating system found in the Communication subsystem. Represents 11% of the total cost.
    c. Phase D ($114,000) - Continuation of the integration and testing costs. Tests the equipment from long-range distances in proper facilities in order to ensure the operation of the subsystem while on the lunar surface. Accounts for 11% of the total cost.
    d. Phase E ($160,000) - Product Assurance and Maintenance costs necessary to control the rover while it traverses the lunar surface. Also accounts for any additional personnel/software needed to accurately maintain the subsystem. Accounts for 16% of the total costs.
    e. Phase F ($20,000) - Management costs for the retrieval of any necessary data from the subsystem as well as the recovery of footage from any cameras equipped in the subsystem. Accounts for 2% of total subsystem costs.
6. Science Instrumentation - Given Team 9's selection of the Strata GPR and a NIRVSS device, the costs for the instrumentation were calculated using the Body Mounted In-Situ Instrument System Model CER for the temperature/pressure-sensing device and the Active Microwave Instrument System Model CER for the GPR which were both found in NCIM Version 9c.[26] This cost totaled $22,620,000 including the costs needed for all phases of the science instrumentation. The breakdown per phase can be found below.
    a. Phase C ($15,400,000) - Includes the costs needed to acquire the necessary GPR and NIRVSS from the respective manufacturers as well as the manufacturing needed after acquisition to account for the devices to fit within the mission vehicle. Accounts for 68% of the total cost for the subsystem.

b. Phase C-D ($2,840,000) - Includes the Integration and testing costs needed to calibrate the GPR and NIRVSS as well as allow them to communicate with the Operating system found in the data handling subsystem. Accounts for 12% of the total cost.
c. Phase D ($2,840,000) - Continuation of integration and testing costs. Allocates 12% of the total costs for accuracy testing in simulated experiments for the GPR and NIRVSS instrumentation in order to ensure accurate data in the mission.
d. Phase E ($800,000) - Product assurance and maintenance costs during the mission in order to ensure the proper functionality and data collection of the science instrumentation. Accounts for 4% of total subsystem cost.
e. Phase F ($740,000) - Management costs necessary for data retrieval and collection of substance from science instrumentation needed for the close-out of the mission. Accounts for 3% of total subsystem cost.

7. Spacecraft Cost Margin - The margin at the PDR stage is a standard 50% due to changing design specifications in the early stage of design development.
8. Total Facilities Costs - The total facilities costs for both testing and manufacturing of the mission vehicle total $25,146,400. These costs include all costs associated with the maintenance and transportation of materials necessary during the manufacturing process. The cost for both manufacturing and testing is explained below.
    a. Manufacturing Facility Cost ($15,776,000) - This cost was estimated using potential manufacturing facilities found from research in the NASA ecosystem which allowed for the necessary design function such as the Ames Research Center in Moffett Field, California that could assist with the production of necessary materials such as multi-layer aerogel composites for the thermal system and Aluminum 7050 Alloy for the chassis.
    b. Testing Facility Cost ($9,370,400) - This cost was estimated with facilities in mind that supported all the necessary tests needed to be performed on the mission vehicle before launch. A facility that meets all these requirements is the NASA Johnson Space Center in Houston,Texas. The cost for this category was estimated using an analogous mission in VIPER which utilized the same facilities at Johnson Space Center for testing.
9. Facility Cost Margin - The margin at the PDR stage is a standard 50% due to changing design specifications in the early stage of design development.

5.4. Scope Management

5.4.1. Change Control Management

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

1. Requesting Changes: Given that changes in any of the three sub-teams likely impact the entirety of the mission, when a team member needs to request a change that requires the use of a CRF, the team member will draft a CRF that highlights the nature of the requested change and provides specifics on what exactly the change entails for the mission as a whole. After drafting this CRF, the team member will send this CRF to their sub-team leader who will analyze the change request and, if approved, send the CRF to the project manager to formally submit. If the change requires a CCB, the team member who requested the change and the team lead will attend the CCB to argue the case for the change. Additionally, if a change requires multiple adjustments across various subsystems both the project manager and the leads of all affected parties will work to approve the required changes and create the CRF necessary to implement these changes. If the requested change falls into the extreme change category, however, the project manager will also be suggested to attend the CCB to assist in the justification of the change and be up to date on what this change entails for the rest of the mission. In the case that changes are minor enough not to entail a CRF at the current stage of the project, changes requested by team members simply need to be communicated to the sub-team leader who will choose to approve or deny the change.

2. Implementing Changes: For the implementation of changes requested by RFAs or ADVs in document feedback, the team will collaborate during the weekly meeting to understand the demands of the change requests and delegate the implementation of the changes to the proper sub-team. This process allows for the entire team to communicate and decide on how to handle the given change requests and come to a consensus on the best possible implementation for the success of the mission. In the case that the requested change is urgent or extremely minor, the change will be handled by the team leads and project manager and communicated to the team in the weekly meeting. If the team does

not agree with the implemented change, the process for requesting a change will be followed to handle implementing the desired change. For the approval of a change by the CCB, a similar process will be followed with the team lead or whoever attended the meeting reporting the results to the project manager who will then announce these changes to the entirety of the team to work towards in the weekly meeting. In the case that a change is not approved by the CCB, the project manager, team lead, and the team member who proposed the idea will work towards either the proposal of a new change request following team protocol or work on a solution that does not require a change. As always, any changes that were approved or denied will be reported to the team through announcements in the proper communication channels and during the weekly team meeting.

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

5.4.2. Scope Control Management

Given the recent changes in budget and other aspects of the mission recently for Team 9, scope control has become a critical aspect of the team's project management. In order to simplify the process of scope control and properly communicate the changes being made within the team, Team 9 has established comprehensive plans to manage scope changes effectively. These scope changes can be split into 2 major categories.

1. Downcsoping Strategies - To deal with major issues that may arise during the mission lifetime such as budget reductions, overrun costs, or schedule delays, Team 9 has made an order of operations to minimize losses and ensure the team's confidence in the ability to accomplish the mission objectives sufficiently. The strategies are listed below in decreasing order of favorability.
    a. Task Prioritization: In the event that the downscoping involves non-financial issues and pertains primarily to scheduling issues, Team 9 will employ critical path analysis to identify what tasks are fundamental to

the success and work of the mission to reallocate resources to prioritize them first. This prioritization will typically favor key aspects of the mission such as science instrumentation and certain subsystems necessary for the functionality of the vehicle while removing features that may be implemented for redundancy.

   b. Resource Reallocation: For both financial and non-financial scope issues, resource reallocation will be considered to preserve the functionality of key aspects of the mission such as the science instrumentation while reducing certain other aspects of the mission such as outreach or travel. This resource reallocation ensures that essential components of the mission stay completed and on schedule. This strategy will also likely impact the TRL levels and manufacturing of less important components leading to less testing and quality checking being done in order to ensure key components functionality.
   c. Scope Reduction: As a last resort, Team 9 will look towards sacrificing non-critical mission components such as secondary science instrumentation to reduce costs and increase time. This method of descoping will always be considered last in the process and will only be undertaken if the team has complete confidence in the ability to complete the mission without the need for the removed component.
2. Upscoping Strategies - To deal with the case where there is leftover resources that could be used for the benefit of the mission, Team 9 will follow the following strategies to ensure all additional resources are used to the best of their ability.
   a. System Enhancement: The first place Team 9 will look to improve the mission vehicle is in existing subsystems such as the science instrumentation and major subsystems such as mechanical or power. These additional resources will likely be used to ensure the ability to complete the mission requirements and also increase confidence within shareholders as well as increasing testing and validation for more favorable TRL levels.
   b. Schedule Changes: If there are additional resources pertaining to scheduling and due dates in the schedule of the mission, Team 9 will look to allocate more time to the testing and validation of the mission vehicle in order to increase confidence in the ability to accomplish the mission tasks.

As is custom, Team 9 also plans to communicate all scope changes in a similar manner to how RFAs and ADVs are handled in the team using the established hierarchical system which will report to the Project Manager who will then communicate any necessary changes to team personnel and sub-team leads for any necessary adjustments.

5.5. Outreach Summary

To increase public awareness and appreciation for the mission, an outreach strategy program will be developed to target high schools and community centers. Targeting high school students is crucial as it provides early exposure to careers in the aerospace industry. By offering fun and interactive activities, the goal is to stimulate their interest and inspire continued pursuit, all while fostering a sense of contribution to the mission. In community center settings, this approach expands the outreach to diverse communities of varying ages, ensuring accessibility and inclusivity for underrepresented groups. The first phase of this program will involve development, including verifying educational materials, scheduling programs, identifying effective learning methods, and allocating the budget appropriately. To make this possible, team members will allocate time to complete professional development workshops that will provide the proper training and resources to ensure the successful implementation of the program. The experiences that will be pursued include NASA's Sparking Participation and Real-world Experiences in STEM (SPARX), NASA CONNECTS Community, and NASA Educator Professional Development (EPD) Opportunities. These workshops will focus on enhancing team members' skills in curriculum development, instructional strategies, and the use of real-world connections in education. Additionally, members will cover effective communication techniques, networking opportunities, and curated NASA resources. By participating in these workshops, team members will be better equipped to deliver high-quality educational programs that meet the diverse needs of learners and achieve the program's objectives. Following program development, dedicated time will be allocated to marketing the program through various channels such as social media, community newsletters, and pre-launch outreach events **(Figure 21*).*** This effort aims to maximize awareness and participation, ensuring that the program reaches a wide audience interested in lunar exploration and scientific discovery specific to CHILLY's rover mission. The program will include interactive experiences pertaining to mission planning with a focus on lunar exploration strategies, research methodologies, and need for additional involvement in the field. Participants will also be introduced to the CHILLY rover, highlighting multiple opportunities for them to actively contribute. As part of the program, an integral outreach method will involve inviting NASA speakers to highlight the importance of CHILLY's mission in advancing lunar exploration. Connections to professionals will be made possible by active member outreach to current individuals working on CHILLY and additional connections made during the professional educator training. A program evaluation system will also be established to evaluate the effectiveness of the outreach initiatives. Methods of assessment will include surveys, attendance, and engagement level tracking. The second phase of the program development will have the goal to build credibility for the program and its offerings through partner and community alliances. To ensure that program participants continue to contribute to CHILLY's rover mission initiatives, post-program events will be scheduled to focus on CHILLY's objectives and progress. Specifically, school-established and local community partnerships that target STEM education will be contacted to facilitate outreach. At this point, the program evaluation system will also include the number of committed partner organizations and leads generated by the partner events. The rate of return or follow-up participants from partner organizations will also be tracked for evaluation purposes. Ultimately, the outreach initiative evaluation metrics should demonstrate an improvement in public awareness and engagement with CHILLY's rover mission objectives. This will be assessed through metrics such as the number of events hosted by partner organizations, enrollment figures, participant retention rates, and quarterly satisfaction surveys. These indicators will help gauge the program's effectiveness in sustaining interest and involvement.

Figure 21. CHILLY's Outreach Plan Flyer

6. Conclusion

Team 9 plans on continuing to refine and optimize all aspects of CHILLY moving to CDR. Moving forward team 9 will further perfect the individual components and subassemblies on the vehicle and the overall design could be optimized to fit within many of the customer requirements and constraints, as well as mitigating risks as well and eliminating all unnecessary risks and costs.

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Declaration of Generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work, the team used Claude and ChatGPT in order to perform calculations, get approximations, perform trade studies, and write certain sections (PCM, heat pipes) for the thermal control system. After using this tool/service, the team reviewed and edited the content as needed and took full responsibility for the content of the deliverable. Additionally, ChatGPT-4 was also used in the creation of some citations.

Appendix

Calculation 1. *Required Torque*

r = Radius of the CHILLY rover's wheels = 0.125 m
m = Mass of rover = 85 kg
g = Gravity on moon = 1.62 m/s²
μ = Coefficient of friction on lunar surface = 0.63 [7]
N = Normal force
f = Friction force
τ = Torque
$\tau_{Required}$ = Required torque for each motor

$N = m \cdot g = 85\,[kg] \cdot 1.62\,[m/s^2] = 137.7\,[N]$
$f = \mu \cdot N = 0.63 \cdot 137.7\,[N] = 86.751\,[N]$
$\tau = F \cdot r = 86.751\,[N] \cdot 0.125\,[m] = 10.843875$ [N-m]
$\tau_{Required} = \tau/4 = 2.71096875$ [N-m]

Calculation 2. *Required Gear Ratio*

$\tau_{Required}$ = Required torque for each motor
τ_{Motor} = Torque each motor produces = 0.15 N-m

Gear ratio = $\tau_{Required}/\tau_{Motor} = 2.8/0.15 = 18.67$