Mission Definition Review (MDR)

"CHILLY"

(MCA Team 09)

Commanded Harvesting of Ice Lunar Lander Yield

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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
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 Definition Review

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 back up 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 [1]. 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 [2]. 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 [3]. 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 [1]. With these, the NIRVSS will be able to monitor changes in surface reflectance, composition, volatile content, and temperature with high precision.

Table 1. *Science Traceability Matrix (STM)*

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	Identify impact of environment, temperature; material composition; ect, 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.	Detect spectral resolution wavelengths between 50 nm and 20 nm	Spectral Resolution:	~ 50 nm	~20 nm	Near-Infrared Volatiles Spectrometer System (NIRVSS)	Mission shall measure physical parameters of gas condensation.
				Temperature Ranges:	From 0°C To 100°C	Above -173°C		
	Examine the influence of gravity on solid-liquid phase change of water ice including sedimentation of regolith in the liquid water.	Identify changes in sedimentation processes of regolith in liquid water in lunar gravity compared to earth gravity using changes in temperature.	Measure composition of liquid water and location of solid regolith over time as regolith particles separate through distance resolution.	Spectral Resolution:	~ 50 nm	~20 nm	Ground Penetrating Radar (GPR) & Near-Infrared Volatiles Spectrometer System (NIRVSS)	Mission shall record physical details of sedimentation process of lunar regolith in liquid water
				Temperature Ranges:	+/- 5°C from 0°C	Above -173°C		
				Distance Resolution:	< 5 cm	~ 3 cm		

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

1.3. 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 in Table 2 in the appendix. 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. Additionally, the mechanical, electrical, command & data handling, thermal, and payload subsystem requirements are also outlined. These requirements were derived from the top-level mission and system requirements, and then further derived into child requirements based on top-level subsystem requirements.

1.4. Concept of Operations

The concept of operations (ConOps), outlined below in Figure 1, describes the procedures necessary for the CHILLY mission to be a success. The mission duration is 20 weeks and starts after landing on the lunar surface. 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. 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 0.5 meters per second. While traveling, the rover detects and avoids hazards as it navigates to the first chosen PSR. Additionally, systems' health telemetry is sent to the orbiter every hour. When the battery of the rover gets low, the rover enters a low power mode. During low power mode, non-essential systems, except the mechanical system, are turned off in order to preserve power. The rover then navigates out of the PSR and travels to an optimal charging position. 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, the robotic arm then extends to the NIRVSS to deposit the samples. The NIRVSS then analyzes the volatile sample in order to accomplish science goal 6n. After collecting enough scientific data, the data is stored by the CDH subsystem and transmitted to the orbiter when an optimal data link is available. The rover then repeats modes for the remainder of the mission duration.

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.

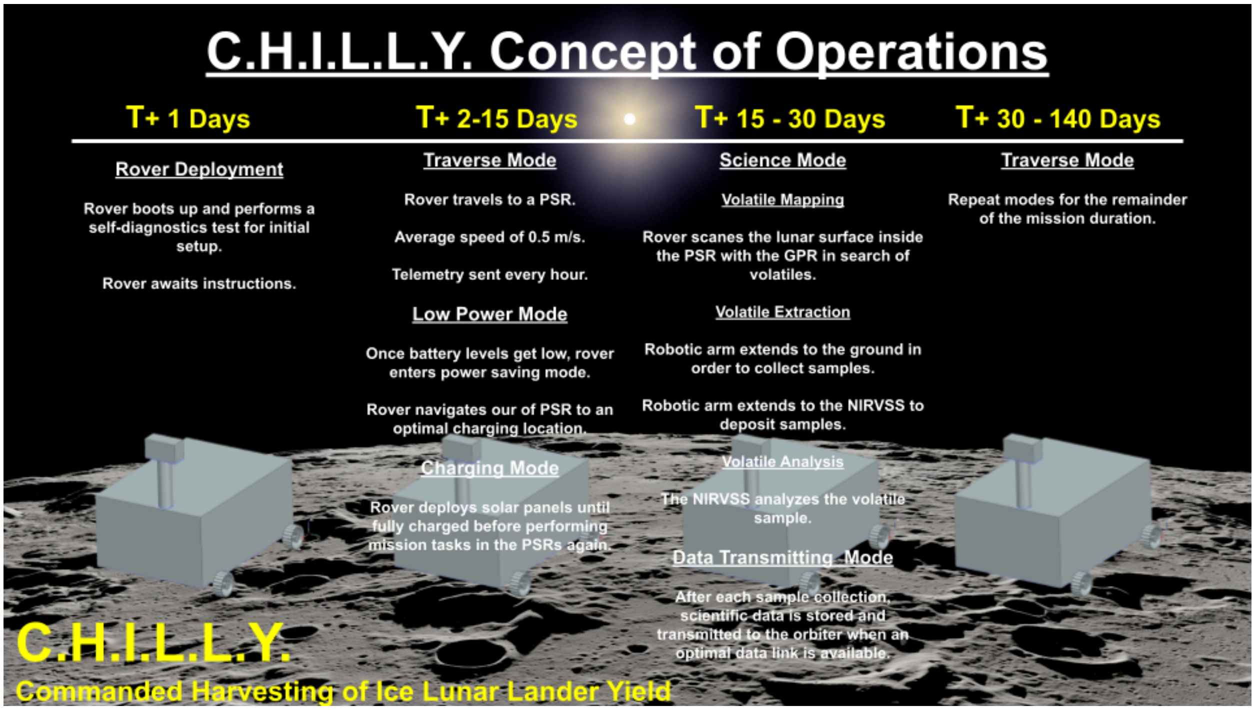

Figure 1. *CHILLY ConOps Graphic [#]*

1.5. MCA 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 leading, 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 which have allowed for 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:

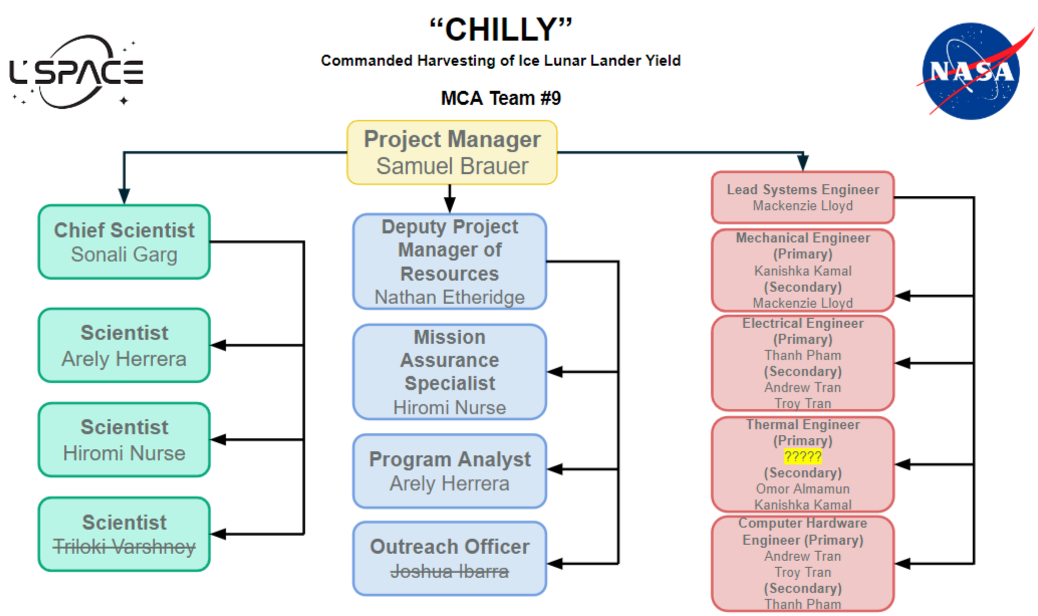

Figure 2. *Team 9 Organizational Chart*

1.6. 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.

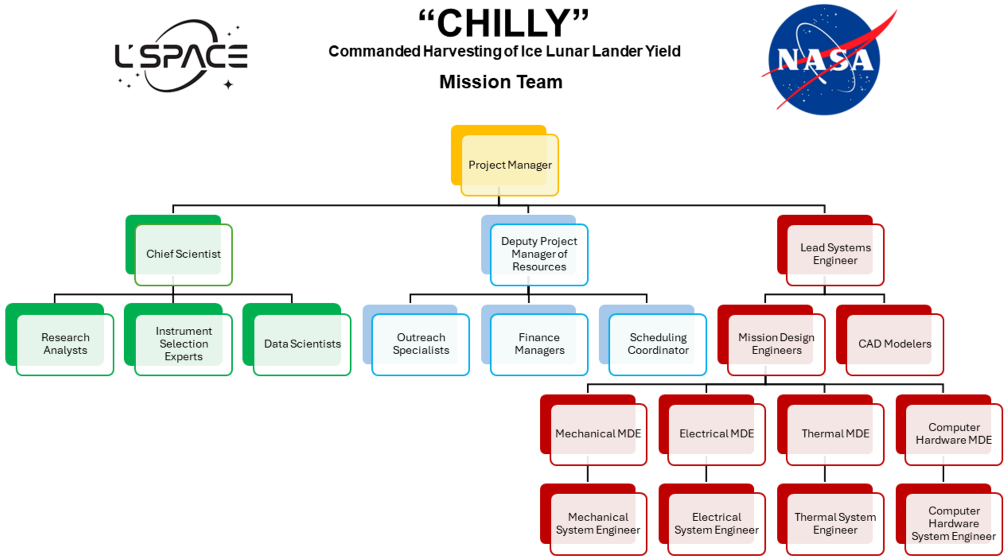

Figure 3. *Full Mission Team Organizational Chart*

1.7. Manufacturing and Procurement Plans

1.7.1. Mechanical Subsystem

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.

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.

Locomotion Subassembly:

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 [4]. ORNL specializes in supercomputing, advanced manufacturing, materials research, neutron science, clean energy, and national security, and has previously proven its reliability to NASA [4]. 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 [5]. Since JPL has not manufactured a wheel similar to CHILLY's before, the lead time should increase by 12 to 24 months.

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 [6]. 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 [7] and would make a good backup company. As this product is also COTS, the lead times should be similar.

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 ℃, but it also does not need a heat source or lubrication [8]. JPL has already been manufacturing and testing the gears, so they have been chosen to manufacture them [9] 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 [10]. 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.

GNC Subassembly:

The CHILLY rover will use an IMU to track its linear and angular acceleration in order to monitor its overall motion. The Northrop Grumman LN-200S is a reliable commercial off-the-shelf (COTS) component that's been used in other NASA rovers. Designed for short to medium-term space missions, the LN-200S is small, lightweight, and highly dependable [11]. If it's in stock, delivery could be as fast as a few days to a couple of weeks. If it needs to be manufactured, the lead time could extend to several weeks or even a few months to cover both production and delivery. If Northrop Grumman cannot provide the LN-200S, the Honeywell HG4930 IMU will be used instead. This is also a COTS component and should have a similar lead time.

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 [13]. 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 [14]. The lead time should remain the same.

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 [15]. 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 [16]. 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.

Sample Collection Subassembly:

In order to collect samples for scientific analysis, the CHILLY rover will utilize a drill. The Honeybee Robotics Nano Drill is small, lightweight, and capable of capturing, retaining, and ejecting samples [17]. Honeybee Robotics is a AS9100 certified, NASA-approved flight hardware supplier that has proven their reliability [17]. Since the Nano Drill is commercial off-the-shelf (COTS), the lead time should be less. If the drill is in stock, the lead time could be anywhere between several days to a couple weeks for the delivery. However, if the drill has to be manufactured, the lead time could take 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 then be used to manufacture a new drill for the CHILLY rover similar to the Nano Drill. However, this will also increase the lead time by 12 to 24 months to account for the design process.

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. 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.

1.7.2. Power Subsystem

Solar Cells:

CHILLY Rover will select Spectrolab as a 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 house in best case [18]. If Spectrolab is not available, an alternative supplier is SolAero with SolAero ZTJ due to their similar performance with Spectrolab XTJ but slightly under-priced in terms of availability [19]. 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:

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 SKY-NANOeps-BMM battery, capables of high capacity, discharge rate, and availability of the technology [20]. 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. Time lead for batteries will vary from 8 to 20 weeks and up to 25 weeks if the main supplier is unavailable, with extension depending on type and customization if required.

Power Distribution Unit:

The 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, equals to 15 watts of power. It also has high efficiency at 80%, circuit safety, and operates from -55C to +125C [21], 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 [22]. The manufacturing process may take approximately up to 20 weeks and up to 25 weeks if the main supplier is unavailable.

Health Monitoring System:

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 ST700), 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 estimation 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.

1.7.3. CDH Subsystem

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.

1.7.4. Thermal Subsystem

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.

1.7.5. Payload Subsystem

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 [25]. 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 [26]. 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 2 was completed in 7 months by Astrobotic and predictions to raise this TRL to be flight ready is anywhere from 12 months to 30 months in total [27]. A possible backup supplier could be Geophysical Survey Systems Inc. (GSSI) which is the leading manufacturer of personalized GPRs in the United States [28]. 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 [#]. 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 [#]. 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.

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 3). Option 1 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 2, 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 lead time for the second option is 24 weeks, which corresponds with the increasing complexity and capability of the device. Option 3 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 3. *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

1.8. Risks and Safety

1.8.1. Risk Analysis

Mechanical Risks

Table 4. *Mechanical Risk Summary*

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
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 cranies 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

For the first risk outlined above, the lunar terrain can be very hard or very soft; covered in craters or smooth for miles, therefore there remains a possibliity that some outliers can emerge if the wheels fails to navigate the slopes or, worst-case- scenario, get stuck. This will result the rover having to detour and spend more energy, and ultimately risk depleting all its energy.

For the second risk, regolith can include dust and rock ranging from various sizes so there is always the probability of the rover driving the wheels causing some to fly into the tight crevices of the rover. This can prevent instrumentation from being deployed, being critical for the mission and unable to complete the main science goals.For the third risk,

For the third risk, though small, there is always the probability of error that there is faulty hardware installed on the rover, which can be exponentially worse in combination with the harsh moon environment. This could cause the loss of structural integrity of the whole mechanical subsystem, and thus the rover.

For the fourth risk, micrometeoroids are not uncommon on the surface of the moon as there is no atmosphere to prevent their descent. Given this natural phenomena, there is a possibility that if one of them is too big and comes in with too much force, it can make some considerable damage to the equipment and thus compromise the power of the rover and/or the thermal regulation.

For the fifth risk, the moon's surface has been recorded to go to -280 F and 260 F at the highest for this mission. If the decision for parts used on the rover are incompatible and fail to withstand the severe temperature gradient from "night" to "day" and vice versa, it can have catastrophic impacts on navigation and upholding the interior hardware to monitor the rover, thus concluding in a failed mission.

Lastly, for the sixth risk, there are some organizations listed for the mechanical subassembly that are research-based and are handed the task to improve the relations between the wheels and suspension linkages. Nonetheless, even if off-the-shelf parts are delayed to support the assembly of the rover, it can delay the launch to the moon and possibly discourage the occurrence of the mission altogether.

Thermal Risks

Table 5. *Thermal Risk Summary*

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
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 Degredation Over Time	3	3	NEW	M	Long-term exposure degrading MLI and aerogel, reducing effectiveness.	Active

L = Likelyhood (1-5)
1 = not likely 5 = extremly likely
C = Consequence (1-5)
1 = low consequence 5 = high consequence

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

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

Louver Malfunction

The mechanical louvers are a crucial component to the thermal control system, their design allows heat to dissipate by the opening and closing of the louvers depending on the thermal conditions. The space environment has extremely harsh conditions exposing the louvers to wear, debris buildup, and the possibility of misalignment. Unfortunately there is a large chance that increases with time that these louvers may experience failure being stuck in one position due to a multitude of factors. These include wear and tear due to lunar dust, and thermal stresses. Such a malfunction would cause the vehicle to improperly thermally regulate. This system heavily relies on these louvers to properly operate in order to keep various components within operating conditions. As a result, it could lead to many critical components to overheat due to the lack of heat dissipation or overcooling. These thermal imbalances could result in a decrease in the performance and reliability of the mission, causing critical damage to many sensitive components and subsystems on board.

Deployable Radiator Malfunction

Deployable radiators are absolutely critical for managing the thermal load of the spacecraft by expelling excess heat that may be trapped away from important systems. Considering that these radiators are quite complex in nature when it comes to the deployment of them, they must be able to perform at their full potential in all conditions. There is a possibility that these radiators may run into some issues, such as failing to deploy or retract properly due to a jam, thermal expansion and contraction, or some damage from space debris. Such a malfunction would severely impact the spacecraft's ability to release excess trapped heat. These deployable radiators provide an extra layer of thermal control and protection during the most thermal intensive parts of the mission. As a result, not being able to deploy the radiators could lead to overheating of the internal components. This overheating could damage the performance of the spacecrafts systems, cause thermal damage to electronics, and threaten the mission's success. Effective thermal protection and management is absolutely essential to maintaining the integrity to the spacecraft.

Material Degradation Over Time

Thermal insulation materials, like Multi-Layer Insulation (MLI) and aerogel, are constantly exposed to the space environment, which includes a lot of radiation, large temperature changes, and impacts from space debris. Once again there is a big possibility that these particular material will degrade over time. This degradation comes mainly by way of UV exposure, thermal cycling, and abrasive lunar dust. Their high performance is directly related to the overall condition of the materials. Thus the continual degradation of these materials over time lowers the overall insulative properties of the material which are crucial for maintaining the spacecrafts stability. As the materials lose their effectiveness their ability to regulate the thermal control on the system goes down which can compromise the integrity of the spacecraft. As a result of the reduced thermal properties of the material, this can lead to thermal instability and imbalances in the spacecraft. This can lead to increased energy consumption , reduced efficiency of the thermal management system, and potentially damage important components. While it is not as immediately catastrophic as the other mechanical failures previously mentioned, it still poses a significant risk to long term performance and reliability of the mission.

	Unstable Antenna Alignment	2	3	↓	M	The rover maneuvering over significant distances creates the chance that the antenna could be misaligned which can negatively impact the transfer of our data which in turn can create loss of data	7/3/24 - Risk found. 7/20/24 - The rover's memory stores data for later transmission when signals improve. Redundant antennas ensure two-way communication if the primary fails, reducing risk

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	Communication Loss due to Moon Liberation	2	1	↓	M	The moons liberation shifting the moon out of view of earth can disrupt the rovers direct communication link with the network and cause signal loss	7/3/24 - Risk found. 7/20/24 - Rover is equipped with a redundant Low Gain Antenna

Payload and Planetary Protection Risks

Table 6. *Payload and Planetary Protection Risk Summary*

ID	Summary	L	C	Trend	Approac h	Risk Statement	Status
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

The risks concerning the payload subsystem were determined by researching the limitations of each science instrument as well as the payload section of the rover as a whole (Table #). Risk 1 concerns payload's performance as a whole is lunar dust. Since movement of the rover will unsettle lunar dust, it is fairly likely for the GPR and NIRVSS to get covered in dust, consequently affecting the payload's signals, and therefore reducing its accuracy in detecting water ice composition and abundance [#] [#]. Since this will affect the completion of the chosen science objectives, mitigation strategies need to be further researched and developed. Possible solutions for dust control include using mechanical motion to remove the dust off of the rover or even applying a protective coating to the GPR and NIRVSS which will reduce the likelihood of dust affecting the performance of the science instruments [#] [#].

Risk 2 is more focused on the GPR itself not being capable of properly imaging the lunar subsurface. Given that the lunar regolith is composed of a variety of sedimentary particles, it is possible that the crowded particles could hinder the GPR's signal, producing cluttered images, which ultimately could make the imaging hard to analyze [#]. This risk is accepted as the amount of sediment in the regolith and water ice can neither be prevented nor altered. Additionally, the GPR used in the CHILLY mission is the most advanced technology for such radars and thus, the imaging cannot be improved at this time either [#]. Therefore, this risk must be accepted in which case the images will take more time to carefully be analyzed.

Specifically for the NIRVSS instrument, risk 3 demonstrates that temperature is a factor that is heavily considered. Due to large temperature changes on the moon, the NIRVSS equipment could undergo thermal strain, which may lead to the device being damaged overtime, thus affecting the abilities of this instrument to perform necessary experimentation. While the moon does have large temperature fluctuations, NIRVSS is specifically built to withstand these temperatures and therefore the likelihood of the temperature affecting the device is low [#]. However, if there is an anomaly in the temperature range then the consequence would be very high as the equipment can be damaged in extreme conditions. For now this risk will be watched and may be mitigated or accepted through further testing as nothing can be done to eliminate such lunar conditions.

Planetary protection is another area that poses significant risk, as seen in risk 4. Since the rover will come into contact with various people and locations, organic material could remain on the rover after launch, which may result in bacteria contaminating the moon, hindering further research and drastically affecting the presence of various materials on the moon [#]. The likelihood of contamination is low due to the fact that the rover will go through decontamination processes prior to settling on the moon. However, should organic material accidentally be introduced to the moon, it could severely affect this mission and future lunar missions [#]. Therefore, a mitigation strategy will be employed to ensure the least amount of contamination occurs when the rover conducts experiments on the moon. Further research must be done to determine which mitigation strategies are the most efficient and effective.

1.8.2. Failure Mode and Effect Analysis (FMEA)

1.8.3. Personnel Hazards

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 [#].

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.

1.9. Schedule

1.9.1. 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 our 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.[1]
    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.[2][3]

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.[4]

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.

1.9.2. 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 7 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. [1]

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, Aluminized Multi-Layer Insulation, Electric Heaters, and Thermally Actuated 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 7. *Schedule Basis*

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 13 (see appendix) 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.

1.10. Budget

1.10.1. Budget Overview

Using the aforementioned schedule as a basis for the planning of the budget, Team 9’s mission budget totals a 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

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.

1.10.2. 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.
    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.
    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.
    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.
    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.

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.[1] 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.[2] 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.[6]
   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.[3][4] 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.[5]

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.

1.10.3. 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 8. *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. This phase has a total of 7 science personnel who will focus on the final fabrication of the Strart GPR and NIRVSS required for the system, 10 engineering personnel who will focus on the finalization of the mission chassis and other communication and thermal subsystems, 7 technicians for assisting with the fabrication of subsystems and science instrumentation along with the testing of software, and 4 administration/management personnel to oversee design and work on the finalization of 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. This phase increases the number of technicians from 7 to 10 total to work on the initial testing of the assembled rover as well as creating the software and drivers required for the rover and its components to communicate with each other once assembled properly.
- 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. This phase also increases the amount of administration personnel to 3 to handle the increase of change requests or other document changes that might occur in this phase.
- 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.
- 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.

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

Table 9. *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.

1.10.4. 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 10. *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	$ -	$ 13,000	$ 84,500	$ 87,750	$ 87,750	**$ 273,000**

Transportation Cost						
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.
- 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.[1][2]
- 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.[1][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]

1.10.5. 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 11. *Outreach Budget*

OUTREACH						
	Phase C	Phase C-D	Phase D	Phase E-F	Phase F	Cumulative Total
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**

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. [1] 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:

1. 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 [3].
2. 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 Francisco, 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 [4][5]. The cost was then taken with additional added overhead to account for any additional events or costs that may be associated with venues.
3. 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 sourced from the United States Department of Transportation [6].
4. 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 [3].

5. 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.

1.10.6. 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 12. *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 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	$	$ 3,493,367	$ -	$ -	**$ 38,814,923**

		17,045,556				
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 [1]. 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.[2][3] 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 [1]. 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 [4]. 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 [1]. 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 [5]. 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 [1]. 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 [1]. 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 [6].

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.

1.11. Scope Management

1.11.1. 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.

1.11.2. 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. Downscoping 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.

1.12. Outreach Plan

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. 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.

1.13. Conclusion

Overall, extensive research has been conducted specifically regarding the manufacturing process of the CHILLY rover and technicalities of the mission progression. Specific suppliers have been scouted for each of the subsystems along with back up options considering lead times and costs for the manufacturing of each part. As each subsystem has been heavily researched, risk analysis has also been performed to account for and mitigate any risk to the physical mission, the mission schedule and budget, and planetary protection. Additionally, the aforementioned mission schedule and budget has been altered to account for budget cuts and overall team efficiency. Minimal changes to the rover have been made to stay within the scope of the mission which has now been detailed in the management details.

As we move forward to PDR, Team 9 will focus on finalizing the overall design of the spacecraft vehicle, updating the cost estimate and schedule, mitigating risks as well and eliminating all unnecessary risks and costs. Given the team had more time, many of the goals previously mentioned would have been accomplished to a higher standard of professionalism. The individual components and subassemblies on the vehicle could be perfected and the overall design could be optimized to fit within many of the customer requirements and constraints. As Team 9 moves forward, a reworking of the individual subteams will be required to better suit many of the time constraints and strengths many of the members may have. Team 9 plans to fulfill all of the aforementioned goals by PDR with the clear path presented to achieve such.

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Declaration of Generative AI Usage

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

Statement: During the preparation of this work, the team used CHAP-GPT in order to perform research. After using this tool/service, the team reviewed and edited the content as needed and takes full responsibility for the content of the deliverable.

Appendix

Appendix

Table 2. *Mission Requirements*

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Top Level 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
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	Analysis	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	Analysis	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req 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 takeoff and landing in order to not get damaged which could jeopardize the mission.	MEC-2	N/A	Analysis	Mechanical	Met
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	Analysis	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	The system must be able to deploy the Nano	MEC-3	N/A	Demonstration	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
	device (the Nano Drill) to the NIRVSS.	Drill to the NIRVSS in 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	Demonstration	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 123°C.	The rover's structure can expand and contract with the temperature	MEC-5	N/A	Test	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		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 accomplish the mission goals and survive the mission duration.	MEC-6.1	N/A	Test	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req 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-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 budget.	MEC-7	N/A	Inspection	Mechanical	Met
MEC-8	The mechanical subsystem shall have a max mass of 30 kg.	The system has a specific mass allowance	MR-4	MEC-8.1 MEC-8.2	Inspection	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		in order to remain within the rover's mass requirement.		MEC-8.3 MEC-8.4 MEC-8.5			
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 stay within the allocated mass in order for the mechanical system to not exceed its allocated	MEC-8	N/A	Inspection	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		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 to it in order to not exceed the system's power allowance.	MEC-9	N/A	Inspection	Mechanical	Met
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	MEC-9	N/A	Inspection	Mechanical	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		not exceed the systems power allowance.					
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 (EPS) 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 $25 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
Command & Data Handling (CDH) Reqs							
CDH-1	The subsystem shall communicate with the primary mission orbiter for the duration of the mission lifetime of 20 weeks.	The system needs to be able to communicate with the orbiter throughout the mission in order to	MR-7 MR-8	CDH-1.1 CDH-6 CDH-8 CDH-9	Demonstration	CDH Subsystem	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		communicate the information collected to accomplish the science objectives.					
CDH-1.1	The CDH system uses Ultra High Frequency (UHF) for communication between rover and orbiter for a bandwidth of a few kilobits per second and S band and X band for a bandwidth of up to tens of mbps.	Communication with orbiter and mission control	CDH-1	N/A	Analysis	CDH Subsystem	Met
CDH-2	The subsystem shall cost a max amount of $15 million.	The system needs to stay within the mission's assigned budget.	MR-6	CDH-2.1	Inspection	CDH Subsystem	Met
CDH-2.1	The CDH System will not cost more than $15 million to build and operate over the span of the 20 week 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 mission in order to accomplish the mission objectives.	MR-2	CDH-3.1 CDH-3.2	Test	CDH Subsystem	Met
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	The 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

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req 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	The CDH system displays 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 10 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 20 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 criticality and optimizes use of	Organize data storage	CDH-1	N/A	Demonstration	CDH Subsystem	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
	available bandwidth for data transmission efficiency.						
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
Thermal Control System (TCS) Reqs							
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

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req 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 within operating temperature throughout the entire mission.	MR-3	N/A	Analysis	Thermal	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	MR-6	N/A	Inspection	Thermal	Met

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
		mission's assigned budget.					
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	Demonstration	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, 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	Demonstration	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	Demonstration	Thermal	Met
TCS-8	The thermal control system shall have 0g of radioactive material.	The customer limited the amount of radioactive material	SYS-1	N/A	Inspection	Thermal	Met

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

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
PAY-5.1.3	The NIRVSS shall be able to differentiate between gaseous hydrogen and oxygen	Instrument must be able to individually determine hydrogen and oxygen condensation parameters	PAY-5.1	N/A	Test	Payload Subsystem	Met
PAY-5.2	The NIRVSS shall be able to measure the composition of water and suspense regolith during the sedimentation process	Mission must be able to complete science objective 6n	PAY-5	PAY-5.2.1 PAY-5.2.2 PAY-5.2.3	Test	Payload Subsystem	Met
PAY-5.2.1	The NIRVSS shall be able to differentiate between water and regolith suspended in liquid water using a spectral resolution of at least 50 nm	Instrument must be able to determine sedimentation characteristics under lunar gravity	PAY-5.2	N/A	Test	Payload Subsystem	Met
PAY-5.2.2	The NIRVSS shall be able to determine the temperature of a given sample around the liquefaction temperature of water	Instrument must be able to determine sedimentation characteristics under lunar gravity	PAY-5.2	N/A	Test	Payload Subsystem	Met
PAY-5.2.3	The NIRVSS shall be able to determine the location of suspended particles in liquid water within TBD cm	Instrument must be able to determine sedimentation characteristics under lunar gravity	PAY-5.2	N/A	Test	Payload Subsystem	met

Table 13. *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	