Preliminary Design Review (PDR)
Team 21
Habitability Explorer for Lunar Pits

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TABLE OF ACRONYMS

ADV	Advisory
ALSD	Apollo Lunar Surface Drill
APXS	Alpha Particle X-Ray Spectrometer
ARC	Ames Research Center
ATS	Air Temperature System
BRAILLE	Biologic and Resource Analog Investigations in Low Light Environments
BRB	Biosafety Review Board
BSL	BioSafety Level
CAD	Computer-Aided Design
CCB	Change Control Board
CER	Cost Estimating Relationship
CEU	Control Electronics Unit
CDH	Command and Data Handling
CDR	Critical Design Review
COSPAR	Committee on Space Research
CRF	Change Request Form
CRM	Continuous Risk Management
DPMR	Deputy Project Manager of Resources
DR	Decommissioning Review
DRR	Disposal Readiness Review
DTN	Disruption Tolerant Networking
EAP	Employee Assistance Program
EPA	Environmental Protection Agency
ERE	Employee-Related Expenses
F&A	Facilities & Administration
FHL	Flammable Hazard Level
FMEA	Failure Mode and Effect Analysis
FPGA	Field Programmable Gate Array
GN&C	Guidance, Navigation, & Control
GSFC	Goddard Space Flight Center
GTS	Ground Temperature System
HCS	Hazard Communication Standard
HDM	Hold Down Mechanism
HELP	Habitability Explorer for Lunar Pits
HMST	Hazardous Materials Summary Table
HRL	Hazard Response Level
ICD	Interface Control Document
ICP	Interface Control Plan
IDD	Interface Definition Document
IRD	Interface Requirements Document
IS	Imaging System
ISRU	In-Situ Resource Utilization
IWG	Interface Working Group
KDP	Key Decision Point
KF	Kalman Filter

KSC	Kennedy Space Center
LADEE	Lunar Atmosphere and Dust Environment Explorer
LES	Local Electronics System
LHDAC	Lander Hazard Detection & Avoidance Camera
LIBS	Laser Induced Breakdown Spectroscope
LiDAR	Light Detection and Ranging
LND	Lunar Lander Neutron and Dosimetry Experiment
LRA	The Laser Retroreflector Array
LROC	Lunar Reconnaissance Orbiter Camera
LVMM	Lunar Volatile and Mineralogy Mapper
LVPS	Low Voltage Power Supply
LW	Longwave
MAKSI	Markov and Kalman State Identification
MAP	Mission Support Future Architecture Program
MCA	Mission Concept Academy
MCCET	Mission Concept Cost Estimate Tool
MCR	Mission Concept Review
MDAA	Mission Directorate Associate Administrator
MDP	Markov Decision Process
MDR	Mission Definition Review
MEMD	Medical and Environmental Management Division
MG	Mission Goal
MLI	Multi-Layer Insulation
MMOD	Micrometeoroid and Orbital Debris
MOVE	Modal Optimized Vibration dust Eliminator
MPASS	Multi-Parameter Aerosol Scattering Sensor
MRR	Mission Readiness Review
MSL	Mars Science Laboratory
MTE	Measuring and Test Equipment
NIRS	National Institute of Radiological Sciences
NIRVSS	Near-Infrared Volatile Spectrometer System
NSS	Neutron Spectrometer System
OBC	Onboard Computer
ORR	Operational Readiness Review
ORSA	Organizational Risk Safety Assessment
OSHA	Occupational Safety and Health Administration
OSMA	Office of Safety & Mission Assurance
P2P	Point-to-Point
PCA	Printed Circuit Board Carrier Assembly
PDF	Probability Density Function
PDR	Preliminary Design Review
PDS	Planetary Data System
PDU	Power Distribution Unit
PLAR	Post-Launch Assessment Review
PLZT	Photovoltaic effect of Lanthanum-modified lead Zirconate Titanate
PM	Project Manager

POMDP	Partially-Observable Markov Decision Process
PP	Planetary Protection
PPE	Personal Protective Equipment
ProSEED	PROSPECT Excavation and Extraction Drill
PTSD	Post-Traumatic Stress Disorder
R&D	Research & Development
RAD	Radiation Assessment Detector
REMS	Rover Environmental Monitoring Station
RFA	Request For Action
RIDM	Risk-Informed Decision Making
RPN	Risk Priority Number
SAMHSA	Substance Abuse and Mental Health Services Administration
SC	Spacecraft
SCI	Science
SciX	Science Explorer
SDE	Science Discovery Engine
SIR	System Integration Review
SLOPE	Simulated Lunar Operations
SMA	Safety and Mission Assurance
SRB	Standing Review Board
SRR	System Requirements Review
SSD	Solid State Detectors
SRM&QA	Safety, Reliability, Maintainability and Quality Assurance
STM	Science Traceability Matrix
SW	Shortwave
SWIFI	Software Implemented Fault Injection
TBD	To Be Decided
TBR	To Be Revised
THL	Toxicity Hazard Level
TRIDENT	The Regolith and Ice Drill for Exploring New Terrain
TRR	Test Readiness Review
TRL	Technology Readiness Level
V&V	Verification & Validation
XRF	X-ray Fluorescence Spectrometer

1 MISSION OVERVIEW

1.1 Mission Statement

The objective of Habitability Explorer for Lunar Pits (HELP) is to send a rover into the Compton Pit, explore its characteristics, and determine its ability to sustain future human habitation. The rover is expected to obtain clear dimensions of the cave including deformations, points of stress, and terrain information. These measurements will be obtained using a terrestrial laser scanner device as the rover slowly traverses the pit. Identifying overhangs and stress points will benefit astronauts, allowing them to detect potential hazards and enforce measures to prevent hazards or protect vulnerable areas from danger. The thermal environment inside lunar pits will likely differ from that of the surrounding surface. The Compton Pit potentially presents areas that shield from solar radiation and the low thermal conductivity of the lunar regolith during nightfall, when extreme temperatures fluctuate. This pit is therefore a prime candidate to host habitable temperatures from day to night. A Rover Environmental Monitoring Station (REMS) device will be used to assess temperature ratings in and around the pit, and an M-42 radiation detector will record critical radiation data while the robot remains inside the pit. Regarding lessons learned from the Compton Pit, an advanced knowledge of lunar caves will be developed in terms of conditions and the probability that life can survive in the pit. Further exploring the lunar environment also develops the understanding of what needs to be done to sustain life under extraterrestrial conditions.

The readily available amount of in-situ resources will be examined as the robot approaches a 3 km distance from the Compton Pit. A Near-Infrared Volatile Spectrometer System (NIRVSS) and a Neutron Spectrometer System (NSS) will be used to record measurements considering volatiles critical to supporting future habitability. These two devices are positioned lower on the HELP rover in order to obtain measurements concerning Oxygen and Hydroxyl, two volatiles that will help decide if this area presents a suitable environment. A ProSEED drill is oriented vertically on the robot to detect in-situ resources directly beneath the rover. Finding the presence of Silicon, Carbon, and Hydrogen will enhance understanding of the lunar environment in the vicinity of the Compton Pit. Comparing data regarding temperature and radiation levels between these surface areas and the lunar pit itself will help draw differences that lead to conclusions regarding other pits too. This mission will improve knowledge of other planets across solar systems with celestial bodies that share a similar landscape to the Moon. Obtaining an overall understanding of these pits will support future decisions that consider movements to sustain life on these comparable celestial bodies. Lunar caves are candidates for providing a stable environment for long-term lunar habitation, and the Compton Pit might just support human exploration on the Moon.

1.2 Science Traceability Matrix

To address the overarching science goals that have been established for this mission, several science goals have been defined. These objectives with consideration of customer restraints and each collect materials and data to fulfill the science goals. Analyzing the resulting data and samples obtained from these science objectives will pave the way for valuable mission discoveries regarding the Compton Pit and the lunar surface surrounding the pit.

The first science goal defined for this mission involves the mission's robotic system and how it will affect future research that will be conducted on the Moon's surface. To ensure that astronauts are efficiently prepared for the mission, two science objectives have been defined. The first objective requires determining the readily available amount of Oxygen and metals as in situ resources in the lunar regolith located around and inside the Compton Pit. The studies of lunar regolith stimulants can be used to determine the limits of the stimulants to validate key components for human survivability during sustained presence on the Moon (Chandra et al. 2010). The PROSPECT Sample Excavation and Extraction Drill (ProSEED) would be a suitable instrument to complete this goal. The system's purpose of gathering core samples to extract regolith samples will aid NIRVSS in determining the concentration of hydrogen, water, hydroxyl, and other volatiles. ProSEED would be able to drill into the lunar surface and collect data measurements to fulfill this objective.

The second objective is to determine the amount of solar wind materials, water, and Hydroxyl molecules present in the lunar regolith located near or within the Compton Pit. Water is an important resource for future habitability. Although there may not be many water molecules, the process of combining Hydrogen and Hydroxyl molecules can be further studied to obtain water necessary to survive. The Moon isn't able to protect itself from high levels of radiation, therefore surface regions can be identified that could be protected from inhabitable radiation levels. The Near-Infrared Volatile Spectrometer System (NIRVSS) acquires spectra between 1600-3400 nm, <15 nm resolution, and can identify key volatiles (solid and gas) and minerals while surface roving and subsurface drilling (Roush and Colaprete, 2015). It is designed to measure surface and subsurface water, carbon dioxide, and methane and is able to map the surface temperature and changes that occur at the landing site (Colaprete, 2022). NIRVSS would be efficient to collect similar minerals to past research experiments. A similar design or instrument would ensure proper data collection. Similarly, the Neutron Spectrometry System (NSS) will measure the amount of hydrogen-bearing materials near the surface at the landing site to determine the potential for water ice (NASA, PEREGRN-1-02). Together, both of these instruments are able to identify the H, O_2, H_2O, and OH molecules and assess how many of the materials at the surface have the potential to become water ice.

The second science goal defined for this mission determines the ability of the robotic system to provide and locate a safe habitat to protect individuals, equipment, and associated infrastructure. The first objective is to characterize the dimensions and deformations of the Compton Pit. The system will have to measure the depth, height, terrain variation, ease of access, and structural integrity of the pit. Mapping these physical features are imperative to determine conclusions for human habitation. Identifying dimensions and deformations is crucial for the safety of astronauts. Additionally, identifying overhangs and stress points will allow astronauts to detect potential hazards that could endanger personnel and equipment. These dangers should be identified to avoid or reinforce vulnerabilities to increase safety. A Light Detection and Ranging (LiDAR) system creates topographic maps that would identify terrain features, slopes, and potential obstacles. Sensing systems can identify potential hazards and allocate preparation to navigate risks and obstacles.

The second science objective is to measure temperature and radiation levels within the Compton Pit. This data will allow astronauts to make decisions regarding sustainability and survivability of the individuals and equipment that will be staying within the potential habitat area. An instrument such as the Multi-Parameter Aerosol Scattering Sensor (MPASS) would provide information about the particles in the environment in real time. Since it is an aerosol-detection system, it will categorize atmospheric particles and monitor them in real time to assess whether the environment is safe enough for life (NASA Technology Transfer Program). It is imperative that the cave remains below a radiation threshold to maintain a safe environment for human habitation.

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Predicted Instrument Performance	Instrument	Mission Requirements
		Physical Parameters	Observables					
“Develop precursor lunar robotic missions and define those scientific activities that astronauts will conduct on the Moon” - Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032	Determine the readily available amount of metals as in situ resources in the lunar regolith located around and inside the Compton Pit.	Identify Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicates, and Anorthite Plagioclase.	Collect spectral signatures of Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicates, and Anorthite Plagioclase present 10 cm below the surface in a 3km area.	Drilling Depth:	10 - 30 cm below the ground	100 -120 cm	PROSPECT Excavation and Extraction Drill (ProSEED)	Identify and process lunar resources remotely, including water and oxygen Develop compatible hardware for extreme lunar environments
				Material Hardness (Mohs Scale)	6	6		
				Control and Operation:	Cordless and remote battery-operated motor with specialized drill bits and modular core stems	Cordless, battery-operated motor with specialized drill bits and modular core stems		
				Material Compatibility:	100-300 K	100 - 323 K		
	Determine the amount of solar wind materials, water, and Hydroxyl molecules present in the lunar regolith located around and inside the Compton Pit.	Identify Hydrogen (H) Oxygen (O2), water (H2O), and Hydroxyl (OH) molecules measure the amount of hydrogen-bearin g materials near the surface at the landing site to determine the potential for water ice.	Collect spectral signatures of H, O2, H2O, and OH in the 10-30 nm range over a 3km area.	Wavelength range:	1600-3400 nm	1300-2500 nm, 2200 - 4400 nm	Near-Infrared Volatile Spectrometer System (NIRVSS)	Map out the temperature and changes on the site Measure subsurface and subsurface water, CO2, and CH4 Analyze the composition and structure of the surface and subsurface with the detection of neutrons.
				Integration time:	1 s-1	712 bits per sample		
				Sensitivity:	Thermal and epithermal neutrons	Thermal and epithermal neutrons		
				Spatial Resolution:	H2O: 20-30 nm NH3 : 10-20 nm CO2 : 10-20 nm CH4 : 20-30 nm	<20 nm and <50 nm		
			Detect water ice and other volatiles to better than 0.5% mass fraction within a 10m radius	Wavelength range:	1 ev- 1 keV	<0.3 ev - 1 keV	Neutron Spectrometer System (NSS)	Detect water ice and other volatiles: Detect in-situ resources on sunlit portion of mission site during the day
				Integration time :	<= 550 cts/s	<= 511 cts/s		
				Sensitivity:	80/ cm^2	80/ cm^2		
				Sample rate:	1/s	1/s		

Life Support & Habitat: mLSH1 - "Provide safe and enduring habitation systems to protect individuals, equipment, and associated infrastructure" (Lunar Exploration Analysis Group (LEAG) Habitation: HAB-SAT Report, Priority Objectives)	Characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves to determine the viability of human habitation.	Define the dimensions and deformations of the lunar pits/caves.	Collect and map the dimensions, deformations, terrain, overhangs, and stress points in a 35m or greater range.	Wavelength range:	400m	450m	RIEGL VZ-400 V-Line 3D Terrestrial Laser Scanner	Map the interior of the pit, develop point cloud for data analysis
				Integration time:	110,000 measurements/sec	122,000 measurements/sec		
				Sensitivity:	4mm precision, 5mm accuracy	Precision, 3mm, accuracy 5mm		
				Spatial Resolution:	5mm	4mm		
		Identify the Galactic Cosmic Ray flux in the Compton Pit, measure variation in its diurnal, seasonal, and solar cycle, and measure temperature variation.	Detects temperature measurements between 273K and 373K and radiation levels that exceed 25,000 millirems.	Temperature range:	273-373 K	143-343 K	Rover Environmental Monitoring Station (REMS)	Collect dosimetry and temperature data in the Compton pit to determine habitability
				Integration time:	1 s	1 s		
				Sensitivity:	2 K	1 - 4.5 K		
				Resolution:	2 K	2 K		
				Detection range:	0.1 MeV - 15 MeV	0.06 MeV - 18 MeV	M-42 Radiation Detector	
				Integration time:	300 s	300 s		
				Sensitivity:	0.5 MeV	0.5 MeV		
				Measuremen t rate:	0.5 cts/s	0.4 cts/s		

Figure 1: Science Traceability Matrix

1.3 Summary of Mission Location

The mission will take place in the Compton Pit. During the selection process, the mission requirements had not been finalized, except for the main goal of finding blackbody behavior. Accordingly, pits were chosen that had the highest likelihood of blackbody behavior. The variables considered were size and the existence of an entrance ramp, to assist the vehicle in accessing the pit. In addition, data provided by the article by Coombs and Hawke affected the selection process. Seven options were chosen: the Mare Moscoviense Pit, the Sinus Iridium Pit, the Compton Pit, the Lacus Mortis Pit, the West Marius Hills Pit, the Mare Insularum Pit, and the Central Mare Fecunditatis Pit. Despite pits such as Mare and riles in the Mare Serenitatis being better candidates to connect to intact lava tubes (Coombs, Hawke), and Mare Tranquillitatis and Mare Ingenii having been shown to exhibit blackbody behavior (Horvath and Hayne, 2022), it was decided that the seven options chosen best fit the search criteria and could provide valuable new data.

The seven options were entered into a trade study to determine the best choices. The selection criteria included the average slope of the surrounding area, the ratio of the average funnel diameter to the average inner diameter, the latitude of the pit, and the angle of the entrance ramp. Using this criteria, the options were narrowed down to three: the Mare Moscoviense Pit, the Compton Pit, and the Sinus Iridium Pit. From those options, the Sinus Iridium Pit was considered to be too small to adequately sustain the mission. The Mare Moscoviense Pit and the Compton Pit exhibit similar characteristics, but the Compton Pit had a higher latitude and was extremely similar in shape to the Mare Ingenii Pit (“Pits Atlas”, n.d.), and was therefore more favorable to the mission, as it had a higher chance of containing ice and exhibiting blackbody behavior (Horvath and Hayne, 2022).

The Compton Pit is a Mare pit at latitude 56.2247 and longitude 106.1955 inside the Compton crater. The pit contains a funnel diameter of 230m X 140m and an inner diameter of 110m X 92m. There is an overhang under the east rim. The pit was photographed three times, with the first measurement displaying a depth of 26.6m, the second measuring 38.7m, and the third measuring 40.0m. However, these measurements were taken partway down the slope and may not be accurate to the true depth of the pit. There is a permanently shadowed region on the southeast rim. The entrance ramp is approximately 120m long with a slope of 20° (“Pits Atlas”, n.d.). The rim of the pit has an elevation of approximately 3488.75m.

Compton Crater is an impact crater that is 164.63 km in diameter (“MOON-Compton”, n.d.), and is known for having a central peak inside of an inner ring. It is 3.85 billion years old and was named after the physicists Arthur Compton and Karl Taylor Compton (Portee, 2019). The pit is 10 km east of the west wall of the crater. It is near the Compton–Belkovich Volcanic Complex, which experiences silicic volcanism, which is rare on the moon (Shirley et al., 2016). However, according to data from Clementine, it is relatively poor in iron.

The landing zone has been determined to be a circle of radius 50m centered at 56.236 N, 106.845 E, based on mission requirements. Its location with respect to the

Compton Pit can be seen in Figure 4. This circle is 300m from the edge of Compton Pit. Within the circle, it was found through JMARS that the elevation has a difference of 0.5m from its highest to lowest section. This results in an average slope of 0.005 degrees. Further research needs to be done to determine external measurements around the pit, as data from the LROC and LOLA are not in high enough resolution to draw accurate measurements.

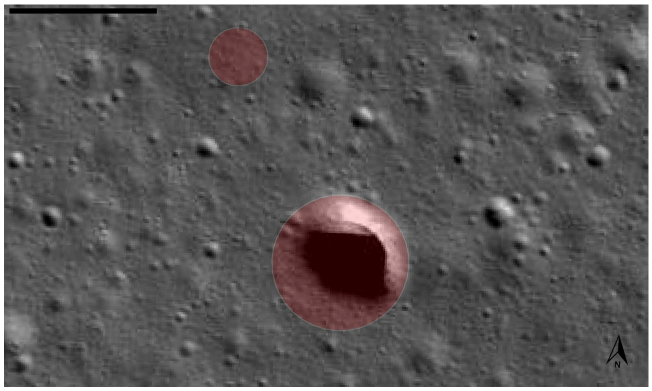


Figure 2: Aerial View of the Compton Pit

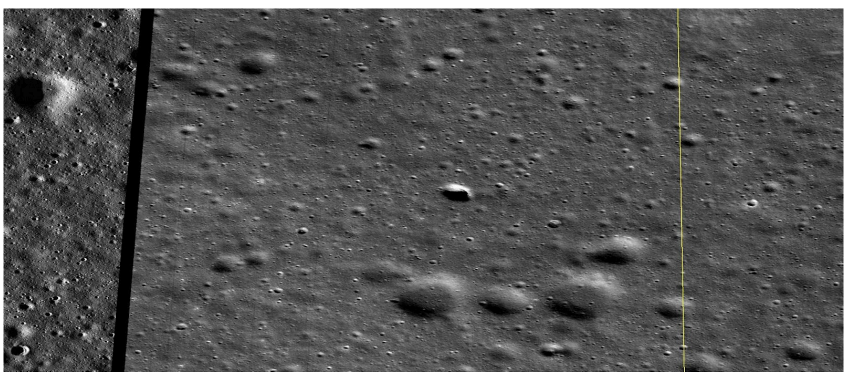


Figure 3: Alternative Angled View of the Compton Pit

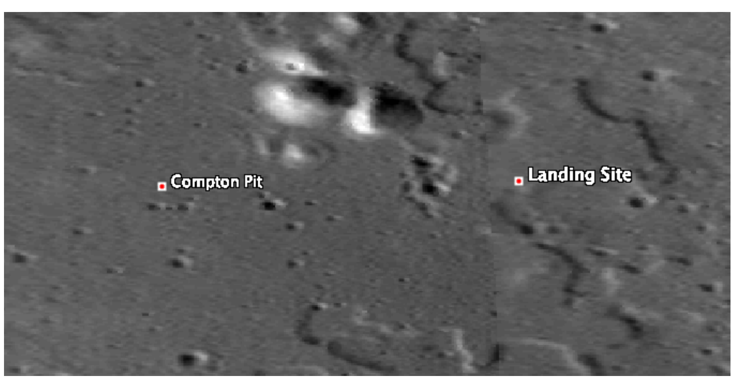


Figure 4: View of Compton Pit and Landing Site

1.4 Mission Requirements

Mission requirements are critical to identifying and prioritizing the events and criteria necessary to ensure that a mission is successfully completed. This criteria is often specified not just for the spacecraft as a whole, mission science, and project programmatics, but is applicable to subsystems and individual subcomponents as well ("Introduction to the Derivation of Mission Requirements Profiles for System Elements" n.d.). This section focuses specifically on the top-level mission requirements that define this mission concept. These requirements are outlined in Figure 5, and each identifies overarching performance, programmatic, and environmental parameters that form the basis for additional child requirements ("Introduction to the Derivation of Mission Requirements Profiles for System Elements" n.d.).

In Figure 5, there are two broad mission goals (MGs) that form the basis for the purpose of this mission. Each MG was outlined by the customer as a major point of interest that must be addressed in the completion of the mission[1]. One goal states that the spacecraft must help identify potential courses of action to be taken on the Moon by astronauts in the future. The second goal ensures that the mission spacecraft will evaluate the habitability of an environment on the Moon. This habitat might provide refuge to astronauts looking to escape the extreme conditions present across the lunar surface. In establishing these two comprehensive requirements, mission requirements are further outlined that address project management, science, and spacecraft subcategories.

Project management (PM) requirements encompass customer constraints defined for mission engineering, science, and programmatics. The budget for the mission has undergone descoping from $425 million to $300 million. The mission launch date is scheduled for March 1, 2030. To demonstrate that the HELP mission is capable of meeting science (SCI) requirements, the Mission Timeline section outlines major milestones the HELP team will follow to increase mission confidence. The goals for HELP involve hydrogen sampling, mineral sampling, and mapping. The HELP rover will search for hydrogen in the lunar regolith, and will use a spectrometer system to determine whether the hydrogen is in the form of free hydrogen, water, or hydroxyl. All are important in-situ resources for human habitation. In addition, the mission rover will use its spectrometer to find other important minerals on the Moon, such as Iron and Pyroxene.

The HELP spacecraft will also evaluate the Compton Pit to determine its suitability for future human habitation. It will evaluate whether or not the Compton Pit exhibits constant temperatures throughout the Moon's orbit, and whether it might provide protection for humans from solar radiation. It will also map the inside of the pit and gather data to inform next steps in regards to planning future habitation of the Moon. While these broader expectations are outlined in Figure 5, more precise requirements are further explained in subsystem requirements tables. These tables take

[1] Top-level mission requirements are based on customer constraints outlined in the MCA Mission Task Document.

a closer look at component-specific requirements, and how they're expected to contribute to the generalized conditions found in Figure 5.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
MG-1	The mission shall develop a precursor lunar robotic mission that will define future scientific activities for astronauts to conduct on the Moon.	To collect volatile and in-situ measurements and quantify how much of each is readily available within a 3 km area surrounding the Compton Pit. These measurements can be further used to draw conclusions about the lunar surface and lunar regolith in general.	-	All	Demonstration	All Subsystems	Met
MG-2	The mission shall evaluate an environment that may provide safe and enduring habitation systems to protect individuals, equipment, and associated infrastructure on the Moon.	To potentially identify an environment in which humans can establish a habitation system that provides protection from extreme lunar conditions.	-	All	Demonstration	All Subsystems	Met
PM-1	The mission shall fall within outlined customer constraints concerning budget, schedule, and spacecraft specifications.	To maintain mission support and to ensure that the mission will fall within programmatic, technical, and scientific expectations.	MG-1 MG-2	PM-1.1 PM-1.2 PM-1.3 PM-1.4 SC-6	Demonstration	All Subsystems	Met
PM-1.1	The mission shall have a cost cap of $300 to expend.	To meet the budgeting customer constraint clarified after the budget descope that saw a decrease in the mission budget from $425 million to $300 million.	PM-1	-	Analysis	All Subsystems	Met
PM-1.2	The spacecraft shall be ready for launch by March 1st, 2030.	To meet the scheduling customer constraint outlined in the MCA Mission Task Document.	PM-1	-	Analysis	All Subsystems	Met
PM-1.3	The mission shall follow the NASA Mission Life Cycle and will coordinate documents to pass the required gate reviews.	To abide by NASA protocols, justify the mission's importance, and increase the probability of mission success.	PM-1	-	Analysis	All Subsystems	Met
PM-1.4	The spacecraft shall land on the Moon at a landing zone 100 km in diameter that doesn't exceed a slope of 10 degrees.	To ensure the primary launch vehicle lands safely on the Moon so the secondary launch vehicle, the mission spacecraft, will be safely deposited to begin meeting mission science requirements.	PM-1	PM-1.4.1	Analysis	Entire Spacecraft	Met

PM-1.4.1	The identified landing zone shall be within 5 km of the selected pit if the spacecraft is a mobile vehicle and is required to traverse to the pit from the landing site.	To limit the distance the mission spacecraft must travel and the obstacles it encounters to reach the Compton Pit from its landing site.	PM-1.4	-	Analysis	Entire Spacecraft	Met
SCI-1	The readily available amount of in-situ minerals and metals shall be measured in the lunar regolith located near the Compton Pit.	To support in-situ resource utilization (ISRU) efforts and prepare for future human missions by analyzing critical elements for life support and construction.	MG-2	SCI-1.1 SCI-1.2	Demonstration	Payload	Met
SCI.-1.1	The amount of Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicates, and Anorthite Plagioclase shall be quantified in the lunar regolith near the Compton Pit.	To identify essential mineral resources needed for oxygen extraction and building materials.	SCI-1	SCI-1.1.1 SCI-1.1.2	Test	Payload	Met
SCI-1.1.1	Spectral signatures of Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicates, and Anorthite Plagioclase shall be collected from the lunar regolith.	To verify the presence of key minerals over a 3 km area, enabling resource mapping in the vicinity of the Compton Pit.	SCI-1.1	-	Test	Payload	Met
SCI-1.1.2	Spectral data will be collected in the 350-500 nm range.	To target the specific wavelengths where these minerals exhibit distinct spectral features, ensuring accurate identification.	SCI-1.1	-	Test	Payload	Met
SCI-2	The amount of solar wind induced materials shall be measured in the lunar regolith near the Compton Pit.	To evaluate the potential for extracting water and other essential materials for future missions and habitation on the Moon.	MG-2	SCI-2.1 SCI-2.2	Demonstration	Payload	Met
SCI-2.1	The amount of Hydrogen (H), Oxygen (O2), water (H2O), and Hydroxyl (OH) molecules shall be quantified in the lunar regolith located near the Compton Pit.	To map the availability of water and essential gasses in the surrounding area, critical for life support and fuel production.	SCI-2	SCI-2.1.1	Test	Payload	Met
SCI-2.1.1	Spectral signatures of H, O2, H2O, and OH molecules shall be collected in the 2.8-3.0 μm range.	This wavelength range is critical for detecting water and hydroxyl molecules, enabling resource assessment for ISRU.	SCI-2.1	-	Test	Payload	Met
SCI-3	The depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels of the Compton Pit shall be characterized.	To assess the viability of lunar pits/caves for future human habitation, supporting exploration and habitation goals.	MG-2	SCI-3.1 SCI-3.2	Demonstration	Payload	Met

SCI-3.1	The dimensions and deformations of the Compton Pit shall be quantified.	To create a detailed topographical map of the cave and surrounding area, ensuring it meets the criteria for human habitation and exploration.	SCI-3	SCI-3.1.1	Demonstration	Payload	Met
SCI-3.1.1	The dimensions, deformations, terrain, overhangs, and stress points of the Compton Pit shall be mapped over a 35 m or greater range.	To ensure the structural integrity of the site and assess potential hazards or areas for safe habitation.	SCI-3.1	-	Test	Payload	Met
SCI-3.2	Temperature and radiation levels shall be measured within the Compton Pit.	To ensure that the environment is suitable for human habitation, with acceptable levels of radiation and manageable temperature variations.	SCI-3	SCI-3.2.1 SCI-3.2.2	Demonstration	Payload	Met
SCI-3.2.1	Temperature measurements shall be detected between 273K and 373K.	To support NASA's Lunar Exploration objectives by exploring the feasibility of using lunar pits/caves as future habitat locations for astronauts.	SCI-3.2	-	Test	Payload	Met
SCI-3.2.2	Radiation levels that exceed 25,000 millirems shall be measured.	To ensure that astronauts or robotic systems can access the cave with minimal risk, supporting long-term missions.	SCI-3.2	-	Test	Payload	Met
SC-4	The spacecraft shall determine the amount of in-situ resources and readily available volatile materials present on the lunar surface in the area surrounding the Compton Pit.	To evaluate the available resources near the Compton Pit given it's a potential location for human habitability.	MG-1	SC-4.1 SC-4.2 SC-4.3 SC-4.4 SC-4.5 SC-4.6	Demonstration	Payload	Met
SC-4.1	The spacecraft shall traverse the lunar surface from the landing site to the Compton Pit.	To ensure that the rover successfully enters the Compton Pit and obtains the necessary science measurements inside the pit.	SC-4	SC-4.1	Demonstration	Mechanical	Met
SC-4.1.1	Mechanical system shall traverse the jagged and uneven lunar surface sufficiently.	To ensure the spacecraft doesn't get stuck or tip over in its transit from landing site to the Compton Pit.	SC-4.1	-	Test	Mechanical	Met
SC-4.2	Payload instruments shall collect samples from the lunar regolith surrounding the Compton Pit.	To ensure science requirements are successfully met by obtaining the necessary science measurements from the lunar surface regolith.	SC-4	-	Demonstration	Payload	Met
SC-4.3	The Data Handling system shall store science measurements obtained by the payload instruments on the lunar surface regolith.	To ensure the science measurements obtained are securely stored and are recorded efficiently in an organized way.	SC-4	-	Test	CDH	Met

SC-4.3.1	Communications components shall relay data stored from the lunar surface regolith to an orbiting spacecraft, which then transmits this data to Earth ground control.	To ensure lessons learned can be drawn from the recorded data and further research on the Moon can be done in the future.	SC-4	-	Test	CDH	Met
SC-4.4	Guidance, navigation, and control system shall circumvent significant obstacles impeding the spacecraft's path from its landing site to the Compton Pit.	To ensure the spacecraft successfully travels from the landing site to the Compton Pit and avoids significant craters and other threatening landmarks.	SC-4	-	Test	GN&C	Met
SC-4.5	Power system shall store energy during daylight hours to power spacecraft components.	To ensure the spacecraft has enough energy to travel, collect measurements, and traverse into permanently shadowed regions.	SC-4	-	Test	Power	Met
SC-4.6	Thermal system shall maintain component operational temperatures during major temperature fluctuations between shaded and lit areas.	To limit stresses and strains placed on system components from extreme lunar temperatures.	SC-4	-	Test	Thermal	Met
SC-5	The spacecraft shall monitor environmental conditions, including potential hazards, while exploring the Compton Pit.	To ensure that the cave is a safe and viable location for habitation, with minimal risks from environmental factors such as micrometeorite impacts or landslides.	MG-1	SC-5.1 SC-5.2 SC-5.3 SC-5.4 SC-5.5 SC-5.6 SC-5.7	Demonstration	Payload	Met
SC-5.1	The spacecraft shall traverse into the Compton Pit via an accessible sloped surface ramp.	To ensure that astronauts or robotic systems can access the cave with minimal risk, supporting long-term missions.	SC-5	SC-5.1	Demonstration	Mechanical	Met
SC-5.1.1	The Mechanical system shall be capable of traversing a sloped surface.	To ensure that the spacecraft can travel into the Compton Pit without getting stuck or tipping over.	SC-5.1	-	Test	Mechanical	Met
SC-5.2	Payload instruments shall evaluate the environmental conditions and habitability of the Compton Pit.	To ensure science requirements are successfully met regarding the Compton Pit, and the pit's habitability is subsequently determined.	SC-5	-	Demonstration	Payload	Met
SC-5.3	Guidance, navigation, and control system shall conduct sequential operations to traverse the robot into the Compton Pit.	To ensure the robot efficiently makes its way into the Compton Pit via the pit's accessible ramp.	SC-5	-	Test	GN&C	Met
SC-5.4	Power system shall store enough energy to explore the Compton Pit for distinct periods of time in permanently shadowed regions.	To ensure the spacecraft can explore darker areas of the pit without running out of energy.	SC-5	-	Test	Power	Met

SC-5.5	Thermal system shall maintain operational temperatures of the spacecraft while exploring the Compton Pit.	To ensure system components won't fail due to potential extreme temperatures in the Compton Pit.	SC-5	-	Test	Thermal	Met
SC-5.6	The Data Handling system shall store science measurements recorded by the payload instruments in the Compton Pit.	To ensure science measurements recorded by the payload instruments are stored efficiently and in an organized manner.	SC-5	SC-5.6	Test	CDH	Met
SC-5.6.1	Communications components shall relay data recordings taken in the Compton Pit to mission ground control.	To ensure lessons learned are drawn from the data stored by the spacecraft's payload instruments.	SC-5.6	-	Test	CDH	Met
SC-5.7	The spacecraft shall complete decommissioning protocols at the end of the HELP mission timeline.	To ensure planetary protection protocols are followed sufficiently.	SC-5	SC-5.7	Demonstration	Power	Met
SC-5.7.1	Power system shall complete passivation protocols to deplete extra stored energy.	To ensure the spacecraft doesn't explode due to energy build-up in the Compton Pit, which would make the pit uninhabitable.	SC-5.7	-	Test	Power	Met
SC-6	The spacecraft shall refrain from using radioactive material in its design that exceeds a total mass of 5 grams.	To limit the amount of safety concerns present while manufacturing and testing the spacecraft, and to follow planetary protection guidelines that protect the lunar environment from contamination.	PM-1	SC-6.1	Analysis	Entire Spacecraft	Met
SC-6.1	The spacecraft shall not incorporate any Radioisotope Thermoelectric Generator (RTG) or any device derived from the design of an RTG.	To minimize mission safety concerns and minimize the risks related to radioactive material in spacecraft manufacturing and testing.	SC-6	-	Analysis	Entire Spacecraft	Met

Figure 5: Mission Requirements Table

1.5 Concept of Operations

The HELP mission's concept of operations begins when the rover lands on the lunar surface. The goal is to land inside the Compton crater at a spot 300m outside of the edge of the Compton Pit. Upon landing, pre-checks of all instrumentation onboard will be run to ensure everything is operating as it should be.

Once all instrumentation is checked and powered on, the rover begins its traverse to the entrance of the pit. Since the rover architecture is similar to the architecture of Chandrayaan-3, the speed the rover traverses at will match the speed of Chandrayaan-3, which was 1 centimeter per second (Kotwal, 2023). Since the rover will land so close to the entrance, it is expected to only take approximately 9 hours to reach the entrance of the pit, where it will begin its science data collection.

Once it reaches the entrance of the pit, the rover will first collect spectral signatures of ilmenite, pyroxene, olivine, anorthite, magnesium-rich silicates, and anorthitic plagioclase using the ProSEED drill. Next, it will collect spectral signatures of hydrogen, oxygen, water, and hydroxide in the 10-30 mm range using NIRVSS. After that, it will detect water, ice, and other volatiles to better than a .5% mass fraction within a 10-meter radius using NSS. This soil evaluation is estimated to take approximately 14 days, based on the time required for the Chandrayaan-3 rover to obtain similar measurements ("Chandrayaan-3", 2024). Next, the rover will collect and map the dimensions, deformations, terrain, overhangs,and stress points in a 35-meter or greater range using RIEGL. Finally, it will collect temperature measurements between 273K and 373K and radiation levels that exceed 25,000 millirems using REMS.

Once this data is collected, the rover will make its descent into the pit. Once it reaches the bottom, it will repeat the soil, temperature, and radiation evaluations, as well as conduct cave mapping. Mapping the cave will allow the team on Earth to understand the dimensions, deformations, terrain, overhangs, and stress points in the cave. The cave mapping process is expected to take approximately a month to completely collect all of the necessary data. The largest caves typically take around 27 days to be completely mapped; therefore, a month is given in case the cave found within the pit is larger than predicted (Gibb, 2021). Once all of the data has been collected, it will then be organized and documented correctly for further research and analysis. The entire Concept of Operations is shown in Figure 6.

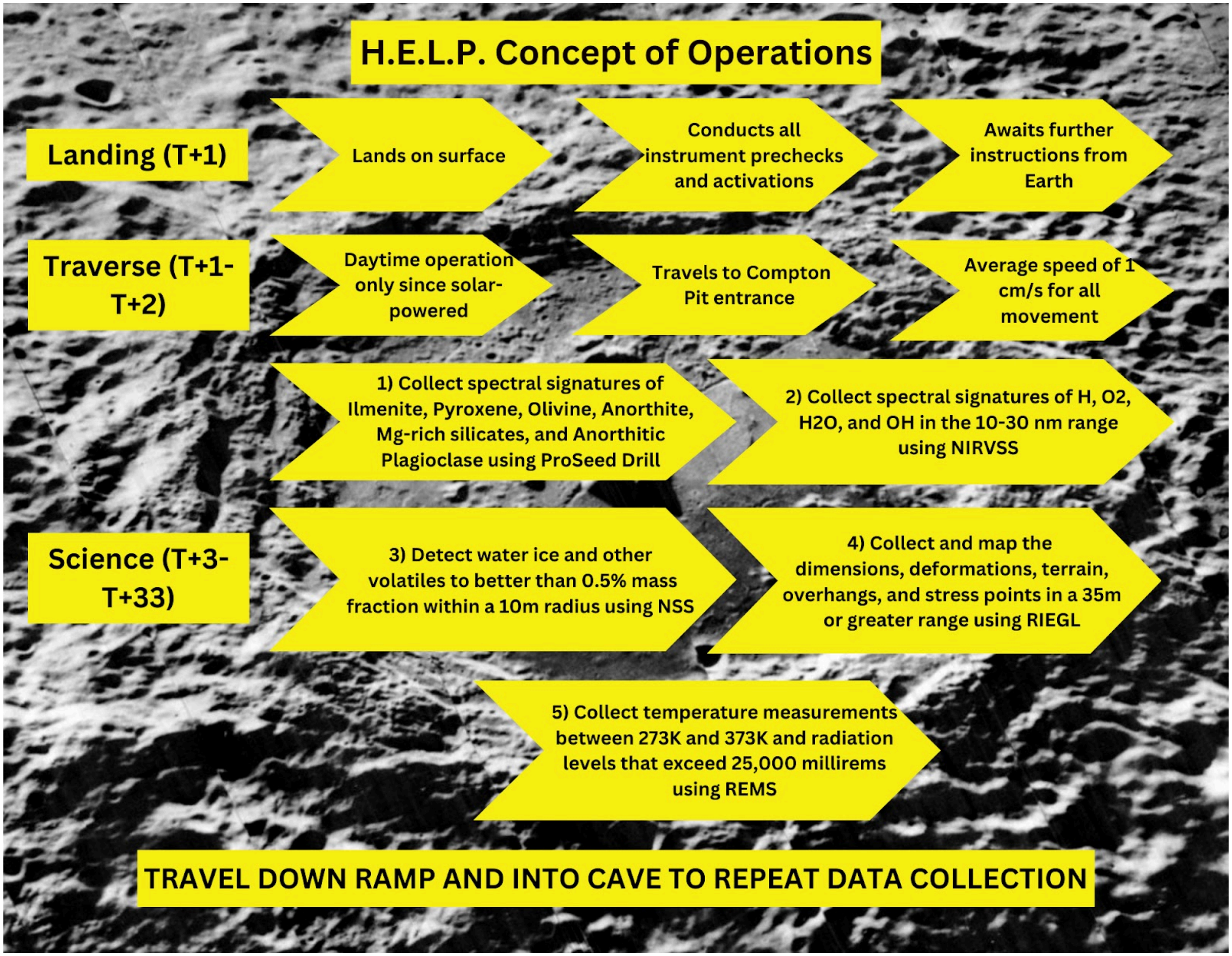


Figure 6: Concept of Operations Graphic

1.6 Vehicle Design Summary

The HELP mission rover is 1.25 meters wide, 1.5 meters long, and 1.7 meters tall. The chassis is a rectangular box, modeled after the Chandrayaan-3 mission rover. The chassis supports a rectangular giraffe-like neck that houses the ProSeed drill that is used to complete the science objectives of the mission. The rest of the instrumentation and subsystems are housed in the rectangular chassis.

The chassis is suspended by a rocker-bogie system, and wire-mesh tires allow for easy, smooth traverse across the lunar surface. Triple-junction solar cells are used for power, which are attached on top of the rectangular chassis. Overall, the total mass of the rover is 266.4 kg, and the total maximum power consumption of the rover is between 686.2 W to 851.2 W. The mass of the HELP spacecraft is beneath the constraint of 300 kg defined by the customer[2].

An image of the vehicle is seen in Figure 7.

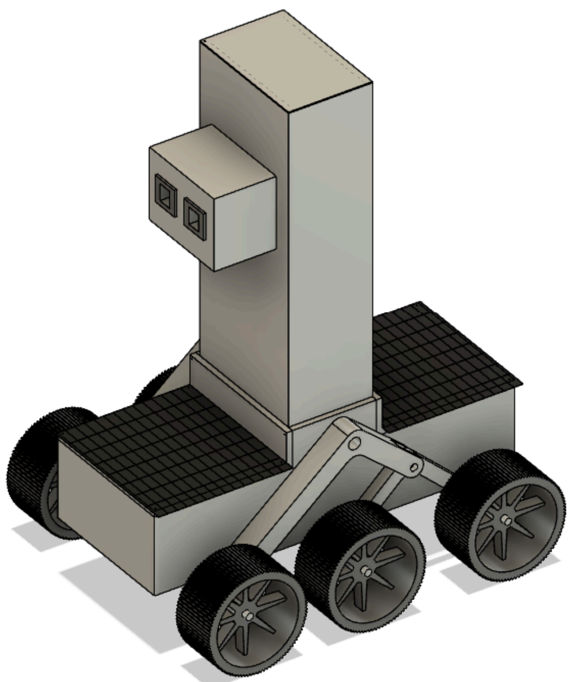


Figure 7: HELP Rover

[2] This mass constraint is defined in the MCA Mission Task Document.

1.7 Science Instrumentation Summary

The instruments aboard HELP are the NIRVSS, NSS, REIGL, ProSEED, REMS, and M-42.

The RIEGL VZ-400 V-Line 3D Terrestrial Laser Scanner (REIGL) is a LiDAR system produced by the REIGL company. It uses lasers to create a point cloud that maps the inside of Compton Pit. This map can be used to create a 3D model of Compton Pit. Through this, it can be determined how HELP can navigate the pit, and where the best sites for human habitation are. In addition, the map can also determine which sites inside the pit would be more likely to exhibit blackbody behaviour, and can guide M-42 measurements.

The ProSEED drill is a simple percussion drill that can take samples of the lunar regolith. It will take samples from up to 100-120 cm below the surface. These samples are important as they can be analyzed to determine whether there are volatiles in the sample or forms of hydrogen.

The NSS is a system that can scan the lunar regolith to determine whether there is hydrogen present. However, the NSS is unable to determine whether the hydrogen detected is free hydrogen, hydroxyl, or water (H2O). The areas that have been determined by the NSS to contain high levels of hydrogen can be drilled by ProSEED and analysed by NIRVSS to determine the molecules present.

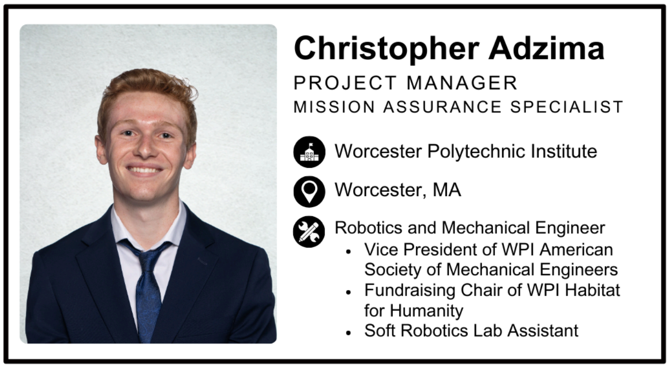
NIRVSS is a spectrometer system that can analyze soil samples collected from the ProSEED drill after detection of volatile molecules in the sample by NSS, as well as continuously analyze the surface under the rover. NIRVSS can detect and differentiate the volatile molecules H, O_2, H_20, and OH via measuring absorption of light spectra on surfaces. The amount of hydrogen near the surface can help predict if there is water ice near the surface of the lunar cave for habitation. NIRVSS will also analyze surface and subsurface composition.

REMS houses a set of thermopiles that will measure the lunar ground temperature to the side of the HELP rover in a range of 143 - 343 K, in 5 minute intervals. These temperature measurements are necessary to determine temperature variation in the Compton Pit over a time scale to determine the potential habitability of the Compton Pit.

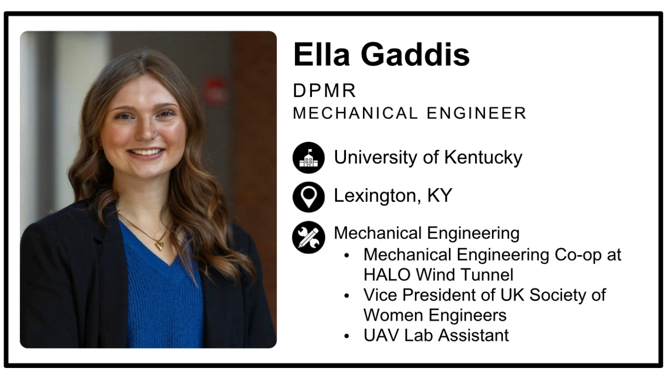
M-42 is a radiation detector that collects dosimetry data in a range of .06 - 18 MeV in 5 minute intervals. M-42 records data by detecting cosmic radiation rays and secondary particles through various detectors for different sources of radiation. M-42 analyzes the energy spectra and flux of detected rays and particles to collect radiation data. Collecting radiation data is necessary to determine the levels of radiation Compton Pit is exposed to, and determine the potential habitability of the Compton Pit.

1.8 Programmatic Summary

1.8.1 Team Introduction



Christopher Adzima is the HELP team's Project Manager and Mission Assurance Specialist. Chris is an undergraduate junior who attends Worcester Polytechnic Institute (WPI) in Worcester, Massachusetts. Chris is actively pursuing a Bachelor of Science in Robotics Engineering and Mechanical Engineering. Chris's involvement on campus has helped contribute to Chris's role in the HELP team and impact on the HELP mission. As Vice President of WPI American Society of Mechanical Engineers, Chris organizes professional events with mechanical engineering organizations and speaks at events structured to improve member knowledge of mechanical engineering. Chris's experience with this club has helped Chris become a leader that feels comfortable communicating with individual team members and speaking during HELP team meetings. As Fundraising Chair of WPI Habitat for Humanity, Chris brainstorms fundraising events to generate funds for club events that help to alleviate housing crisis concerns. Chris communicates with a team of executives to plan these opportunities, similar to how Chris has discussed task distribution and team member expectations within the HELP team. As a Soft Robotics Lab Assistant, Chris observes and helps identify interface strategies that bridge 3D printed soft robotic fingers with Hall effect sensors to collect force data. This experience has helped Chris outline interface techniques for the HELP spacecraft and identify potential risks to mission success as a Mission Assurance Specialist.



Ella Gaddis serves as the HELP mission Deputy Project Manager of Resources and Mechanical Engineer. Ella is an undergraduate junior at the University of Kentucky, pursuing a bachelor's of science in mechanical engineering and an undergraduate certificate in aerospace engineering. Ella's experiences both on and off campus have helped to prepare Ella for the aforementioned roles on the HELP team. As the vice president of UK's chapter of the Society of Women Engineers, Ella plans social events for its members and is in charge of its DanceBlue team that fundraises for the UK Pediatric Cancer Hospital. Ella has also worked in UK's UAV Lab, assisting with test flights and data analysis of drone prototypes. Through this lab, Ella was also able to be a part of NASA's National Eclipse Ballooning Project, a project where many institutions worked together by prepping and launching weather balloons that measured the effect of eclipses on gravity waves. While participating in the academy, Ella worked as a mechanical engineering co-op at the Honda Automotive Laboratories of Ohio (HALO) wind tunnel that Honda uses for aerodynamic and aero-acoustic testing of both passenger cars and racecars. All of these experiences have helped Ella excel on both the engineering team and the programmatics team.

Enayah Tur Rahman

CHIEF SCIENTIST
SCIENTIST

George Mason University

4400 University Dr (Fairfax, VA)

Math

- Researcher at MEGL

Enayah Rahman is the Chief Scientist of the HELP mission, as well as one of the scientists. Enayah is an undergraduate student at George Mason University, majoring in Mathematics. Enayah is an undergraduate researcher at the Mason Experimental Geometry Lab, researching traveling waves in reaction-diffusion systems. This experience has helped Enayah understand the fundamentals of research, and better contribute to the L'SPACE project. Enayah is also project director at the nonprofit HatchHope Yawarith Foundation, where Enayah handles donations, website upkeep, and turning raw images and videos into compelling narratives. These skills help with the presentation of data on deliverables for the programme.

Ethan Gamboa

LEAD SYSTEM ENGINEER
MECHANICAL ENGINEER

University of Florida

Gainesville, Florida

Aerospace engineering
- Student pilot
- NCAS alumni

Ethan Gamboa is the lead system engineer and mechanical engineer for the HELP mission. Ethan is currently a sophomore studying Aerospace Engineering at University of Florida. While participating in the Mission Concept Academy, Ethan has been actively gaining flight hours as well as participating in NCAS. The experience Ethan has gained throughout these activities has equipped Ethan with the skills used to assist in the HELP mission.

Christopher Gravina

CDH ENGINEER
SCIENTIST

Rochester Institute of Technology

Rochester, NY

Physics and Applied Mathematics
- LSPACE NPWEE
- Math Modeling Research
- Math and Physics ASC Tutor
- House of General Science Committee Head

Christopher Gravina is Computer Hardware Engineer and Scientist for the HELP team. Chris is an undergraduate senior at Rochester Institute of Technology pursuing a Bachelor in Science in Physics and Applied Mathematics, recently accepted into the accelerated BS MS Physics program. Chris has prior experience in proposal writing through research grants and LSPACE NPWEE. Chris is currently involved in mathematical fluid dynamic research, developing software fluence with computers needed for a CDH Engineer. Chris is a walk-in tutor for math and physics courses, gaining problem solving and communication skills necessary for a large team mission such as HELP. Chris has contributed to the making and exhibition of several science projects by the House of General Science, a science interest based organization for campus students. In HELP, Chris uses science background to determine mission requirements and perform trade studies on potential science instruments.

Doris Levry

MISSION ASSURANCE SPECIALIST
OUTREACH OFFICER

University of Maryland College Park

College Park, MD

Mechanical Engineering
- Black Engineering Society
- QUEST Honors Scholar
- ClarkLEAD Ambassador
- Maryland Promise Peer Mentor
- Community Bridges Ambassador

Doris Levry is the Mission Assurance Specialist and Outreach Officer for the NASA L'SPACE Mission Concept Academy HELP team. Doris, a junior majoring in Mechanical Engineering at the University of Maryland, College Park, uses technical skills and vast leadership experience to guarantee mission success. Doris Levry's work as a consultant in the QUEST Honors Program sharpened Dori's skills in system analysis, workflow optimization, and successful solution implementation. By creating strong quality assurance procedures and supporting risk management plans to satisfy mission requirements, Doris Levry put these abilities to use at L'SPACE. Doris Levry can handle complex engineering problems with precision due to previous consulting experiences. In the role as the Black Engineering Society's Technical Outreach Community Help (TORCH) Program Leader, Doris Levry demonstrated a strong capacity for outreach. Doris's capacity to spearhead significant projects carried over naturally into the position as an Outreach Officer, where Doris Levry actively cultivates alliances and advances the HELP team's outreach objectives. In order to maximize alignment with project objectives, Doris Levry also assessed the strengths and weaknesses of both internal and external teams. In work with L'SPACE, Doris Levry combines technical expertise and analytical thinking to ensure that team goals are met.

Noah Doorsammy

THERMAL ENGINEER
MECHANICAL ENGINEER

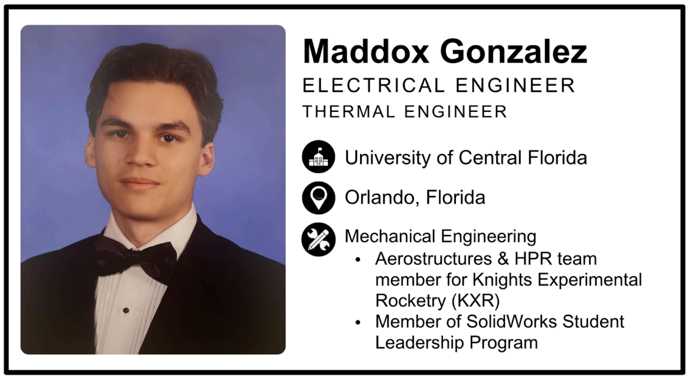
University of Central Florida

Orlando, Florida

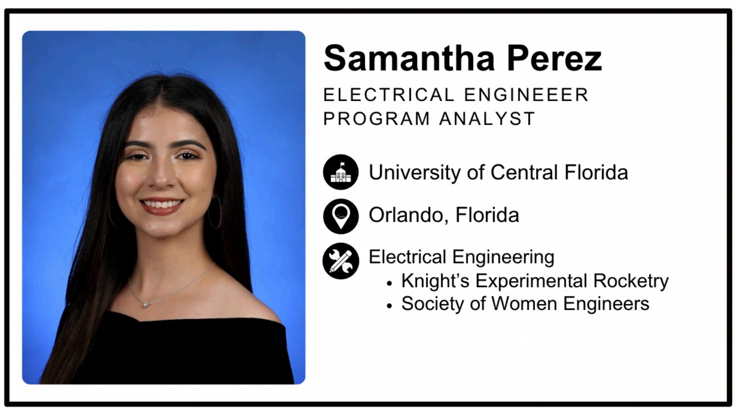
Aerospace Engineering
- Society of Hispanic Professional Engineers
- Knights Experimental Rocketry
- Bright Future's Award Recipient
- UCF's Top 10 Knight's Award Recipient

Noah Doorsammy is the Thermal and Mechanical Engineer for the HELP mission in the NASA L'SPACE Mission Concept Academy. Noah is currently an undergraduate senior at the University of Central Florida studying Aerospace Engineering. While participating in the L'SPACE program, Noah is also participating on other Aerospace Engineering projects such as the NASA Student Launch Challenge with Knights Experimental Rocketry (KXR) and other projects led by the Society of Hispanic

Professional Engineers (SHPE). Noah has used previous knowledge and experience in engineering to assist with the development of the thermal and mechanical subsystems for the HELP rover.



Maddox Gonzalez is the Electrical and Thermal Engineer for the HELP mission. Maddox is currently a sophomore at the University of Central Florida, majoring in Mechanical Engineering and a minor in Mathematics. Maddox's experience as a mathematics tutor has provided Maddox with the skills necessary to effectively communicate information with the team. Additionally, Maddox's work in the Aerostructures and High Powered Rocketry teams have provided Maddox with more skills vital to working in a team environment.



Samantha Perez is an Electrical Engineer and Program Analyst for the HELP mission. Samantha is currently a sophomore studying Electrical Engineering with a minor in Information Technology at the University of Central Florida. While participating in the L'SPACE program, Samantha has been active with the Knight's Experimental Rocketry organization as a part of the IREC team, as well as being an active member of the Society of Women Engineers. The experience Samantha has gained through these organizations, equipped Samantha with the technical and interpersonal skills to be an asset to the HELP team.

Kyle Lin is the Computer Data Hardware Engineer for the HELP mission. Currently a undergraduate junior in Stony Brook University, studying computer engineering. While working in L'SPACE, Kyle has used previous experience as a computer engineer to assist in figuring out how major CDH systems in the HELP rover to function.

1.8.2 Team Management Overview

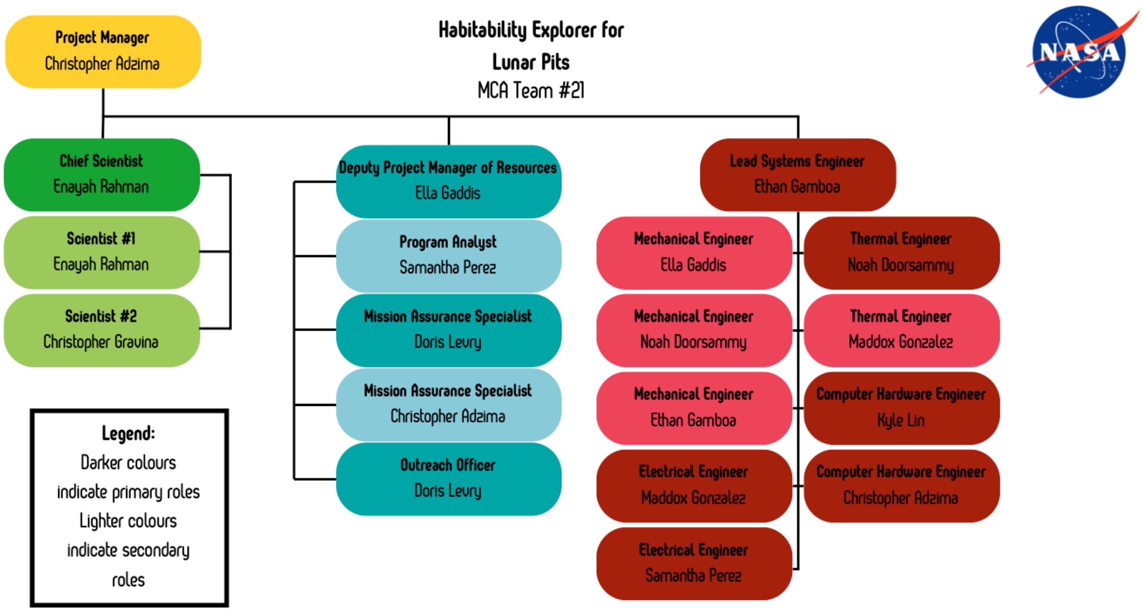


Figure 8: Team Organization Chart

The HELP Team is presently equipped to handle this mission. In order to efficiently manage the workload, the organizational structure now includes designating specific leads and sub-teams for Science, Programmatics, and Engineering. Designating each sub-team as responsible for its own area has prevented overlap and ensured that the mission's many components are moving forward simultaneously. Even with a smaller team, a balanced workload is maintained by allocating any additional or new duties according to each individual's skill and availability.

The HELP mission decision-maker is the Project Manager (PM), but in most cases involving trade studies, the PM delegates the decision to a deliberation lead with greater knowledge of the decision being made. This lead is either the Chief Scientist or the Lead Systems Engineer. These roles are responsible for understanding each alternative presented by subteam members and documenting an analysis of the options presented to make an informed decision. The leads also relay the decision alternatives and thought process to the PM so that the PM clearly understands the decision-making process and can share necessary information with other subteams impacted by the decision. This process is continuously iterated as RIDM and CRM are completed to evaluate options, assess related risks, and reconsider decisions to ensure mission safety and assurance.

Adapting to an unexpectedly reduced team size is a continued challenge for the HELP team. Regarding this specific mission, the main Program Analyst dropped forcing the role to be transferred to spreaded across the other members as shown in the new team management chart.

Passive communication is also a continued problem. Team members often complete tasks without regularly updating the group. On occasion, this has led to misunderstandings regarding the assignment status of each member. To overcome this, the emphasis has changed to proactive communication and regular check-ins, allowing all members to participate successfully and stay informed about one another's progress. Throughout the project's difficult stages, the team mentor has remained impartial and balanced while offering wise counsel and assisting with decision-making and dispute resolution as needed.

To prepare for the completion of the PDR document and clarify task division, a task breakdown sheet was implemented for this assignment. This task breakdown assigned sections of the PDR document to members of the HELP team, thereby clarifying expectations for the document and how each member can contribute. The breakdown of sections and document tasks can be reviewed in Appendix B, in a figure known as the PDR Task Breakdown Table. After these tasks were initially assigned, each team member gave confirmation of personal approval of the breakdown.

1.8.3 Major Milestones Schedule

Major Milestone	Date Completed
Submit Critical Design Review	January 23, 2026
Submit System Integration Review	March 1, 2027
Complete Test Readiness Reviews (TRR) of Instrumentation and System	March 1. 2028
Submit Operational Readiness Review (ORR)	February 1, 2029
Submit Mission Readiness Review	January 1, 2030
Launch mission at Cape Canaveral, FL	March 1, 2030
Submit Critical Events Readiness Review	April 19, 2030
Submit Decommissioning Review	May 6, 2030
Submit Disposal Readiness Review and Conclude Mission	June 6, 2030

Figure 9: Major Milestones Schedule

The major milestone of the HELP mission include submission of the following reviews: Critical Design Review, System Integration Review, Test Readiness Reviews of Instrumentation and System, Operational Readiness Review, Mission Readiness Review, Critical Events Readiness Review, Decommissioning Review, and Disposal Readiness Review. The mission launch will take place at Cape Canaveral, Florida on March 1, 2030. The dates of these review submissions are outlined in the table below. A more detailed overview of the mission timeline from Phases C-F can be found in the Mission Schedule section.

1.8.4 Budget Overview

The budget set for the HELP mission is $300 million. To account for this, the mission has been streamlined to a final cost estimate of $299,295,566. The total budget for the HELP mission accounts for personnel, outreach, travel, and direct costs throughout the mission's lifecycle. The team allocated about 30% of the budget to support Phase C and to fund the design stage of the mission. Furthermore, Phase D has taken over half of the budget at 66% as majority of the manufacturing and testing will occur during this time. Lastly, Stages E and F accounts for little over 1% of the budget as the mission will by that point be in action.

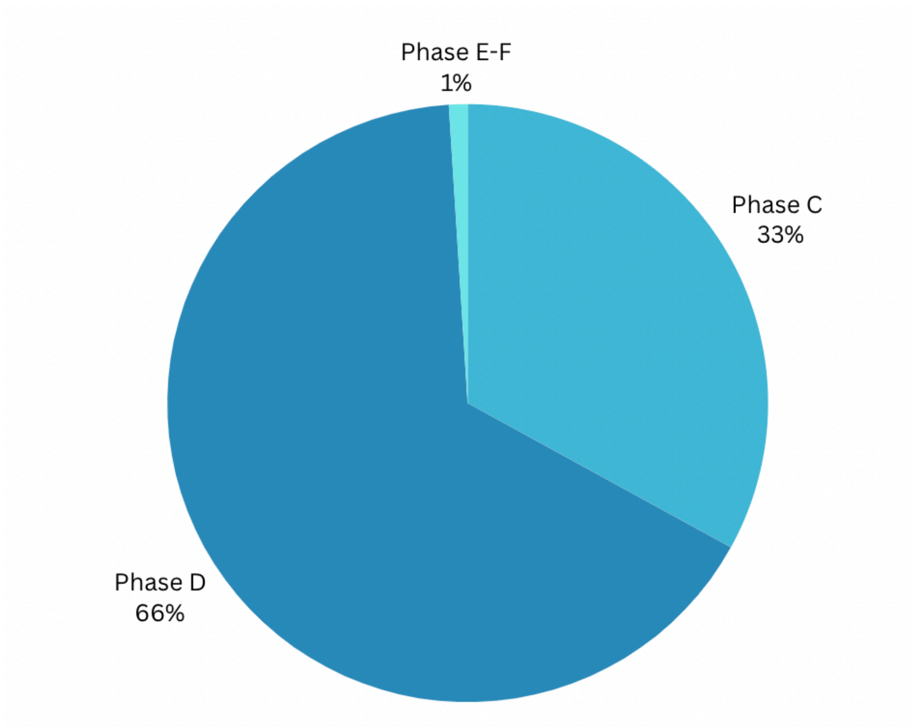


Figure 10: Phase Cost Distribution Pie Chart

2 OVERALL VEHICLE AND SYSTEM DESIGN

2.1 Spacecraft Overview

The HELP mission rover is 1.25 meters wide, 1.5 meters long, and 1.7 meters tall. The chassis is a rectangular box, modeled after the Chandrayaan-3 mission rover. The chassis supports a rectangular giraffe-like neck that houses the ProSeed drill that is used to complete the science objectives of the mission. The rest of the instrumentation and subsystems are housed in the rectangular chassis. The chassis is suspended by a rocker-bogie system, and wire-mesh tires allow for easy, smooth traverse across the lunar surface.

The power subsystem utilizes solar panels to supply power to all instrumentation. These are controlled by a single-axis tracking device that monitors the position of the sun in relation to the rover, thus optimizing the power collection. Power is stored in solid state batteries that can be used even when the rover is in total darkness. A dual bus system will be used to distribute power to every component.

To prevent overheating of the spacecraft's components, the spacecraft will have a network of heating pipes that will transform heat into vapors and expel them from the rover using radiators. The radiators, as well as all other exposed components, will be coated with an MLI that will reflect back to space. Heat will be monitored with thermocouples, and an active cooling system will also be implemented.

As for the science, the following instruments are house in the rectangular part of the chassis: the Near-Infrared Volatile Spectrometer System (NIRVSS), the Neutron Spectrometer System (NSS), the RIEGL Terrestrial Laser Scanner, the Rover Environmental Monitoring System (REMS), and the M-42 Radiation Detector. The final instrument, the ProSeed drill, will be housed in the tall structure of the vehicle, due to its height.

The following table lists the mass and max power draw for all subsystems.

Subsystem	Mass (kg)	Max Power Draw (W)
Mechanical	127	360
Power	53.8	22
CDH	15.55	115
Thermal	21.83	38.9
Science	48.244	150.3-315.3
TOTAL	266.4 kg	686.2 W - 851.2 W

Figure 11: Mass and Power Draw for HELP Subsystems

2.1.1 Mechanical Subsystem Overview

The mechanical subsystem of the HELP mission has a mass of 127 kilograms and a max power draw of 360 watts. This subsystem is made up of several subassemblies, which include the suspension, chassis, mobility, and guidance, navigation, & control. The chassis is a rectangular body that supports a tall, giraffe-like neck that houses the ProSEED drill and cameras for guidance, navigation, and control. The chassis is made of aluminium alloy 2219-T851 and is supported by a 6-wheel rocker-bogie suspension system, which previous rover missions including Perseverance and Chandrayaan-3 have implemented (“Perseverance Rover Components”). Rocker-bogie systems allow for easier traverse on lunar terrain, which is explained in further detail in the mechanical sub-assembly section. The rockers are connected by a differential to allow each wheel to move independently. Each wire-mesh tire is made of zinc-coated steel strands and has its own motor in the wheel hub, similar to the Apollo Lunar Roving Vehicle (Williams, 2016).

2.1.1.1 Mechanical Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MECHANICAL-1	Rover shall be able to navigate the lunar pit efficiently.	It will not be able to take data correctly without being able to navigate the chosen pit.		MECHANICAL-1.1, MECHANICAL-1.2, MECHANICAL-1.3, MECHANICAL-1.4	Demonstration	Mechanical	Met
MECHANICAL-1.1	Rover shall be able to descend a slope of .667 degrees.	This is the slope of the lunar pit chosen.	MECHANICAL-1		Demonstration	Mechanical	Met
MECHANICAL-1.2	Rover shall be able to handle rocky, sandy, uneven terrain.	The surface environment (rocks, dust, holes, etc.) should not affect the mobility of the rover.	MECHANICAL-1		Demonstration	Mechanical	Met
MECHANICAL-1.3	Rover chassis must not drag the ground at any point during traverse.	As little ground contact as possible will extend the life expectancy of rover.	MECHANICAL-1	MECHANICAL-1.3.1	Demonstration	Mechanical	Met
MECHANICAL-1.3.1	Rover suspension system shall keep chassis at a level ground clearance.	This will protect both the rover body and the instrument setup inside.	MECHANICAL-1.3		Demonstration	Mechanical	Met
MECHANICAL-1.4	Rover shall move at a speed of approximately 1 cm/s.	Heritage mission (Chandrayaan-3) moved at this same speed.	MECHANICAL-1		Demonstration	Mechanical	Met
MECHANICAL-2	Rover shall be able to withstand the lunar environment.	This is to keep all instrumentation and mechanical components safe and damage-free.		MECHANICAL-2.1, MECHANICAL-2.2, MECHANICAL-2.3	Demonstration	Mechanical	Met
MECHANICAL-2.1	Rover body material shall be resistant to dust on the lunar surface.	The lunar surface is dusty which can cause corrosion of the rover.	MECHANICAL-2		Demonstration	Mechanical	Met
MECHANICAL-2.2	Rover body shall be resistant to radiation.	There are high levels of cosmic radiation on the moon.	MECHANICAL-2		Demonstration	Mechanical	Met
MECHANICAL-2.3	Rover body shall be able to operate in extreme temperatures.	Temperatures on the moon range from -208 degrees Fahrenheit to 250 degrees Fahrenheit.	MECHANICAL-2		Demonstration	Mechanical	Met

MECHANICAL-3	Rover body shall absorb and support all forces during the mission.	All instrumentation and systems must be protected.		MECHANICAL-3.1, MECHANICAL-3.2	Demonstration	Mechanical	Met
MECHANICAL-3.1	Rover chassis shall support all weights of the internal instrumentation.	Instrumentation must be protected.	MECHANICAL-3		Demonstration	Mechanical	Met
MECHANICAL-3.2	Rover body shall absorb all shock during traverse.	Lunar environment is harsh and instrumentation must be operational.	MECHANICAL-3		Test	Mechanical	Met

Figure 12: Mechanical Requirements Table

The mechanical subsystem must meet several requirements in order to function as efficiently as possible.

The first parent requirement is that the rover shall be able to navigate the lunar pit chosen efficiently. Doing so will ensure that data is taken correctly and the mission is successful. There are four child requirements from this, the first being that the rover shall be able to descend a slope of 0.667 degrees. This is the slope of the ramp of the Compton Pit. The second child requirement is that the rover shall be able to handle rocky, sandy, and uneven terrain. The imperfections of the lunar surface cannot affect the mobility of the rover. The third child requirement is that the rover chassis must not make contact with the ground at any point during traverse in order to limit damage to the chassis underbody. A child requirement of this is that the suspension system must keep the chassis at a level ground clearance in order to avoid surface contact. The final child requirement is that the rover must traverse at any average speed of 1 centimeter per second to stay on track with the mission schedule. This speed reflects the speed of the Chandrayaan-3 mission, which had similar mission objectives.

The second parent requirement is that the rover shall withstand the lunar environment. The first child requirement of this is that the rover body shall be resistant to dust on the surface, which can cause corrosion and be detrimental to performance. The second child requirement is that the rover body shall be resistant to radiation since there are high levels of cosmic radiation on the moon. The third child requirement is that the rover shall be able to operate in extreme temperatures. The lunar surface can reach temperatures of up to 250 degrees Fahrenheit and drop to as low as -205 degrees Fahrenheit, and these fluctuations must not affect how the rover traverses or how the instruments operate ("Weather on the Moon").

The third and final parent requirement is that the rover shall be able to absorb and support all forces during the mission. The first child requirement from this is that the rover chassis must support the weights of all instrumentation and systems of the mission. This not only protects them but also ensures that these operate as they are supposed to. The second child requirement is that the rover body shall be able to absorb all shock that acts on its body. The harsh environment on the Moon should not affect how the rover performs.

All of this information, as well as verification method and requirement status, can be found in Figure 12.

2.1.1.2 Mechanical Sub-Assembly Overview

The mechanical subsystem includes the following sub-assemblies: the chassis, the suspension, the mobility, and the guidance, navigation and control. These subassemblies are modeled after different heritage missions that are discussed in further detail in the following sections. Overall, the TRL score is 4, since validation in a relevant environment has not been conducted at this point.

Chassis

A chassis is defined as the base frame of a vehicle that provides structural support to the vehicle's instruments. In the HELP mission, the chassis is the rectangular box and the neck-like structure. The chassis is supported by a 6-wheel rocker bogie system, which is explained in the suspension subsection.

The bottom rectangular shape of the HELP robot chassis was modeled after Chandrayaan-3's rover, Pragyan. This was chosen because the HELP mission and the Chandrayaan-3 mission had similar science objectives, giving it a TRL score of 4 since it has not been tested by the HELP engineers. The chassis is 1.5 meters long, 0.6 meters wide, and 1.78 meters tall. These large dimensions are due to the fact that the HELP mission requires many science instruments, including a ProSeed drill that is 1.7 meters tall. The chassis is made of aluminum alloy 2219-T851 because of its low cost, low density, and high strength. Because of this, the entire chassis weighs right at 60 kilograms.

Mobility

The mobility sub-assembly includes the wheels and motors that allow for motion of the robot. The HELP mission will be utilizing the same wire-mesh tires that the Apollo Lunar Roving Vehicle (LRV) used, giving this a TRL score of 4. The LRV's tires were made of zinc coated steel strands, and each wheel had its own motor and electric drive inside the wheel hub (Williams, 2016). Including the motor in the wheel itself means that space in the chassis does not have to be taken up by motors, which is crucial due to the number of instruments the HELP mission is implementing. However, regardless of space, wire mesh tires are superior because they provide increased stability and longer life (Asnani, Delap, and Creager, 2009). The mass, power draw, and dimensions of these tires were scaled by ½ to fit the HELP mission, so each wheel is about 41 centimeters in diameter, 1.5 kg in mass, and requires 90 watts to operate (Williams, 2016.)

Suspension

The suspension sub-assembly of a rover is defined as the system that connects the vehicle chassis to the wheels, typically in a rocker-bogie system in space environments ("Perseverance Rover Components", 2020). The "rocker" part is a large arm on either side of the rover, connected through the chassis by a differential that allows each rocker to rotate in its own direction, while the "bogie" part refers to the smaller linkage system that pivots in the middle of the rocker (Verma et. al, 2017). Most space rovers use a rocker-bogie system because they allow each wheel to move independently, which keeps the chassis at steady level and wheels on the ground at all times. This lets the rover navigate many types of terrain, whether it is rocky, sandy, or uneven. Because the rocker-bogie system is common in space rovers, a TRL score of 4 is given. The HELP rover's rocker-bogie suspension keeps the chassis 0.2 meters above the ground.

Guidance, Navigation, and Control (GNC)

Guidance, navigation, and control (GNC) is defined as the system and components used for vehicular positioning (“Guidance, Navigation, and Control”, 2024). For the HELP mission, GNC overlaps with science because a LiDar sensor is already used for scanning and mapping the Compton Pit. LiDar can also be used to control distance and velocity, so the RIEGL sensor that is used for the science objectives will be used for navigation as well. In addition, two cameras will be used so the personnel on Earth can see the surface through the rover’s “eyes”. These cameras will be mounted to the neck part of the chassis. The TRL of this subsystem is 4.

2.1.1.3 Mechanical Subsystem Recovery and Redundancy Plans

The mechanical subsystem does not need any redundant subassemblies. Duplicating the chassis, suspension, mobility, and guidance, navigation, and control subassemblies is not feasible in the scope of this mission. Unfortunately, due to the size and application of these subassemblies, if they fail during the mission, there is nothing that can be done to rectify this while the rover is on the lunar surface.

Recovery is built into each of the subassemblies as well. The tires are made to work efficiently in any kind of terrain that might be encountered on the lunar surface, and the chassis and suspension are highly unlikely to fail or encounter risks since the surface is mostly flat. Overall, the mechanical system is very safe and one of the least likely to run into any problems during the mission.

2.1.1.4 Mechanical Subsystem Manufacturing and Procurement Plans

The mechanical subsystem is a very vital subsystem to this mission, it incorporates a vast majority of the physical equipment in the rover and if any of the instruments were to fail, the rover would be in major jeopardy. The mechanical is also likely the subsystem to take the longest manufacturing, due to the fact that most items require time and intense precision. Due to how important this subsystem is, the contractor company must be able to be reliable and knowledgeable of the production items in order for everything to run smoothly and in an orderly fashion.

Mesh Wheels will be utilized on the spacecraft, and contracted from Northrop Grumman Corporation. Northrop Grumman has experience in creating solutions for spacecraft mobility in aerospace applications, and has the ability to engineer lightweight, durable wheels. The spacecrafts’ wheels will be contracted from Sierra Nevada Corporation in the event Northrop is unable to provide the wheels. Mechanical subsystems are very important for this subsystem and therefore Northrop Grumman Corporation will be chosen to manufacture the rest of these items as well. Northrop Grumman Corporation is a very reliable company and has experience in manufacturing the items needed for this mission. In the case Northrop Grumman Corporation isn’t able to manufacture the mechanical subsystem then Sierra Nevada Corporation will be contacted as the backup supplier. Choosing the same main contractor and same main backup supplier allows for production to run smoother and for things to get done faster.

The mesh wheels part of manufacturing subsystems estimated lead time will be from March 2027 until October 2027. The contractor will get started right away and will time its time and be highly precise in its manufacturing. This will take seven months due to how vital mesh wheels will be on this mission, they also need the extra time to check and revise everything. The rest of the mechanical subsystem will be split up but all started march 2027 in order to make the most of the contractor's time. The rest of the parts will likely be down around December 2027 and the whole mechanical subsystem will likely be done by January 2028, due to the fact the contractors have to check and revise all the productions and test if it all works properly. The reason why the Northrop Grumman Corporation will work on manufacturing this subsystem the full amount of time in phase D is due to how important the mechanical part is. If Northrop Grumman Corporation isn’t able to complete the manufacturing of the mechanical subsystem then the backup supplier Sierra Nevada Corporation will take over and may take until march 2028, as they try and pick up where Northrop Grumman Corporation left off. The reason why it may take until march 2028, is due to Sierra Nevada Corporation being notified later and needing time to organize before productions can be made.

2.1.1.5 Mechanical Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
MECHANICAL-1	Rover shall be able to navigate the lunar pit efficiently.	Demonstration	Requires operation to ensure efficiency	MECH-1 demonstrations below.
MECHANICAL-1.1	Rover shall be able to descend a slope of .667 degrees.	Demonstration	Operation of rover	Operate rover on numerous slopes
MECHANICAL-1.2	Rover shall be able to handle rocky, sandy, uneven terrain.	Demonstration	Operation of rover	Operate rover on similar Earthen terrains
MECHANICAL-1.3	Rover chassis must not drag the ground at any point during traverse.	Demonstration	Operation of rover	Simulate lunar trajectory and demonstrate success
MECHANICAL-1.3.1	Rover suspension system shall keep chassis at a level ground clearance.	Demonstration	Operation of rover	Operate rover at numerous slopes
MECHANICAL-1.4	Rover shall move at a speed of approximately 1 cm/s.	Demonstration	Operation of rover	Operate rover for an extended period of time to prove consistent speed
MECHANICAL-2	Rover shall be able to withstand the lunar environment.	Demonstration	Operation of rover	MECH-2 demonstrations below.
MECHANICAL-2.1	Rover body material shall be resistant to dust on the lunar surface.	Demonstration	Operation of rover	Subject rover to dusty environment
MECHANICAL-2.2	Rover body shall be resistant to radiation	Demonstration	Operation of rover	Subject rover to radiation
MECHANICAL-2.3	Rover body shall be able to operate in extreme temperatures.	Demonstration	Operation of rover	Subject rover to extreme temperatures
MECHANICAL-3	Rover body shall absorb and support all forces during the mission.	Demonstration	Operation of rover	MECH-3 verifications below
MECHANICAL-3.1	Rover chassis shall support all weights of the internal instrumentation.	Demonstration	Operation of rover	Subject rover to various forces
MECHANICAL-3.2	Rover body shall absorb all shock during traverse.	Test	Testing must be conducted to prove this capability.	Vibration table and fixture to ensure 3-axis vibration.

Figure 13: Mechanical Verification Matrix

Verification is the process of ensuring all subsystems and components perform as intended. Regarding mechanical verification, the mechanical system does not have individual components to test but rather subassemblies. Most mechanical requirements require a demonstration for verification, since the mechanical system requires operation to prove success. However, the requirement related to shock absorption testing is in fact a test, due to the fact that special instrumentation is needed to provide this proof. All requirements and associated preliminary verification methods and plans can be found in Figure 13.

2.1.2 Power Subsystem Overview

The Power Subsystem for the spacecraft begins with the Solar panels. The spacecraft's solar panels will be contracted from The Boeing Company's Spectrolab. The specific model being utilized is the XTJ Prime multi junction solar cells. Each solar cell on the panel will be 40 x 80 x 2 cm, and have a weight of 1.5 kg. The primary purpose of the solar panels is to effectively and efficiently provide enough power to the power storage sub assembly, in order to power the entirety of the spacecraft. There are multiple points of failure where the solar panels may become compromised and fail to generate power. One of these times is when lunar dust or regolith covers the surface of the panels. This instance has been addressed in the development of our single-axis tracking system, and will be covered later on. Another point of failure may be when the spacecraft is experiencing moments of total darkness, such as a lunar night. This issue will be addressed by ensuring that the battery remains fully charged throughout periods where the solar panels generate power. The solar panel will also be able to fold into itself and be compactly/safely stored within the spacecraft. This is to ensure that the solar panels remain safe during periods of time where the solar panel is not being used but may be compromised.

The single axis tracking system is vital to the spacecraft and power sub assembly, in order to ensure that the solar panels constantly aim towards the sun for max power generation. The single axis tracking system will be contracted from The Boeing Company. We will utilize their Single axis tracking system. This specific tracking system will have dimensions of 0.5 x 0.2 x 0.15 m, as well as a weight of 2.5 kg. Additionally, the tracking system will also have a way to safely vibrate. This is to ensure that the build up of lunar regolith does not compromise the integrity of the spacecraft's solar panels. The single axis tracking system will also have the option to fold into the spacecraft along with the solar panels in the event that the surrounding environment is too dangerous, and may compromise components of the spacecraft.

The Storage sub assembly consists of the Solid-State Battery. The HELP mission has elected to use a Solid-State Lithium Ion Battery as it has a greater capacity, lower charge times, and better safety features. The nature of the battery allows for it to be heated and cooled to more variable temperatures than a regular lithium ion battery. The battery has the dimensions of 12 x 10 x 6 cm, and a weight of 2.2 kg per battery. A redundancy the power storage system might face includes loss of power over time, as the rover plans to explore areas of permanent darkness and will need to maintain as much power as possible over long stretches

The Power Management and Distribution subsystem focuses on delivering power stored inside of our batteries, to the components across the spacecraft. In order to distribute power to all necessary components, we will employ a dual bus system. Our primary bus will be the main distribution point for our power system, while the secondary bus will remain as a back up bus in the event that the primary bus is compromised. Our power subsystem must also be fully autonomous. This means that the system must have a way of gathering data on the components which it is powering and have the ability to act if a component is compromised. To ensure this is possible, our power distribution unit will have the ability to gather data on the status of the components which it is supplying power to, and relay that information to the spacecraft where the spacecraft may make any necessary adjustments to ensure the mission is not compromised. We will also route cables along the most optimal path between the batteries and the power control unit, as well as the power control unit, and the individual components. This will ensure that we reduce energy loss, as well as weight on the spacecraft. The power subsystem will also have the option to enter a low power mode in the event that the spacecraft is in an area of permanent darkness and the batteries are low. This low power mode will allow the power subsystem to only provide power to critical loads, such as communication devices and navigation. Non critical loads will remain unpowered until the spacecraft begins to receive adequate charging from its solar panels. This means that we must also take into account our critical and non critical loads when wiring our components to the power system.

2.1.2.1 Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Relevant Subsystem	Verification Method	Req Met?
PS- 1	The power subsystem supply power to all components	It is vital to the mission that all components are sufficiently powered		All	Electrical	Demonstration	Met
PS-1.1	The solar panels on the spacecraft must generate enough power to sufficiently charge the batteries	The battery needs a sufficient amount of power to supply to each component	PS- 1	PS- 1.1.1, PS- 1.1.2	Electrical	Analysis	Met
PS- 1.1.1	The solar panel system should include protections against power surges during peak sunlight exposure	We must protect the solar panels from possible damage	PS- 1.1		Electrical	Inspection	Met
PS- 1.1.2	The solar panels shall be capable of automatic repositioning to optimize energy capture based on sunlight availability.	Repositioning the direction the solar panels face will help maximum power generation	PS- 1.1		Electrical	Test	Met
SYS- 1	The power subsystem must have redundancies	To ensure that the power system may operate smoothly in the event a component fails	PS- 1	SYS- 1.1	Electrical	Inspection	Met
SYS- 2	The power subsystem must be protected against the environment. Elements such as lunar dust, rough terrain, and radiation.	To ensure that the power system continues to run smoothly through the harsh environment	PS- 1		Electrical	Demonstration	Met
SYS- 1.1	The power subsystem must be able to gather data on the health of its components, and adjust the power system accordingly	to ensure that the power system may operate autonomously, and employ any necessary measures to keep the system running	SYS- 1	SYS- 1.1.1, SYS- 1.1.2	Electrical	Demonstration	Met
SYS- 1.1.1	The power subsystem must have an integrated failsafe system	To ensure that the power system may operate smoothly in the event a component fails	SYS- 1.1		Electrical	Demonstration	Met
SYS- 1.1.2	The power subsystem must have readily available back-up power sources	To ensure that if a battery fails, back up batteries may continue to provide power to the system	SYS- 1.1		Electrical	Inspection	Met

SYS- 1.1.3	The power subsystem must be able to deliver power to all components while during lunar nights, and during periods of no power generation.	To ensure that the power subsystem constantly remains powered throughout any period of time	SYS- 1.1		Electrical	Demonstration	Met
BAT- 1	The battery should have a sufficient capacity to power the spacecrafts' systems	To ensure that the power systems remain operational during periods when solar power is unavailable	PS- 1	BAT- 1.1, BAT- 1.2	Electrical	Analysis	Met
BAT- 1.1	The battery should have protection circuits to prevent overcharge, over-discharge, and short circuits.	To maintain battery health, extend its lifespan, and prevent potential damage to the spacecraft's power systems.	BAT- 1		Electrical	Inspection	Met
BAT- 1.2	The battery system should monitor and report battery health and charge status.	To prevent unexpected power loss and enable proactive maintenance for continuous spacecraft operation.	BAT- 1		Electrical	Demonstration	Met

Figure 14: Power Requirements Table

The main requirement for the power subsystem is to effectively provide power to all components and electronics within the spacecraft. In order to generate power, solar panels will be used. These solar panels should be protected against points of failure caused by harsh environments, or power surges due to sudden increases of sunlight exposure. The amount of energy captured will be maximized by allowing the solar panel to rotate to face the sun. These solar panels will be connected to numerous batteries throughout the power system. These batteries must have enough capacity to provide enough power to all components throughout the configuration. Additionally, these batteries must be protected from overcharge, short circuiting, power surges, and other points of failure. Lastly, these batteries must also be able to supply the spacecraft with enough power to last a lunar night, or periods of no power generation. Furthermore, the power system must also be fully autonomous and have instruments to check the status of its components. In the event of failure, the power system can utilize fail safes to ensure the components continue to receive power. The entire subsystem must be under a length, width, and height of 1 x 1 x 0.75 m, due to the fact that this subsystem must be stored comfortably within the spacecraft. Additionally, the entire subsystem must remain under 55 kg.

2.1.2.2 Power Sub-Assembly Overview

The Power Subsystem has a variety of subassemblies to meet the pre established requirements including Power Generation, Storage, and Management/Distribution.

The Power Generation Subassembly focuses on the optimization of power generation to sustain all the subsystems and complete the HELP mission. Among the components of this subassembly is the solar panels. XTJ Prime multi junction solar cells will be contracted from The Boeing Company’s Spectrolab. Each panel will be 0.4 x 0.8 x 0.02 m, and have a weight of 1.5 kg. These solar panels will collect energy during the rover’s time in sun exposure. To optimize the amount of solar energy collected, there will be a solar tracking system implemented to the rover to ensure that enough power will be generated to support all the subsystems even if the rover ventures into an area of permanent darkness. For simplicity, the mechanism for orienting the solar panel to face the sun will be a single axis tracking system. This single axis tracking system utilized will be Boeing’s Single-Axis Lightweight Solar Tracker. The tracker will have dimensions of 0.5 x 0.2 x 0.15 m, as well as a weight of 2.5 kg. To ensure the safety of the solar panels, the solar panels have been designed to be deployable. In the event that the surrounding environment is ruled dangerous and may compromise the safety of the solar panels, the solar panels also have the option of folding back into the spacecraft until it may be safely deployed again. Solar panels will also have redundancies implemented in them. The solar panel arrays will be designed in such a way that the solar panels will still be operational if a portion of a panel were to be compromised. Another problem that may arise with the use of solar panels is lunar dust covering the panels, ultimately leading to a decrease in energy capture. To combat this, a vibration mechanism will be installed into the single axis tracking device. The aim of this device will be to safely vibrate the solar panel in the event that the solar panel is compromised by any lunar debris, with the goal of shaking off this debris. In order to make the solar panels as efficient as possible for this mission, these panels will be made from lightweight materials and will use multi junction cells. Multi efficient cells are beneficial due to the fact that the solar panels (when in areas that are not permanently dark) will be exposed to intense sunlight, as there is no atmosphere on the moon to dampen the intensity of the sun. Because the spacecraft will experience times of permanent darkness, it is vital to the mission that the solar panels seamlessly charge batteries throughout the power system, which in turn will be used to power the components of the spacecraft.

The Storage Subassembly works to store excess power collected by the Power Generation subassembly for later use. The primary component of this subassembly is the solid state battery. Panasonic's All-Solid-State Lithium-Ion Battery will be utilized for this mission. These batteries have an energy density of 500 wh/kg and a capacity of 200 Ah. Additionally, the batteries will have dimensions of 12 x 10 x 6 cm, and a weight of 2.2 kg per battery. These batteries utilize a solid electrolyte, as opposed to a liquid or gel electrolyte to minimize risks. Additionally, these batteries also boast higher energy densities as opposed to normal batteries. In the context of the mission and the specific size requirements for the spacecraft, this is beneficial due to the fact that the battery will still have a high energy capacity, all the while remaining compact. Solid state batteries will also help mitigate risks normally associated with batteries. Some of these risks include a lack of flammable liquid electrolytes, and the reduced likelihood of short circuiting. An important factor of the energy storage system is the storage system's longevity. It is crucial to the success of the mission that the battery has a sufficient lifetime to provide power to all components throughout the duration of the mission. As mentioned earlier, solid state batteries are a great choice when taking into account longevity due to the risk mitigation benefits that are associated with these batteries. Furthermore, it will be ensured that the battery satisfies all power requirements for the components that are connected to the batteries, as well as install back up batteries. Back up batteries and redundancies play a crucial role in ensuring all systems powered by the power system remain operational throughout the mission.

The Management and Distribution subsystem focuses on delivering power stored inside of the batteries, to the components across the spacecraft. The spacecraft will utilize Northrop Grumman's Space Power Distribution Unit. This unit is able to handle a maximum of 5 kW, with dimensions of 35 x 25 x 15 cm, and a weight of 2.8 kg. This power distribution has operational experience in the James Webb Space Telescope. In order to distribute power to all necessary components a dual bus system will be employed. The primary bus will be the main distribution point for the power system, while the secondary bus will remain as a back up bus in the event that the primary bus is compromised. The power subsystem must also be fully autonomous. This means that the system must have a way of gathering data on the components which it is powering and have the ability to act if a component is compromised. To ensure this is possible, the power control unit will have the ability to gather data on the status of the components which it is supplying power to, and relay that information to the spacecraft where the spacecraft may make any necessary adjustments to ensure the mission is not compromised. Cables will travel along the most optimal path between the batteries and the power control unit, as well as the power control unit, and the individual components. This will ensure that energy loss is minimized, as well as weight on the spacecraft. The power subsystem will also have the option to enter a low power mode in the event that the spacecraft is in an area of permanent darkness and the batteries are low. This low power mode will allow the power subsystem to only provide power to critical loads, such as communication devices and navigation. Non critical loads will remain unpowered until the spacecraft begins to receive adequate charging from its solar panels. Critical and non critical loads must also be considered when wiring components to the power system.

	Technical Readiness Level	**Explanation**
Generation Subassembly	8	The Solar Panels and Single-Axis Solar Tracker have been used in previous space exploration missions, however the vibration device being implemented to safely remove lunar dust is still experimental.
Storage Subassembly	6	The Solid-State battery should theoretically withstand the space environment without many of the prohibitions that would be encountered with other types of batteries, however, the Solid State battery has not been tested in any missions previously.
Management and Distribution Subassembly	9	The power distribution unit and methods have been previously utilized in other missions and are designed specifically for space exploration.
Power Subsystem	8	Overall the power subsystem should be qualified to fly as most of the components have been tested under these circumstances and have proven to be functional.

Figure 15: Power Technology Readiness Level Table

2.1.2.3 Power Subsystem Recovery and Redundancy Plans

Several redundancies have been installed into the power system in order to ensure that the integrity of the mission is not compromised. For starters, a dual bus system will be implemented. The primary bus serves to provide power to the components, while the secondary bus serves as a backup in case the primary bus fails. Redundancies are also prevalent for the solar panels. The array of the solar panels will be designed so that if an area of the solar panel is compromised, other areas of the solar panel may continue to provide energy to the system. Alongside this redundancy, the mechanism that the solar panel is mounted to will have the ability to safely vibrate the solar panel, in order to remove any lunar dust covering the surface of the panel. Lastly, solar panels will have the ability to be deployed or folded into the spacecraft whenever necessary. The spacecraft has the ability to autonomously monitor the health of its power system, identifying faults or inefficiencies and taking immediate corrective actions. For example, if the primary bus fails, the system can automatically switch to the backup bus to ensure uninterrupted power delivery. Additionally, when energy levels fall below critical thresholds, the spacecraft will autonomously enter a low power mode, prioritizing only the most essential systems like communication and navigation.

2.1.2.4 Power Subsystem Manufacturing and Procurement Plans

The power subsystem will be vital to powering our rover throughout the mission, without these items our mission will not be able to run. The power subsystem will mostly consist of the solar panels and batteries needed to power and charge our rover. The contractors involved in productions will need to be knowledgeable in this area in order to have everything done on time as well as efficiently done.

The spacecraft’s solar panels will be contracted and sourced from The Boeing Company’s Spectrolab. If the Boeing company is unable to provide the solar panels, then SolAero Technologies will be contacted. The Boeing Company’s Spectrolab is the world leader in high efficiency solar panels, with a substantial amount of experience in spaceflight. Spectrolab panels have additionally assisted in previous NASA missions, as well as commercial and military satellites.The power distribution system will be provided by Northrop Grumman. Northrop Grumman will be able to supply highly customizable power distribution systems, which will allow for seamless integration for the spacecraft. Additionally, Northrop Grumman has experience in government and commercial space missions, making them a great resource to contract the power distribution unit (PDU). In the event Northrop Grumman is unable to supply the power distribution unit, Lockheed Martin will be contacted instead. Lastly, the solid state battery will be contracted from Panasonic. Panasonic is a global leader in battery technology, and will be able to provide batteries with high energy densities, long cycle life, and great temperature tolerances. These characteristics make Panasonics’ solid state battery the ideal candidate for the spacecraft's power storage unit. Solid Power will be contacted in the event that Panasonic is unable to supply the batteries.

The estimated lead time for production of the solar panels will be from March 2027 to October 2027 due to it being vital to the mission. The power distribution unit and batteries will be manufactured from April 2027 to November 2027. The power subsystems full estimated lead time will be between March 2027 to December 2027, the last month will be used for testing and making sure everything is working optimally.The Boeing Company, Northrop Grumman, and Panasonic will work on manufacturing specific power subassemblies used throughout the spacecraft. This time frame allows the specific manufacturers to deliver the subassemblies in a timely manner, provide time to use backup suppliers if needed, and allows for the integration of the power subassemblies throughout each subsystem. The power subsystem will be used throughout the interior such as the batteries and power distribution system, while the solar panels are used on the exterior of the spacecraft. Additional time was provided for the power system due to the significant importance of the subsystem itself and to allow time for the specific integration between the power, thermal, and mechanical subsystems. In the event that the backup suppliers are used they will take an extra month of manufacturing time (January 2028), due to the late notice.

2.1.2.5 Power Subsystem Verification Plan

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan	Relevant Subsystem	Verification Method
PS- 1	The power subsystem supply power to all components	Demonstration	It is vital to the mission that all components are sufficiently powered	Test the power subsystem under various loads to confirm it powers all components	Electrical	Demonstration
PS- 1.1	The solar panels on the spacecraft must generate enough power to sufficiently charge the batteries	Analysis	The battery needs a sufficient amount of power to supply to each component	Test the solar panels' power output to ensure sufficient battery charging.	Electrical	Analysis
PS- 1.1.1	The solar panel system should include protections against power surges during peak sunlight exposure	Demonstration	We must protect the solar panels from possible damage	Verify the solar panel system's surge protection by simulating peak sunlight conditions and testing response to power fluctuations.	Electrical	Demonstration
PS- 1.1.2	The solar panels shall be capable of automatic repositioning to optimize energy capture based on sunlight availability.	Test	Repositioning the direction the solar panels face will help maximum power generation	Test the solar panels' tracking mechanism to ensure optimal energy capture under different sun positions.	Electrical	Test
SYS- 1	The power subsystem must have redundancies	Inspection	To ensure that the power system may operate smoothly in the event a component fails	simulating failures in primary components and confirming backup systems activate	Electrical	Inspection
SYS- 2	The power subsystem must be protected against the environment. Elements such as lunar dust, rough terrain, and radiation.	Demonstration	To ensure that the power system continues to run smoothly through the harsh environment	Test for resistance to lunar dust, rugged terrain, and radiation to ensure reliable performance in harsh environments.	Electrical	Demonstration
SYS- 1.1	The power subsystem must be able to gather data on the health of its components, and adjust the power system accordingly	Demonstration	to ensure that the power system may operate autonomously, and employ any necessary measures to keep the system running	system diagnostics and failure simulations.	Electrical	Demonstration

SYS- 1.1.1	The power subsystem must have an integrated failsafe system	Demonstration	To ensure that the power system may operate smoothly in the event a component fails	testing its response to power subsystem failures, ensuring it activates when necessary.	Electrical	Demonstration
SYS- 1.1.2	The power subsystem must have readily available back-up power sources	Inspection	To ensure that if a battery fails, back up batteries may continue to provide power to the system	testing the transition to and operation of backup systems under low power or failure conditions.	Electrical	Inspection
SYS- 1.1.3	The power subsystem must be able to deliver power to all components while during lunar nights, and during periods of no power generation.	Demonstration	To ensure that the power subsystem constantly remains powered throughout any period of time	testing the battery discharge and power delivery under simulated no-generation conditions.	Electrical	Demonstration
BAT- 1	The battery should have a sufficient capacity to power the spacecrafts' systems	Analysis	To ensure that the power systems remain operational during periods when solar power is unavailable	testing the ability to power all spacecraft systems for the required duration under typical operational conditions.	Electrical	Analysis
BAT- 1.1	The battery should have protection circuits to prevent overcharge, over-discharge, and short circuits.	Inspection	To maintain battery health, extend its lifespan, and prevent potential damage to the spacecraft's power systems.	performing tests to ensure they prevent overcharge, over-discharge, and short circuits under operational conditions.	Electrical	Inspection
BAT- 1.2	The battery system should monitor and report battery health and charge status.	Demonstration	To prevent unexpected power loss and enable proactive maintenance for continuous spacecraft operation.	conducting tests to ensure it accurately tracks and reports battery health and charge status under operational conditions.	Electrical	Demonstration

Figure 16: Power Verification Matrix

2.1.3 CDH Subsystem Overview

The CDH Subsystem Overview is not completed at this time for the HELP mission. It has been assigned top priority going into the CDR.

2.1.3.1 CDH Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
CDH-1	Rover should deliver information through a satellite	It should be able to verify data and send the information back to Mission Control		CDH-1.1, CDH-1.2	Test	Payload, CDH	Met
CDH-1.1	The rover's subsystem should be able to communicate with satellite at 384,400 km and its lander	160,000 km will separate the rover because it's on the Moon and Mission Control is on the Earth, information needs to be transmitted to both ends	CDH-1		Demonstration	CDH	Met
CDH-1.2	The rover's subsystem should deliver information at 8.495 GHz frequency	The satellite with be able to gather information from the rover because it has a different frequency and won't get interference	CDH-1		Analysis	CDH	Met
CDH-2	Information gathered should be stored in subsystems	Mission Control will be able to know the state of the rover and be able to get data received back when it returns to Earth		CDH-2.1, CDH-2.2	Demonstration	CDH	Met
CDH-2.1	The subsystem should be able to handle and manage the information its retrieved	Constant stream of communication should be sent to Mission Control so the rover can gather data and sample materials	CDH-2	CDH-2.1.1, CDH-2.1.2	Inspection	CDH	Met
CDH-2.1.1	The rover should have an Onboard Computer	The OBC will be able to use the tools and subsystems effectively. It will be responsible for the control of all subsystems on board	CDH-2.1	CDH-2.1.1.1	Inspection	CDH	Met
CDH-2.1.1.1	The rover's OBC should have 2 specs	In order to have a collaborative nature of the rover's and lander's subsystems, the rover should have an OBC in order to accomplish CDH-2	CDH-2.1.1		Analysis	CDH	Met
CDH-2.2.1	The rover should have a battery backup	If any of the solar panels are compromised, a battery backup can help us deliver vital information even if it cannot return back to Earth	CDH-2.2		Demonstration	CDH, Electrical	Met

Figure 17: CDH Requirements Table

2.1.3.2 CDH Sub-Assembly Overview

The CDH subsystem is composed of several subassemblies each with its own niches and their task for the mission. For example, the Communication Subsystem is needed to communicate between the rover and satellites on Earth.

Communication Components

Antennas: Required for worldwide communication. A High Gain antenna (X-band) allows communication allowing data to be transmitted from the rover to Earth station. An Omnidirectional Antenna (X-band), allows the rover to receive instructions from Earth Stations allowing it perform tasks.

Frequencies: Allows rover to receive instructions and controls it. There are several bands of frequencies that need to be articulated so the rover can be controlled without interference. S-band and X-band are both bands that can be used for lunar research.

Technology Readiness Level: 7, several communication subsystems have been tested in previous missions and used for similar tasks.

The Data Handling Subsystem is needed to manage data across all subsystems and handle data between communications from satellite to rover.

Data Handling Components

The Onboard Computer (OBC): The OBC will be able to use the tools and subsystems effectively. It will be responsible for the control of all subsystems on board and report information gathered from the lunar surface and ensure all subsystems aren’t compromised.

Electronic Data Storage: The electronic data storage bank is responsible to store all data within the subsystems to allow data that has been gathered to be kept before sending it to Mission Control. This will also allow data to reside in a location in case of a compromise of the communication components.

Technology Readiness Level: 7, several OBCs and data storage units have been used in previous missions in space.

Subassembly	Mass (Kg)	Max Power Draw (W)
Phased Array	12	90
Transponder	0.75	5
High Gain Antenna	1.4	10
Low Gain Antenna	1.4	10

Figure 18: CDH Component Mass and Max Power Draw Table

2.1.3.3 CDH Subsystem Recovery and Redundancy Plans

A vital subsystem component of CDH is the On Board Computer, to make sure it stays active and running. If this subsystem does fail, the mission would be compromised due to its integral implementation and usage in other subsystems as it is the main system that manages information and communication from the rover to Mission Control Fail Safes are established to ensure all programs run efficiently and effectively.

2.1.3.4 CDH Subsystem Manufacturing and Procurement Plans

The CDH subsystem is very important when regarding how data will be handled and how communications will be worked. In order for this subsystem to be successful the contractor has to be very knowledgeable and cautious about productions. Contractors will have to meet specific requirements due to how demanding this subsystem is and to ensure production is done correctly. CDH will allow for the mission to run smoothly and collect the data this rover is looking for and for it to be processed accurately.

In regards to the spacecrafts' communications and data handling, an onboard computer is vital to the success of the mission. The onboard computer will be contracted from Lockheed Martin Corporation. Lockheed's onboard computers provide a reliable computing power, and are ideal for aerospace applications due to their radiation tolerance. Raytheon Technologies Corporation will be contracted to provide the onboard computer if Lockheed Martin is unable to. Lastly, the spacecraft needs a means of storing information. This will be possible through the use of Electronic Data Storage. The spacecrafts' electronic data storage will be contracted through Teledyne Technologies Incorporated. Teledyne has the ability to provide high capacity data storages that are resilient against radiation exposure, making them the ideal candidate for this mission. Leidos Holdings Incorporated will be relied on to provide the Electronic Data Storage in the event Teledyne is unable to.

The onboarding computer estimated lead time for CDH will likely be from March 2027 to August 2027. This shouldn't be as extensive as other subsystems due to the fact that there is less hardware and materials involved, although it will still need to be tested at later dates. The electronic data storage will begin production in April 2027 and finish by October 2027, a little after the onboard computer is produced. The reason why CDH subsystems estimate lead time will be between March 2027 to December 2027 is because it's not as extensive as other subsystems but still needs a lot of time to incorporate testing and system checks of production. Boeing Company's Spectrolab, Panasonic, and Northrop Grumman Corporation will be the primary manufacturers of this subsystem. These companies will need this time in order to make sure each CDH subassembly is manufactured correctly and works efficiently. In the case these companies don't work out, the backup suppliers will take over and most likely take an extra month until January 2028, due to how late the backup suppliers would be notified. Unprecedented time delays may also happen due to the fact many companies have to work together to finish productions for this subsystem.

2.1.3.5 CDH System Verification Plans

No CDH subsystem verification plans have been outlined at this time. Therefore, finalizing these plans have been assigned the highest priority in the HELP mission going into the CDR.

2.1.4 Thermal Control Subsystem Overview

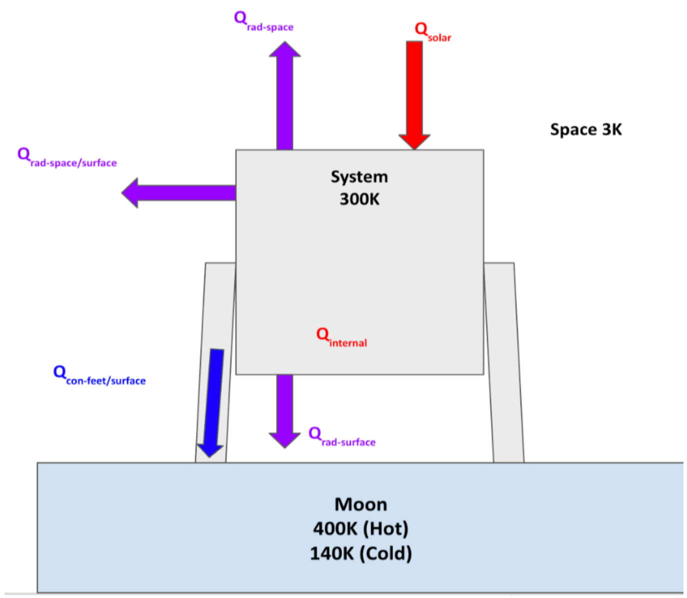


Figure 19: Concept Spacecraft With Modes of Heat Transfer Represented

First Order Thermal Analysis

Knowns and Assumptions	Values
n radiating to space	1
n radiating to space/surface	4
n radiating to surface	1
Space node temperature (T2), k	3
Surface temperature hot (T3), k	400
Surface temperature cold (T4), k	140
q_solar flux, W/m^2	1440
Surface Area of faces, m^2	1.875
Emissivity base (MLI coating) , e	0.005
Absorptivity Base (MLI coating) , a (alpha)	0.2
System temperature (T1), k	300
Stephan Boltzman Constant	0.0000000567
Q_internal, W	686.2
F	1

Figure 20: Variables Used in Heat Transfer Calculations

For the first order thermal analysis, both the hot and cold scenarios will be simulated as a cube to calculate the values for the heat flow maps. The knowns and assumptions used for these calculations are found in the figure above with values that are commonly known about the lunar surface.

Hot Scenario

$Q_{internal} = max\ power\ draw$, (W)	686.2
$Q_{solar} = q_{solar\ flux} * A_s * a$, (W)	530.25
$Q_{rad-space} = e\sigma F A_s (T_1^{\ 4} - T_2^{\ 4})$, (W)	4.31
$Q_{rad-space/surface} = 4 * e\sigma F(A_s/2)(T_1^{\ 4} - T_2^{\ 4}) + e\sigma F(A_s/2)(T_1^{\ 4} - T_3^{\ 4})$, (W)	3.95
$Q_{rad-surface} = e\sigma F(A_s/2)(T_1^{\ 4} - T_3^{\ 4})$, (W)	-4.65
$Q_{in} = heat\ going\ in$, (W)	1220.85
$Q_{out} = heat\ going\ out$, (W)	8.26
$Q_{net} = Q_{in} - Q_{out}$, (W)	1212.59

Figure 21: Equation Estimations That Consider a Hot Scenario

Based on the hot scenario, there is a significant amount of heat going into the spacecraft compared to the heat leaving the spacecraft. The thermoelectric coolers, heat pipes, fluid loops, radiators and MLI coating will have to produce more cooling and dissipate heat at a significantly increased rate to maintain optimal operating conditions for the rover.

Cold Scenario

$Q_{internal} = max\ power\ draw$, (W)	686.2
$Q_{solar} = q_{solar\ flux} * A_s * a$, (W)	0
$Q_{rad-space} = e\sigma F A_s (T_1^{\ 4} - T_2^{\ 4})$, (W)	4.31
$Q_{rad-space/surface} = 4 * e\sigma F(A_s/2)(T_1^{\ 4} - T_2^{\ 4}) + e\sigma F(A_s/2)(T_1^{\ 4} - T_4^{\ 4})$, (W)	10.65
$Q_{rad-surface} = e\sigma F(A_s/2)(T_1^{\ 4} - T_4^{\ 4})$, (W)	2.05
$Q_{in} = heat\ going\ in$, (W)	686.2
$Q_{out} = heat\ going\ out$, (W)	17.01
$Q_{net} = Q_{in} - Q_{out}$, (W)	669.19

Figure 22: Equation Estimations That Consider a Cold Scenario

Based on the cold scenario, there is a significant amount of heat generated within the spacecraft compared to the heat leaving the spacecraft. The thermoelectric coolers, heat pipes, fluid loops, radiators and MLI coating will have to produce more cooling and dissipate heat at a significantly increased rate to maintain optimal operating conditions for the rover. An increase in the amount of coolers should also be implemented to combat the excess of heat that is generated within the spacecraft.

All of the thermal subassemblies work together to heat and cool all of the subsystems within the spacecraft to maintain an optimal operating temperature of 20 C. Heating and cooling subassemblies are embedded and designed around all of the major components of the spacecraft to ensure that heat spots are dissipated and that operating temperatures can be met. If operating temperatures are not met, the entire spacecraft and the subsystems within the spacecraft will fail. Thermocouples and thermal switches are used to monitor and regulate fluctuations in temperature so that the spacecraft can autonomously make adjustments so that it doesn't overheat or get too cold while it's operating. Each subassembly works together to make sure that the spacecraft can operate smoothly and complete the mission.

2.1.4.1 Thermal Control Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
THRM- 1	Maintain an operating temperature of 20 C inside of the spacecraft in order for all electronics and equipment to properly operate	Any extreme temperatures may cause the electronics/ equipment to fail and put the mission at risk		All	Demonstration	Thermal	Met
SYS- 1	The spacecraft must be able to regulate its own temperature autonomously using installed heating and cooling systems	Allows for the spacecraft to adapt to environmental conditions without the need of human intervention	THRM- 1	SYS- 1.1, SYS- 1.2	Test	Electrical	Met
SYS- 1.1	The spacecraft should be equipped with a thermal control system that will allow the spacecraft to adjust its internal temperature based off of real time data	The spacecraft will be able to appropriately adjust the temperature of the spacecraft to protect the vital electronics and components inside	SYS- 1		Inspection	Thermal	Met
SYS- 1.2	Redundancy should be implemented into the thermal management systems' control systems and components	To ensure that the interior temperature remains regulated in the event that some components begin to fail	SYS- 1	SYS- 1.2.1, SYS- 1.2.2	Test	Electrical	Met
SYS- 1.2.1	The thermal management systems' control systems should have redundant control pathways, and a failover mechanism	Further ensure that in the event that a component stops working, the system may continue to operate on a backup system.	SYS-1.2		Analysis	Electrical	Met
SYS- 1.2.2	The spacecraft should have redundant heaters and coolers installed	If a heater or cooler begin to fail, a backup will be installed to replace the broken component	SYS-1.2		Test	Thermal	Met
RET- 1	Prevent the interior temperature of the spacecraft from dropping below operating temperatures at 20 C	The delicate electronics and equipment in the spacecraft may easily be damaged by extremely low temperatures	THRM- 1	RET- 1.1, RET- 1.2	Demonstration	Thermal	Met

RET- 1.1	Reduce the amount of heat radiated from the spacecraft onto the moon and space	The equipment on board has specific operating temperatures that must be followed	RET- 1	RET- 1.1.1, RET- 1.1.2	Inspection	Thermal	Met
RET- 1.1.1	Surfaces of the spacecraft will be covered with MLI coatings for low IR emissivity	The surfaces of the spacecraft will be able to minimize the amount of heat radiated into space and the surface of the moon	RET- 1.1		Inspection	Thermal	Met
RET- 1.2	The spacecraft should have a heat exchanger installed	Heat exchangers use fluid in conjunction with fluid loops to transfer heat from a heated fluid, to the spacecrafts' interior	RET- 1.2		Inspection	Mechanical	Met
REL- 1	Control and measure the amount of heat within the spacecraft in order to maintain operating temperatures at 20 C	Delicate electronics and components will be easily damaged by overheating if the interior heat is not regulated.	THRM- 1		Demonstration	Thermal	Met
REL- 1.1	The spacecraft will have cooling systems installed inside to disperse heat away from hot spots that exceed 20 C	Help regulate the temperature of the interior of the spacecraft to prevent electronics from overheating	REL- 1	REL- 1.1.1, REL- 1.1.2	Demonstration	Mechanical	Met
REL- 1.1.1	The interior should have heat pipes installed for optimal heat transfer	Heat pipes will efficiently transfer heat from hotter areas of the spacecraft, to cooler areas	REL- 1.1		Inspection	Mechanical	Met
REL- 1.1.2	The interior should have fluid loops installed throughout to reduce hotspots	Fluid loops will be able to absorb heat inside the interior and transfer it to a radiator away from hot spots.	REL- 1.1		Inspection	Mechanical	Met
REL- 1.2	The spacecraft should have multiple retractable radiators installed on the exterior of the spacecraft	Assist in dissipating excess heat from within the interior	REL-1	REL- 1.2.1	Inspection	Mechanical	Met

Figure 23: Thermal Requirements Table

The main requirement for the thermal management system is to maintain a specific temperature of 20 C inside of the interior of the spacecraft to ensure that all delicate components and electronics can operate. Any extreme temperatures caused by the harsh environment will damage the electronics and put the mission at risk. Other requirements outlined in the table above will ensure that this requirement is met. For starters, the spacecraft must be able to regulate its own temperature autonomously. This will allow the spacecraft to gather data on the current state of its interior and activate components as necessary to ensure that the interior remains within a safe temperature range. Also, the spacecraft will use many redundancies and fail safes to ensure the thermal management system remains operational if a component fails. To prevent the temperature from dropping too low, it is necessary to reduce the amount of heat radiated into space. This requirement can be met by utilizing reflective coating on the components, as well as applying MLI to the surfaces of the spacecraft. On the other hand, the temperature mustn't climb too high. To meet this requirement, a system of heat and fluid pipes will be installed to transfer heat away from hot spots within the spacecraft. Radiators will also be installed to complement the heat and fluid pipes. These radiators will serve as the end points of the pipes, where the radiators will help dissipate excess heat within the spacecraft.

2.1.4.2 Thermal Control Sub-Assembly Overview

The Thermal Management Subsystem has a variety of subassemblies to meet the pre established requirements including heating, cooling, insulation, and temperature monitoring.

Within the thermal subsystem, multiple active heating and cooling systems will be implemented to further guarantee mission success when it pertains to keeping the electronics and payloads within the system safe and being able to maintain stable operating temperatures. Active thermal control systems rely on an external power source and are known to be better at maintaining temperature controls where temperature fluctuations can occur at a higher level (NASA 2024).

The main requirement for this mission requires the spacecraft to be able to maintain a stable operating temperature around 20 C so that the electronics and payloads within the spacecraft can operate efficiently and avoid any potential damage due to temperature fluctuations. Due to the average temperatures within a lunar cave being at -17 C, retaining heat is the main priority of this thermal system. Based on the trade study comparing different types of active heating systems, space heaters were chosen to provide heat and maintain a stable operating temperature for this system. Space heaters "use an electrical-resistance element in between two sheets of flexible electrically insulating material" which allows the spacecraft to maintain a stable temperature (NASA 2024). The specific kind of heaters used in spacecraft are Kapton electrical heaters and have a TRL of 7 in low earth environments. The specific Kapton electrical heater that will be used in the thermal system is the Omega Polyimide Heater Kit. This system fits within the size constraints set by the mission requirements, comes in multiple sizes and shapes to create an optimal and efficient thermal system, has a generally low power consumption of 1.56 W/cm^2 which can prevent overheating and conserve power for the other systems, and it is able to withstand the different temperature fluctuations from the lunar surface and the lunar cave from -200 C to 200 C. A closed loop temperature feedback will be implemented to help regulate the temperature within the spacecraft (NASA 2024).

It is vital to the integrity of the mission that the thermal management system prevents overheating of components within the spacecraft. To combat this, several other components will help disperse and release heat.

A heat exchanger will be installed into the thermal management system. The aim of this component is to raise the interior temperature of the interior of the spacecraft by using the heated fluid inside of the fluid loops, and using this energy to raise the inside temperature of the spacecraft. Alongside these heat exchangers, numerous heaters will be installed throughout the spacecraft such as Omega Polyimide Heater Kit mentioned above.

The spacecraft will have a network of heating pipes installed throughout in order to help regulate heat. These heat pipes will convert the heat into vapors that may be transported throughout the pipes and released. Once the vapors are condensed back into a liquid, the liquid is then transported back to the hot areas through capillary action to start the process over again. They are an efficient closed-loop system that transports excess heat through temperature gradients, typically from an electrical device to a colder surface. In this case, the colder surface will be deployable radiators attached to the outside surface of the spacecraft. The TRL of this subassembly is a 4 due to its similar use in low earth environments within 6U CubeSat deployed from the ISS in 2020 (NASA 2024).

A network of fluid loops will also be used simultaneously with heat pipes. While the heat pipes transfer the heat throughout the pipe network as vapors, the fluid inside of the fluid loops absorb the heat, which is then transferred throughout the pipes. These pipes consist of a circulating pump that transports the fluids from a heat exchanger to heat sink. A heat source is then mounted to the heat exchanger and the fluid is pumped transporting the heat from the source to the sink. The spacecraft's heat sink will also include the use of deployable radiators, which is also used by the heating pipes to dissipate heat. The TRL of this subassembly is a 5 due to its similar use in low earth environments within 6U CubeSat deployed from the ISS in 2020 (NASA 2024).

Both the heat pipes and fluid loops will collect heat from hot spots within the spacecraft, and transfer the heat to radiators which the pipe networks are connected to.These radiators will then efficiently release the heat from the spacecraft through radiative heat transfer. The radiators on the spacecraft will also be retractable, which will allow the spacecraft to deploy or retract the radiators along with the solar panels whenever necessary. Additionally, radiators will be coated with a reflective coating that will assist in the retaining heat in the interior. The TRL of this subassembly is a 5 due to its similar use in low earth environments within 6U CubeSat deployed from the ISS in 2020 (NASA 2024).

An active cooling system will also be implemented within this design to provide cooling when the spacecraft is exposed to direct sunlight on the lunar surface and if the spacecraft starts to overheat within the lunar cave from to the other electronics and payloads. As mentioned previously, fluid loops will be used within the thermal system to help regulate the heat and cooling within the spacecraft. Thermoelectric coolers will also be used within the thermal subsystems to provide specialized cooling to specific components of the spacecraft that are more susceptible to temperature fluctuations and damage caused by it. Thermoelectric coolers are " miniature solid-state heat pumps which provide localized cooling via the Peltier effect, which is cooling resulting from passing electric current through a junction formed by two dissimilar metals" (NASA 2024). The benefits of using thermoelectric coolers are that they have no moving parts, are compact, lightweight, and reliable. Based on the trade study comparing different types of active cooling systems, the thermoelectric coolers met both requirements of being compact and having a small mass.They also had a significantly less amount of power consumption than the other two systems while still being able to provide the same amount of cooling.The TRL of this subassembly is a 4 due to its similar use in other low orbit spacecraft (NASA 2024).

As with other subsystems in the spacecraft, the cooling system must be fully autonomous and controlled by the spacecraft. Reflective coatings and MLI will be applied on spacecraft components exposed to space.The goal of these coatings will be to reduce the amount of energy absorbed by these components.

MLI coatings typically "consist of multiple inner layers of a thin material with low IR emissivity and a durable outer layer" (NASA 2024). The amount of radiative heat transfer is limited due to the multiple layers of reflectors. MLI coating can be used as "a thermal radiation barrier to both protect spacecraft from incoming solar and IR flux, and to prevent undesired radiative heat dissipation to space" (NASA 2024). The combined use enables the spacecraft to retain and reflect heat when needed. Maintaining efficient operating temperatures is the main goal of the thermal subsystem and MLI coating helps the spacecraft maintain these temperatures. The TRL of this subassembly is a 5 due to its similar use in low earth environments within 6U CubeSat deployed from the ISS in 2020 (NASA 2024).

In addition with MLI coatings, the use of adhesive tapes will be used underneath to cut down the cost of materials while still providing the same amount of performance levels. Adhesive tapes are easy to apply and remove, saving time and money when manufacturing the spacecraft (NASA 2024). Physical components such as radiators will be covered in the reflective coating, while larger areas like the surface of the spacecraft will be covered with MLI. It is just as important to ensure that the interior temperature of the spacecraft does not drop too low. This is due to the fact that the delicate electronics and components operate within a range of temperatures. To ensure that the temperature does not drop too low within the spacecraft, multiple interior heating solutions have been installed into the interior of the spacecraft. The TRL of this subassembly is a 4 due to its similar use in low earth environments within 6U CubeSat deployed from the ISS in 2020 (NASA 2024).

Just as mentioned earlier, the components used to heat the spacecraft must also be fully autonomous, and have the ability to be adjusted by the spacecraft according to the data that it collects. It is vital that both the heating and cooling system of the thermal management system are controlled by the spacecraft in order for both systems to balance each other out, and ensure that the interior remains within the specified temperature range. If the thermal management system is to be fully autonomous, then it is crucial that the spacecraft has a way of monitoring the interior temperature of the spacecraft. It is also vital that the spacecraft has the ability to control individual components to ensure that there is a balance between the two systems, and the interior remains within the temperature range.

To begin collecting data on the status of different systems, sensors will be utilized throughout the different systems. Each sensor will be strategically placed in various parts of the interior, such as near the centralized power distribution unit, the heating and cooling systems, and other components that generate or produce heat. Additionally, redundant sensors will be placed at these strategic locations to ensure that the spacecraft may continue to gather data on the temperature of the components, and make adjustments as necessary.

Thermocouples will be used to gather data on temperatures throughout different areas of the interior of the spacecraft. This is due to the fact that compared to other sensors, thermocouples tend to be more cost effective, have a smaller size, and provide fast and accurate response times.The TRL of this subassembly is a 4 due to its similar use in low earth environments within 6U CubeSat deployed from the ISS in 2020 (NASA 2024).

Thermal switches will also be used to switch the heat conduction path between thermocouples to control the temperature of heat producing components. A thermal switch “typically connects a heat producing component and a low temperature sink” which are the deployable radiators used in this spacecraft (NASA 2024). The combination of thermocouples and thermal switches is that thermal switches allow the spacecraft to passively modulate a thermal coupling, enabling for the spacecraft to be fully autonomous.The TRL of this subassembly is a 4 due to its similar use in low earth environments within 6U CubeSat deployed from the ISS in 2020 (NASA 2024).

The overall TRL of this thermal subassembly is a 4 since the lowest TRL of the entire system is a 4.

2.1.4.3 Thermal Control Subsystem Recovery and Redundancy Plans

To ensure the thermal management system remains fully operational throughout the course of the mission, several redundancies have been implemented in order to ensure the interior temperature of the spacecraft remains within the specified range. For starters, the spacecraft will have multiple thermoelectric coolers and Omega Polyimide Heater Kits installed. In the event that one of these components were to go out, the back up heater or cooler will seamlessly take the place of its counterpart to ensure the thermal management system continues to run smoothly. Additionally, multiple radiators will be installed, as well as being retractable, similar to the solar panels. The installation of both fluid loops and heat pipes also play an important role in the event that one of these networks were to be compromised. The operational system may continue to work with the heat exchange and radiators in order to ensure that heat is being properly distributed, as well as dissipated throughout the interior. Lastly, the thermal management system will also be fully autonomous. Equipped with instruments and sensors to measure the temperature at different strategic points of the interior, the spacecraft will use this data to make any adjustments necessary to ensure that the heating and cooling systems balance each other out.

It is essential to have redundancies for each of these components because the spacecraft requires the entire system to remain at stable operating temperatures to function properly and efficiently while in use. If the thermal subsystem fails, so does the entire mission and all of the interior components would be damaged. Multiple heating and cooling subassemblies are included in the design so that the spacecraft can remain functional if any of the subassemblies fail. Multiple layers of MLI coatings and adhesive tapes are included so the interior remains insulated and protected from the temperature changes that can occur on the lunar surfaces and within the lunar caves. Many of the components also act as a redundancy to other components in case one of them fails, other subassemblies are performing the same function so the entire system does not fail. In the event that a subassembly fails, the thermal subsystem has many failsafes to ensure the system remains operational.

2.1.4.4 Thermal Control Subsystem Manufacturing and Procurement Plans

The Thermal Management System requires a variety of different components to seamlessly work together in order to ensure that the temperature within the spacecraft does not fluctuate extremely. The heating/cooling units will be contracted from Lockheed Martin. These units designed by Lockheed Martin have the ability to maintain precise temperature control, as well as experience in multiple missions, making Lockheed Martin a reliable candidate. Northrop Grumman will be contacted in the event Lockheed Martin is unable to provide the units. The MLI Coating will be manufactured in house with NASA resources. This is due to the fact that the MLI coating will require precise control over the production process, which ensures that the coating meets the expected requirements for the thermal management system. Fluid Loops will be supplied by Jacobs Engineering Group. Jacobs Engineering Group has significant experience in integrating fluid loops into thermal management systems for similar applications to the spacecraft. The Aerospace Corporation will be contacted in the event that Jacobs Engineering Group is unable to provide the fluid loops. Heat pipes will be utilized in conjunction with fluid loops, and contracted by Sierra Nevada Corporation. Sierra Nevada has experience in space missions, specifically involving integrating heat pipes into thermal management systems, making them the perfect candidate to supply the heat pipes. General Dynamics Corporation will be contacted in the event Sierra Nevada is unable to provide the Heat pipes. Radiators are another integral component of the thermal management system, and will be contracted from The Boeing Company. Boeing has the ability to manufacture advanced radiators for aerospace applications, making them the ideal candidate to source the radiators from. Raytheon Technologies Corporation will be contacted as a backup to Boeing. Lastly, the thermal management systems heat exchanger will be contracted from Teledyne Technologies Incorporated. Teledyne Technologies has experience with heat exchangers in aerospace applications, and can guarantee reliable and efficient thermal control systems. Aerojet Rocketdyne will be contracted in the event Teledyne technologies is unable to supply the heat exchangers.

The thermal subsystems estimated lead time will be between March 2027 to December 2027. Lockheed Martin, Jacobs Engineering Group, Aerospace Corporation, Sierra Nevada Corporation, The Boeing Company, and Teledyne Technologies Incorporated will work on manufacturing specific thermal subassemblies used throughout the spacecraft. Each subassembly will be integrated within each subsystem to ensure optimal efficiency throughout the mission. NASA resources will be used to manufacture the MLI coatings specifically on the exterior of the spacecraft while the other subassemblies are being manufactured. This time frame allows the specific manufacturers to deliver the subassemblies in a timely manner, provide time to use backup suppliers if needed, and allows for the integration of the thermal subassemblies throughout each subsystem.

2.1.4.5 Thermal Control Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Preliminary Verification Plan
THRM- 1	Maintain an operating temperature of 20 C inside the spacecraft.	Demonstration	Measure the interior temperature over a certain period of time to see if it remains constant .
SYS- 1	Regulate its own temperature autonomously using installed heating and cooling systems.	Test	Expose spacecraft to different temperature fluctuations and see if it can maintain a constant operating temperature.
SYS- 1.1	Equipped with a thermal control system that allows for adjustments based on real time data.	Inspection	Visually inspect if there is a thermal control system.
SYS- 1.2	Redundancy for thermal management's controls and components.	Test	Simulate component failure and see if the redundant components turn on.
SYS- 1.2.1	Systems should have redundant control pathways and failover mechanisms.	Analysis	Simulate component failure and see if the redundant components turn on.
SYS- 1.2.2	Have redundant heaters and coolers installed.	Test	Simulate component failure and see if the redundant components turn on.
RET- 1	Prevent the interior temperature from dropping below 20 C operating temperatures.	Demonstration	Visually see if the spacecraft can maintain a constant temperature.
RET- 1.1	Reduce the amount of heat radiated from the spacecraft onto the moon and outer space.	Inspection	Inspect the external components of the spacecraft to ensure thermal isolation.
RET- 1.1.1	Surfaces of the spacecraft will be covered in MLI coatings.	Inspection	Visually inspect all external components are sealed and have MLI coating.
RET- 2	The spacecraft should have a heat exchanger installed.	Inspection	Visually inspect for heat exchanger.
REL- 1	Able to control and measure the amount of heat within the spacecraft to maintain 20 C.	Demonstration	Measure the interior temperature over a certain period of time to see if it remains constant .
REL- 1.1	Spacecraft will have a cooling system installed to dissipate heat away from hot spots that exceed 20 C.	Demonstration	Measure the interior temperature over a certain period of time to see if it remains constant .
REL- 1.1.1	Interior should have heat pipes installed for optimal heat transfer.	Inspection	Visually inspect for heat pipes.
REL- 1.1.2	Interior should have fluid loops installed to reduce heat spots.	Inspection	Visually inspect for fluid loops.
REL- 1.2	The spacecraft should have multiple retractable radiators installed on the exterior.	Inspection	Visually inspect for retractable radiators on the exterior of the spacecraft.

Figure 24: Thermal Verification Table

Figure 24 was created to show the specific methods used to test and verify that the requirements were met. Each requirement was labeled with terms such as demonstration, test, inspection, or analysis. These terms then had an associated plan next to them to explain how these requirements were met. All of the thermal requirements had a plan to verify that each individual requirement had been met.

2.1.5 Payload Subsystem Overview

To address the overarching science goals that have been established for this mission, several science goals have been defined. These objectives with consideration of customer restraints and each collect materials and data to fulfill the science goals. Analyzing the resulting data and samples obtained from these science objectives will pave the way for valuable mission discoveries regarding the Compton Pit and the lunar surface surrounding the pit.

The first science goal defined for this mission involves the mission's robotic system and how it will affect future research that will be conducted on the Moon's surface. To ensure that astronauts are efficiently prepared for the mission, two science objectives have been defined. The first objective requires determining the readily available amount of Oxygen and metals as in situ resources in the lunar regolith located around and inside the Compton Pit. The studies of lunar regolith stimulants can be used to determine the limits of the stimulants to validate key components for human survivability during sustained presence on the Moon (Chandra et al. 2010). The PROSPECT Sample Excavation and Extraction Drill (ProSEED) would be a suitable instrument to complete this goal. The system's purpose of gathering core samples to extract regolith samples will aid NIRVSS in determining the concentration of hydrogen, water, hydroxyl, and other volatiles. ProSEED would be able to drill into the lunar surface and collect data measurements to fulfill this objective.

The second objective is to determine the amount of solar wind materials, water, and Hydroxyl molecules present in the lunar regolith located near or within the Compton Pit. Water is an important resource for future habitability. Although there may not be many water molecules, the process of combining Hydrogen and Hydroxyl molecules can be further studied to obtain water necessary to survive. The Moon isn't able to protect itself from high levels of radiation, therefore surface regions can be identified that could be protected from inhabitable radiation levels. The Near-Infrared Volatile Spectrometer System (NIRVSS) acquires spectra between 1600-3400 nm, <15 nm resolution, and can identify key volatiles (solid and gas) and minerals while surface roving and subsurface drilling (Roush and Colaprete, 2015). It is designed to measure surface and subsurface water, carbon dioxide, and methane and is able to map the surface temperature and changes that occur at the landing site (Colaprete, 2022). NIRVSS would be efficient to collect similar minerals to past research experiments. A similar design or instrument would ensure proper data collection. Similarly, the Neutron Spectrometry System (NSS) will measure the amount of hydrogen-bearing materials near the surface at the landing site to determine the potential for water ice (NASA, PEREGRN-1-02). Together, both of these instruments are able to identify the H, O_2, H_2O, and OH molecules and assess how many of the materials at the surface have the potential to become water ice.

The second science goal defined for this mission determines the ability of the robotic system to provide and locate a safe habitat to protect individuals, equipment, and associated infrastructure. The first objective is to characterize the dimensions and deformations of the Compton Pit. The system will have to measure the depth, height, terrain variation, ease of access, and structural integrity of the pit. Mapping these physical features are imperative to determine conclusions for human habitation. Identifying dimensions and deformations is crucial for the safety of astronauts. Additionally, identifying overhangs and stress points will allow astronauts to detect potential hazards that could endanger personnel and equipment. These dangers should be identified to avoid or reinforce vulnerabilities to increase safety. A Light Detection and Ranging (LiDAR) system such as REIGL creates topographic maps that would identify terrain features, slopes, and potential obstacles. Sensing systems can identify potential hazards and allocate preparation to navigate risks and obstacles.

The second science objective is to measure temperature and radiation levels within the Compton Pit. This data will allow astronauts to make decisions regarding sustainability and survivability of the individuals and equipment that will be staying within the potential habitat area. An instrument such as the Multi-Parameter Aerosol Scattering Sensor (MPASS) would provide information about the particles in the environment in real time. Since it is an aerosol-detection system, it will categorize atmospheric particles and monitor them in real time to assess whether the environment is safe enough for life (NASA Technology Transfer Program). It is imperative that the cave remains below a radiation threshold to maintain a safe environment for human habitation.

2.1.5.1 Science Instrumentation Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification Method	Relevant Subsystem	Req Met?
Payload-1	ProSEED drill functions nominally	It should be able to gather samples for analysis		Payload-1.1, Payload-1.2, Payload 1.3, Payload 1.4	Demonstration	Payload	Met
Payload-1.1	ProSEED can drill at a depth of 10-30cm	The range of 10-30 cm allows for adequate sample gathering, although a more accurate sample comes from deeper drill depths.	Payload-1		Demonstration	Payload	Met
Payload-1.2	ProSEED can drill through a Mohs 6 material	The drill should be able to gather samples in field conditions, and not break down due to harder rocks.	Payload-1		Demonstration	Payload	Met
Payload-1.3	ProSEED has a motor with specialized drill bits and modular core stems	The drill should be able to take samples from any given area in the pit.	Payload-1		Demonstration	Payload	Met
Payload-1.4	ProSEED will be able to drill material with temperatures of 100-300K.	In order for the mission to succeed in the field, the instruments must be able to operate within the expected temperature conditions of Compton Plt.	Payload-1		Demonstration	Payload	Met
Payload-2	The NIRVSS spectrometer functions nominally	It should be able to take spectral samples and analyse the lunar regolith.		Payload 2.1, Payload 2.2, Payload 2.3, Payload 2.4	Demonstration	Payload	Met
Payload-2.1	NIRVSS has a wavelength range of 1600-3400nm	The spectrometer should be able to detect a wide variety of volatiles, as well as characterize hydrogen signatures	Payload 2		Demonstration	Payload	Met
Payload-2.2	NIRVSS has an integration time of 1/s	The device should be able to integrate data fast enough to gather data as the sample changes over time.	Payload 2		Demonstration	Payload	Met
Payload-2.3	NIRVSS is sensitive to thermal and epithermal neutrons	The spectrometer should be able to detect neutrons to better help with data collection of the pit.	Payload 2		Demonstration	Payload	Met

Payload-2.4	NIRVSS has an accurate spatial resolution for varying molecules	The spectrometer should be able to accurately characterize the molecules found in samples	Payload 2	Payload-2.4.1, Payload-2.4.2, Payload-2.4.3, Payload-2.4.4	Demonstration	Payload	Met
Payload-2.4.1	NIRVSS has a spatial resolution of 20-30nm for H2O	The spectrometer should be able to accurately identify H2O	Payload 2.4		Demonstration	Payload	Met
Payload-2.4.2	NIRVSS has a spatial resolution of10-20nm for NH3	The spectrometer should be able to accurately identify NH3	Payload 2.4		Demonstration	Payload	Met
Payload-2.4.3	NIRVSS has a spatial resolution of 10-20nm for CO2	The spectrometer should be able to accurately identify CO2	Payload 2.4		Demonstration	Payload	Met
Payload-2.4.4	NIRVSS has a spatial resolution of 20-30nm for CH4	The spectrometer should be able to accurately identify CH4	Payload 2.4		Demonstration	Payload	Met
Payload-3	The NSS spectrometer functions nominally	It should be able to take spectral samples and analyse the lunar regolith.		Payload-3.1, Payload 3.2, Payload 3.3, Payload 3.4	Demonstration	Payload	Met
Payload-3.1	The NSS has a wavelength range of 1ev-1kev	The spectrometer should be able to detect hydrogen signatures	Payload-3		Demonstration	Payload	Met
Payload-3.2	The NSS has an integration time less thn or equal to 550 counts/s	The device should be able to integrate data fast enough to gather data as the sample changes over time.	Payload-3		Demonstration	Payload	Met
Payload-3.3	The NSS has a sensitivity of 80/cm^2	The spectrometer should be able to take precise measurements, to better help gather data and determine a drilling spot.	Payload-3		Demonstration	Payload	Met
Payload-3.4	The NSS has a sample rate of 1/s	The device should be able to sample fast enough to gather data as the sample changes over time.	Payload-3		Demonstration	Payload	Met

Payload-4	REIGL functions nominally	The system can accurately map the inside of Compton Pit		Payload-4.1, Payload 4.2, Payload 4.3, Payload 4.4, Payload-4.5	Demonstration	Payload	Met
Payload-4.1	REIGL has a range of 400m	The system should be able to accommodate the size of	Payload-4		Demonstration	Payload	Met
Payload-4.2	REiGL has an integration time of 110,000 measurements/s	The device should be able to integrate data fast enough to gather data as the sample changes over time.	Payload-4		Demonstration	Payload	Met
Payload-4.3	REIGL has a precision of 4mm	The system should be able to take precise measurements, to better help gather data	Payload-4		Demonstration	Payload	Met
Payload-4.4	REIGL has an accuracy of 5mm	The system should be able to create an accurate model of Compton Pit	Payload-4		Demonstration	Payload	Met
Payload-4.5	REIGL has a spatial resolution of 5mm	The system should be able to generate a high-resolution model of Compton Pit	Payload-4		Demonstration	Payload	Met
Payload-5	REMS functions nominally	The system should be able to accurately and precisely measure the temperature of Compton Pit		Payload-5.1, Payload 5.2, Payload 5.3, Payload 5.4	Demonstration	Payload	Met
Payload-5.1	REMS can measure a range from 273-373K	The device must be able to take measurements within the expected temperature conditions of Compton PIt.	Payload-5		Demonstration	Payload	Met
Payload-5.2	REMS has an integration time of 1/s	The device should be able to integrate data fast enough to gather data as the sample changes over time.	Payload-5		Demonstration	Payload	Met

Payload-5.3	REMS has a sensitivity of 2K.	The system should be able to take precise measurements, to better help gather data	Payload-5		Demonstration	Payload	Met
Payload-5.4	REMS has a resolution of 2K.	The system should be able to generate a high-resolution model of the temperature Compton Pit	Payload-5		Demonstration	Payload	Met
Payload-6	The M-42 functions nominally	The system should be able to accurately and precisely measure the radiation of the pit.		Payload-6.1, Payload 6.2, Payload 6.3, Payload 6.4	Demonstration	Payload	Met
Payload-6.1	The M-42 has a detection range of 0.1-15 MeV	The device must be able to take measurements within the expected radiation conditions of Compton PIt.	Payload-6		Demonstration	Payload	Met
Payload-6.2	The M-42 has an integration time of 300s	The device should be able to integrate data fast enough to gather data as the sample changes over time.	Payload-6		Demonstration	Payload	Met
Payload-6.3	The M-42 has a sensitivity of 0.5 MeV	The system should be able to take precise measurements, to better help gather data	Payload-6		Demonstration	Payload	Met
Payload-6.4	The M-42 has a measurement rate of 0.5 counts/s	The device should be able to integrate data fast enough to gather data as the sample changes over time.	Payload-6		Demonstration	Payload	Met

Figure 25: Science Instrument Requirements Table

The ProSEED drill is required to drill at a depth of 10-30 cm below the lunar regolith. It is expected to exceed this goal, drilling at a depth of 100-120 cm. It is also required to drill through a material that ranks 6 on the Mohs hardness scale, have a motor with specialized drill bits and modular core stems, and be able to drill material with temperatures of 100-300K.

The NIRVSS is required to have a wavelength range of 1600-3400 nm , an integration time of 1/s, a sensitivity to thermal and epithermal neutrons, and a spatial resolution of 20-30nm, 10-20 nm, 10-20 nm, and 20-30 nm for H_2O, NH_3, CO_2, and CH_4, respectively.

The NSS is required to have a wavelength range of 1 eV -1 KeV, an integration time less than or equal to 550 counts/s, a sensitivity of 80/cm^2, and a sample rate of 1/s.

The RIEGL VZ-400 V-Line 3D Terrestrial Laser Scanner is required to have a range of 400m, an integration time of 110,000 measurements/s, a precision of 4mm, an accuracy of 5mm, and a spatial resolution of 5mm.

The REMS is required to be able to measure a range of 273-373 K, have an integration time of 1/s, and sensitivity and resolution of 2K.

The M-42 is required to have a detection range of 0.1-15 MeV, an integration time of 300s, a sensitivity of 0.5 MeV, and a measurement rate of 0.5 counts/s.

2.1.5.2 Payload Subsystem Recovery and Redundancy Plans

To ensure the reliability of the Near Infrared Volatile Spectrometer System (NIRVSS) throughout the mission, recovery and redundancy strategies have been implemented to mitigate risks of failure and maximize data collection. NIRVSS uses sensors such as photodetectors and spectrometers, therefore, in case they fail, there will be redundant units to continue its functionality (Colaprete et. al.). Dual power supply lines will be incorporated to prevent power outages. If one fails then the secondary line will maintain operations. The system will utilize multiple data storage units to ensure data collection preservation. To preserve communication pathways, there will also be primary and secondary communication protocols. The design of NIRVSS will be a modular design that can be broken into smaller parts, allowing easy replacement for failed components with backup parts. This will minimize the risk that could result from the failure of an instrument.

The NIRVSS will have built-in diagnostic capabilities to monitor the health of critical components (Clark, et. al). It will report potential failures and allow efficient corrective actions. Fault detection will find abnormalities in data processing and the system can attempt a recovery procedure such as rebooting certain components or switching them to backup components. In the event of a subsystem failure, operational protocols will be established to guide mission operators with a step by step process to switch to redundant systems or conduct repairs. If data loss occurs during operations, the protocols will be in place to ensure that important data isn’t lost. The recovery and redundancy strategies for the NIRVSS ensure high reliability and continuous operation throughout the mission. These strategies will allow NIRVSS to mitigate risks involving component failures and environmental challenges.

The Neutron Spectrometer System (NSS) is designed to operate in challenging environments. To ensure mission success and data preservation, recovery and redundancy strategies will be implemented to maintain operational capability in the event of component failure or environmental challenges. The NSS shall incorporate redundant neutron detection models. If there is failure with a system, there will be a secondary system to be put in place. Similarly, with dual redundancy power systems, there will be a backup in case of a failure with the primary power system. Each system will be able to independently provide power to all subsystems. To ensure that data isn't lost, multiple data storage units will be implemented so data can always be retrieved and analyzed. There will be multiple communication paths to transmit data to the background. Similar to the NIRVSS, NSS will also have a modular design to allow easy replacement of malfunctioning components with backup components.

To ensure recovery strategies are implemented, the NSS will include onboard diagnostic systems to continuously monitor the performance of critical components. The Adaptive Recovery Procedures will employ advanced algorithms to detect faults in real-time. If a failure occurs, the NSS can automatically initiate recovery procedures such as switching to backup components. There will be protocols in place to guide mission operations with a step-by-step process in addressing these failures. To check data integrity, the NSS will implement data integrity verification protocols to ensure that the data collected remains intact. If there are transmission failures, the system can request a retransmission of critical data from storage. The recovery and redundancy strategies for the NSS ensure high reliability and continuous operation throughout the mission. These strategies will allow NSS to mitigate risks involving component failures and environmental challenges, enhancing its ability to provide vulnerable scientific data during planetary exploration missions.

To ensure the thermal management system remains fully operational throughout the course of the mission, several redundancies have been implemented in order to ensure the interior temperature of the spacecraft remains within the specified range. For starters, the spacecraft will have multiple coolers and heaters installed. In the event that one of these components were to go out, the back up heater or cooler will seamlessly take the place of its counterpart to ensure the thermal management system continues to run smoothly. Additionally, multiple radiators will be installed, as well as being retractable, similar to the solar panels. The installation of both fluid loops and heat pipes also play an important role in the event that one of these networks were to be compromised. The operational system may continue to work with the heat exchange and radiators in order to ensure that heat is being properly distributed, as well as dissipated throughout the interior. Lastly, the thermal management system will also be fully autonomous. Equipped with instruments and sensors to measure the temperature at different strategic points of the interior, the spacecraft will use this data to make any adjustments necessary to ensure that the heating and cooling systems balance each other out.

2.1.5.3 Payload Subsystem Manufacturing and Procurement Plans

The Payload subsystem is heavily science focused, consisting of most of the mission's science instruments. This is vital to the mission and must be done correctly. The contractors have to be highly experienced in making scientific instruments in order for everything to run smoothly in the manufacturing process. Without these instruments this mission will not be able to be completed as intended and are vital.

Many scientific instruments will be utilized during this mission, and contracted by Teledyne Technologies Incorporated, and in the event that Teledyne Technologies Incorporated cannot manufacture some instruments then Raytheon Technologies Corporation will manufacture the rest. Both these contractors specialize and have experience making tech, making them a great choice for making the scientific instruments. In all, both companies have the ability to manufacture the ProSEED, NIRVSS, NSS, M-42, and REMS that this mission is looking for. The REIGL will be manufactured by a separate company and will be purchased as it cannot be manufactured.

The ProSEED will start March 2027 and finish May 2027, NIRVSS will start April 2027 and finish June 2027, NSS will start May 2027 and finish July 2027, M-42 will start June 2027 and finish August 2027, and REMS will start July 2027 and finish September 2027. The Scientific instruments subsystems estimated lead time will be between March 2027 to October 2027, the extra month of October will be used to test all instruments and make sure everything is working optimally. Teledyne Technologies Incorporated will be in charge of manufacturing these instruments and will need this allocated time in order to test each instrument and make sure it's working efficiently. In the case that Teledyne Technologies Incorporated cannot manufacture the scientific instruments then Raytheon Technologies Corporation will take over. Raytheon Technologies Corporation may take an extra month and finish in November 2027, due to late notice. Both companies would be responsible for manufacturing ProSEED, NIRVSS, NSS, M-42,and REMS that this mission is looking for.

2.1.5.4 Payload Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Preliminary Verification Plan
Payload-1	ProSEED drill functions nominally	Demonstration	Test the system in simulated field environment
Payload-1.1	ProSEED can drill at a depth of 10-30cm	Demonstration	Test the system in simulated field environment
Payload-1.2	ProSEED can drill through a Moh’s 6 material	Demonstration	Test the system in simulated field environment
Payload-1.3	ProSEED has a motor with specialized drill bits and modular core stems	Demonstration	Test the system in simulated field environment
Payload-1.4	ProSEED will be able to drill material with temperatures of 100-300K.	Demonstration	Test the system in simulated field environment
Payload-2	The NIRVSS spectrometer functions nominally	Demonstration	Test the system in simulated field environment
Payload-2.1	NIRVSS has a wavelength range of 1600-3400nm	Demonstration	Test the system in simulated field environment
Payload-2.2	NIRVSS has an integration time of 1/s	Demonstration	Test the system in simulated field environment
Payload-2.3	NIRVSS is sensitive to thermal and epithermal neutrons	Demonstration	Test the system in simulated field environment
Payload-2.4	NIRVSS has an accurate spatial resolution for varying molecules	Demonstration	Test the system in simulated field environment
Payload-2.4.1	NIRVSS has a spatial resolution of 20-30nm for H2O	Demonstration	Test the system in simulated field enviornment
Payload-2.4.2	NIRVSS has a spatial resolution of10-20nm for NH3	Demonstration	Test the system in simulated field enviornment
Payload-2.4.3	NIRVSS has a spatial resolution of 10-20nm for CO2	Demonstration	Test the system in simulated field enviornment
Payload-2.4.4	NIRVSS has a spatial resolution of 20-30nm for CH4	Demonstration	Test the system in simulated field enviornment
Payload-3	The NSS spectrometer functions nominally	Demonstration	Test the system in simulated field environment
Payload-3.1	The NSS has a wavelength range of 1ev-1kev	Demonstration	Test the system in simulated field enviornment
Payload-3.2	The NSS has an integration time less thn or equal to 550 counts/s	Demonstration	Test the system in simulated field environment
Payload-3.3	The NSS has a sensitivity of 80/cm^2	Demonstration	Test the system in simulated field enviornment
Payload-3.4	The NSS has a sample rate of 1/s	Demonstration	Test the system in simulated field enviornment
Payload-4	REIGL functions nominally	Demonstration	Test the system in simulated field enviornment
Payload-4.1	REIGL has a range of 400m	Demonstration	Test the system in simulated field enviornment
Payload-4.2	REiGL has an integration time of 110,000 measurements/s	Demonstration	Test the system in simulated field enviornment
Payload-4.3	REIGL has a precision of 4mm	Demonstration	Test the system in simulated field enviornment
Payload-4.4	REIGL has an accuracy of 5mm	Demonstration	Test the system in simulated field enviornment
Payload-4.5	REIGL has a spatial resolution of 5mm	Demonstration	Test the system in simulated field enviornment

Payload-5	REMS functions nominally	Demonstration	Test the system in simulated field enviornment
Payload-5.1	REMS can measure a range from 273-373K	Demonstration	Test the system in simulated field enviornment
Payload-5.2	REMS has an integration time of 1/s	Demonstration	Test the system in simulated field enviornment
Payload-5.3	REMS has a sensitivity of 2K.	Demonstration	Test the system in simulated field enviornment
Payload-5.4	REMS has a resolution of 2K.	Demonstration	Test the system in simulated field enviornment
Payload-6	The M-42 functions nominally	Demonstration	Test the system in simulated field enviornment
Payload-6.1	The M-42 has a detection range of 0.1-15 MeV	Demonstration	Test the system in simulated field enviornment
Payload-6.2	The M-42 has an integration time of 300s	Demonstration	Test the system in simulated field enviornment
Payload-6.3	The M-42 has a sensitivity of 0.5 MeV	Demonstration	Test the system in simulated field enviornment
Payload-6.4	The M-42 has a measurement rate of 0.5 counts/s	Demonstration	Test the system in simulated field enviornment

Figure 26: Payload Verification Table

2.2 Interface Control

In order for the HELP spacecraft to successfully navigate the lunar surface, weather its extreme surface conditions, and record science measurements, the rover's individual subsystems must blend to operate as one complete system. This can be accomplished by practicing interface management, a process that involves monitoring the contributions of multiple subdivisions of a mission spacecraft, and ensuring products effectively interoperate between one another ("NASA Systems Engineering Handbook" 2007). The HELP mission team is overseeing the implementation of interface management protocols to address potential issues that may arise due to improper subsystem integration.

An interface is defined as a boundary at which two or more subsystems interact (Wheatcraft 2021). The six subsystems outlined for interfacing to occur include the mechanical, payload, data handling, communications, thermal, and power subsystems of the HELP spacecraft. The N^2 diagram and system block diagram seen in Figures 27 and 28 are graphical representations of how each of these subsystems interact between one another[3].

The N^2 diagram displayed in Figure 27 provides a top-level overview of the interfaces between subsystems. Each spacecraft subsystem is represented by a colored square on the diagonal of the diagram, and the transfer of inputs and outputs is represented by a directional arrow. Arrows pointed upwards signify inputs to a given system in that column, whereas arrows pointed downward signify outputs to the subsystem in that given column[4]. These guidelines form a basis for not only the N^2 diagram, but the block diagram as well. The top-level, broad transfer of inputs and outputs in Figure 27 is further interpreted in Figure 28, where interface techniques are more visually represented. The interface design used for the block diagram is based on a similar block diagram model created for the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft (Biswas et al. 2016).

The interfaces represented in the block diagram clarify how each subsystem will interact with one another. Five interfacing techniques are outlined in the legend of Figure 28: power, thermal control, wiring, point-to-point signal, and mechanical. Solar power distribution, represented by the blue arrows in Figure 28, is transferred between subsystems via high-resistance wires. High-resistance wires are capable of controlling current transferred between subcomponents. This wire's ability to withstand extreme temperatures and withhold strong resistances within a confined space makes them useful for this space application ("The Resistance of Wire Explained " 2024). Thermal control is a complex subsystem composed of several thermal components. However, the entirety of its temperature maintenance is represented by the red arrows seen in Figure 28. Data transfer is an incredibly important aspect of the HELP mission - not only for recording science measurements but for handling ground control commands and

[3] The N^2 Chart and Block Diagram examples provided in the Resources and Examples section of the SRR Instructions documents were referenced and interpreted to understand how the HELP mission's subsystems might interact with one another across interfaces.
[4] This information was acquired from the L'SPACE Systems Topics Skill Module.

system state updates as well. These processes rely on insulated wires represented by the green highlighted arrows in Figure 28. The black dashed lines seen in Figure 28 represent mechanical, or physical, interfaces between subsystem components.

Establishing a point-to-point (P2P) connection between components can be incredibly useful. Considering this interface technique is implemented on the mission spacecraft, a P2P connection will be a wireless, private data connection between two or more subcomponents (Betz 2024). While cabled connections often run faster, this wireless solution remains a sufficient option that is secure, cost-effective, and able to operate remotely (Betz 2024). In Figure 28, any signal utilizing this P2P connection is represented by solid, black arrows.

The power subsystem is responsible for distributing power throughout the entire spacecraft throughout the entirety of Phase F. It is comprised of three primary components: a solar panel system, solid state battery, and a dual-bus power distribution system. The solar panels collect solar energy to be distributed via the dual-bus and solid state battery. These panels are mounted on a single axis tracking device, which allows the solar panels to rotate from east to west given the position of the Sun ("Innovation under the Sun" 2023). Therefore, a mechanical interface has been established in Figure 28 that branches between the mechanical and power subsystems.

The solar energy is transferred via high-resistance wiring to both the dual-bus and the solid state battery. The dual-bus distributor consists of two independent UCS systems that together transfer energy throughout spacecraft subcomponents in the mechanical, payload, data handling, command, and thermal subsystems ("UPS5000-E-(200 KVA–300 KVA) User Manual" 2024). This energy input is reflected by the upwards arrows along the power row in the N^2 diagram. The solid state battery is capable of storing large amounts of energy and offloading it at a later time ("Solid-State Battery Technology: 2024 Energy Storage Advancements" 2024). Therefore, the battery receives the power from the solar panels, stores it for use in permanently shadowed regions, and distributes it as necessary to the dual-bus to be allocated throughout the system.

The thermal subsystem is responsible for maintaining operable temperatures throughout the duration of the mission, therefore its input to every other subsystem is thermal management processes. This series of inputs is visualized in Figure 27. Thermal control is represented as an output to the power subsystem due to the thermal subsystem being directly impacted by energy input from the dual-bus system. This subsystem consists of a variety of subcomponents that interact differently depending on the application. Multi-layered insulation (MLI) is applied directly to the drive assembly architecture, therefore this is a mechanical interface. The radiator assists in the heat dissipation and temperature control of the fluid loops and heat pipes integrated into the system (Butler, Ku, and Swanson n.d.). The thermoelectric coolers and Omega Polyimide Heat Kit will utilize the high-resistance wiring to maintain operable temperatures throughout each subsystem on account of the wire's ability to withstand stronger temperatures.

The communications subsystem handles command inputs to the mechanical, payload, and data handling subsystems. By establishing a wireless P2P connection between the Mastcam-Z, drive assembly, and the Onboard Computer (OBC), the OBC can interpret visual data, store it, and transmit and P2P output connection back to the X-band transponder of the communications subsystem to subsequently send a signal to ground control. The X-band transponder sends a wired transfer of data to the high gain antenna that maintains a downlink of communications from the spacecraft to Earth (Bolles 2024b). As a result, navigation commands are dispatched to the drive assembly of the HELP rover, measurement collection commands are signaled to the payload instruments at science collection points, and ground control commands are dealt with inside of the OBC to monitor the state of components and the storage of data.

The data handling system is incredibly important in that it is responsible for safely securing the data obtained from science measurements and for updating competent status to continue system operation. The OBC is at the focal point of the data handling subsystem. This component executes and dispatches commands, monitors system telemetry, and handles subcomponent states useful for conducting failure detection ("Onboard Computers" n.d.). As collection commands are inputted to this system via insulated wiring, science measurements are recorded and system telemetry is reported back to ground control and the thermal and power systems to respond accordingly. Telemetry will contain data that reveals how certain subcomponents of the space are presently operating ("Definition of TELEMETRY" 2024). The OBC monitors the state of subsystem components via an onboard fault detection system and a multi-layered surface detection system. Utilizing a P2P connection, telemetry data is transmitted to the OBC, which subsequently provides a status update to the thermal and power subsystems to make changes accordingly. The OBC acquires data from subcomponents in each of the other subsystems as well. Data concerning science measurements will be transmitted over insulated wiring to be both stored in an electronic bank storage and transmitted to Earth. The other data concerning the mechanical, thermal, and power subcomponents are sent directly to the OBC to assist in state estimation.

The payload subsystem is especially complex. This subsystem hosts the six science instruments utilized in the collection of science measurements, as well as the onboard fault detection system that monitors the state of many system subcomponents. After receiving commands from the data handling and communications subsystems to begin collecting the data, the payload subsystem then outputs the recorded measurements back to the data handling subsystem to be stored and transmitted. This transfer of data occurs over the wired connection that branches between each instrument, the OBC, and the electronic storage back represented in Figure 28.

The onboard fault detection system applies protocols implemented by Markov and Kalman State Identification (MAKSI) to continuously update probabilistic state estimations (Washington 2000). Data is transferred via P2P connections to the onboard fault detection system to calculate these estimations. Given this data, observations are made regarding subsystem components, and state estimations are made using a Kalman filter (KF) (Washington 2000). Markov decision processes (MDPs) will handle cases where multiple probabilistic states are present for a given component, and partially-observable MDP (POMDP) will combine these states into one discrete version to be analyzed (Washington 2000). By comparing the component's current state to a previous state where it was known that the component was functioning properly, fault detection can efficiently occur aboard the HELP spacecraft. Therefore, the payload subsystem must output the calculated state estimate for it to be compared in future state comparisons. This system then generates subsystem telemetry to be transmitted back to Earth via a P2P signal.

The mechanical subsystem contains components that physically impact the HELP rover. This subsystem relies on navigation commands to control the drive assembly, a current state estimate of mechanical components, and thermal control and power distribution to maintain subsystem operation. The rover's drive assembly is monitored by a multi-layered surface damage detection system that is physically layered over the robot's architecture. This layering uses wired software to identify damage points along the surface hardware (Williams et al. n.d.). Then, status updates are output via a P2P connection to the OBC to be further analyzed. The photovoltaic effect of lanthanum-modified lead zirconate titanate (PLZT) is a piece of vibration technology that assists with removing dust from the solar panels and thermal components (Jiang et al. 2019). This component is therefore wired to each of these components and its operation is maintained through thermal and power management. The single-axis tracking device is wired and physically connected to the spacecraft's solar panels to optimize solar energy absorption. A preemptive shield of Corning type 7940 artificial fused silica is also applied to the solar panels, seen by the mechanical connection visualized between the two in Figure 28.

Moving forward, with these interfaces defined, several interface management procedures will be utilized to track the integration and functionality of these interfaces or change them if necessary. An Interface Working Group (IWG) will be formed that consists of team members from each of the engineering subteams outlined in Figure 45. This IWG will oversee interface control and will work with the team leadership members of the team[5] to discuss and coordinate interface changes should the need arise ("NASA Systems Engineering Handbook" 2007). In any instance where a change must be made, an Interface Change Request will be submitted to the customer to verify a new interface's integration. These changes are more likely to occur towards the end of Phase C and throughout Phase D, as the system architecture is manufacturing and subsystems begin to become intertwined.

In addition, documents that monitor the status of interface control will be created and examined. This documentation includes an Interface Requirements Document (IRD), an Interface Control Document (ICD), an Interface Definition Document (IDD), and an Interface Control Plan (ICP) ("NASA Systems Engineering Handbook" 2007). The subsystems outlined in Figure 27 will be considered in creating the IRD. This document defines interface requirements that clarify the logical, cognitive, and physical interfaces that bridge these subsystems together - similar to how the five interface

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[5] The Project Manager, Deputy Project Manager of Resources, Chief Scientist, and Lead Systems Engineer.

techniques were outlined previously for this mission (Alexander 2016). These requirements stem from system inputs and outputs represented in the N^2 diagram. The ICD goes into more detail, as it directly defines the design solution that addresses interface requirements outlined in the IRD (Alexander 2016). Depending on the situation, this document may instead be a drawing or a model, so as to better visualize the interface strategy. The ICD is especially useful for bridging progress between two or more subsystems.

A IDD will be completed by each subsystem at a system interface. In comparison to the ICD, this form is specifically for a singular subsystem to document verification that components will mesh with the applied interface technique (Alexander 2016). This document will keep the engineering subteams accountable for maintaining the compatibility of subcomponents. The ICP is a document that defines interface control, change management strategies, and subteam expectations. The HELP IWG will format this document to include risks associated with each interface and the necessary steps to take should a problem arise (Alexander 2016). In following these procedures and practicing interface management protocols, the HELP spacecraft will function efficiently as one complete system, preparing it for mission success on the lunar surface.

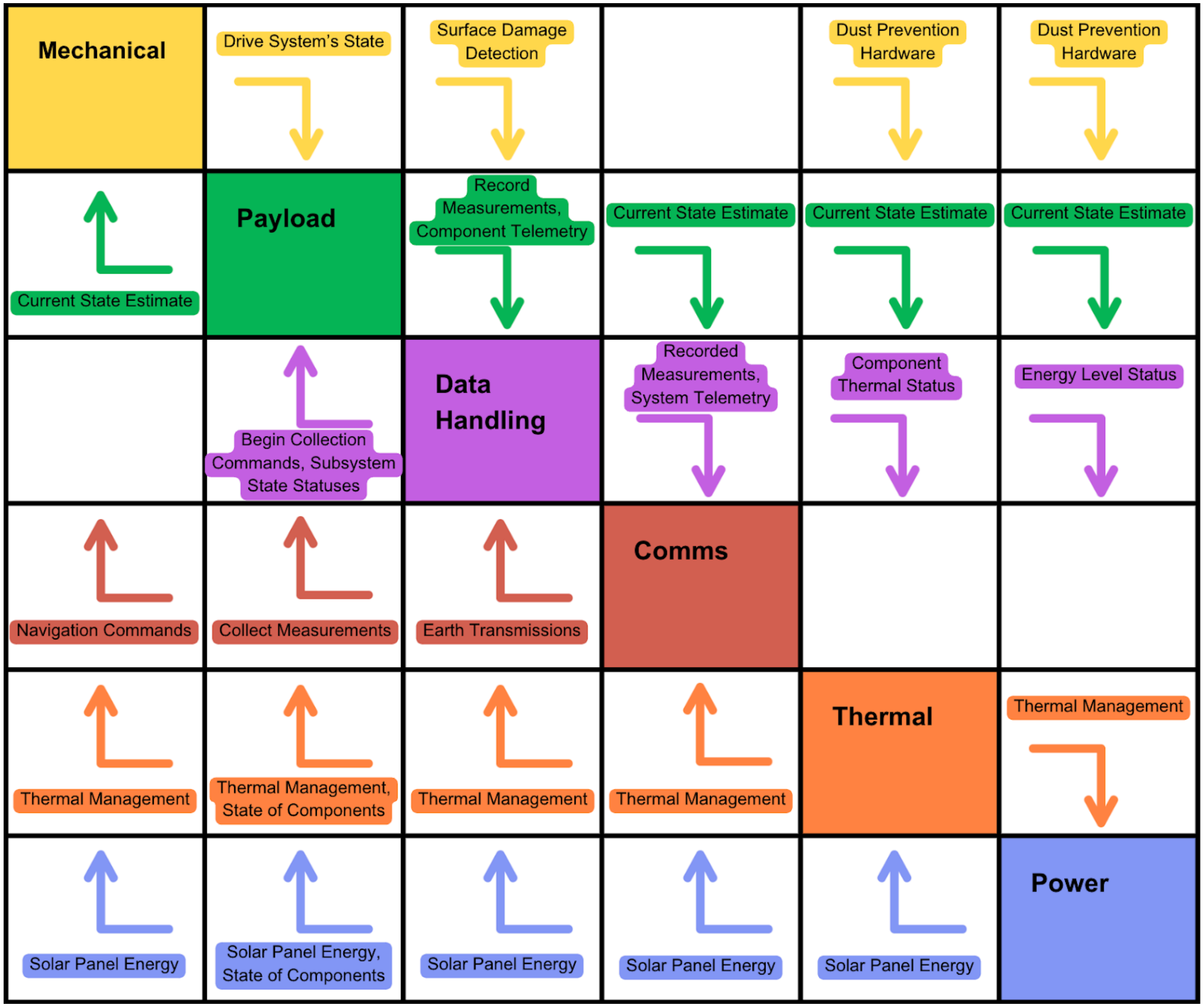

Figure 27: N^2 Diagram

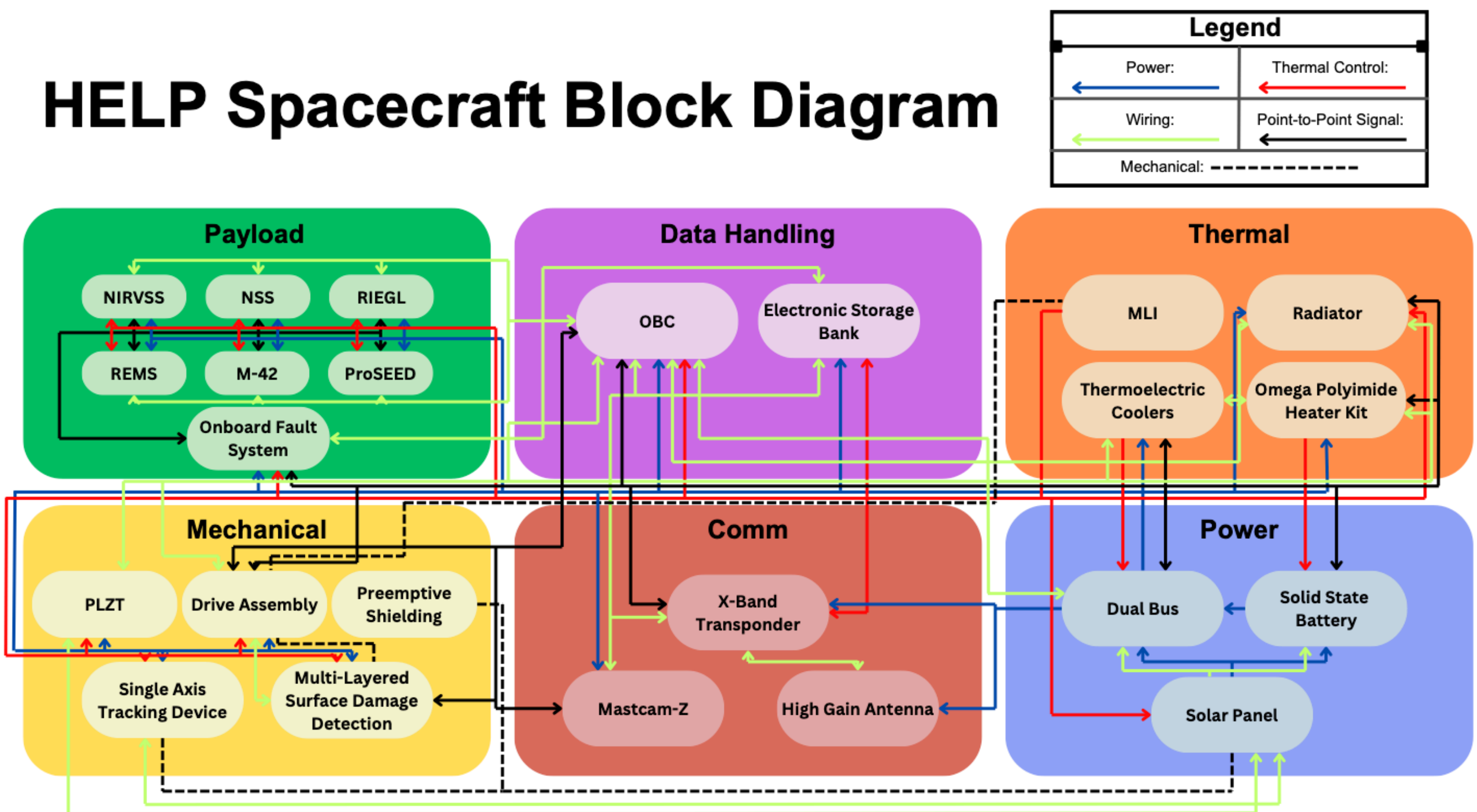

Figure 28: Spacecraft System Block Diagram

3 SCIENCE MISSION PLAN

3.1 Science Objectives

The science objectives in this mission are to identify water, oxygen, hydrogen, and hydroxyl and other volatiles in the regolith inside Compton Pit, and to characterize the depth, temperature, radiation, height, volume, and ease of access of the pit. These objectives were chosen as learning about the in-situ resources of the pit is helpful to determining whether Compton Pit is a good candidate for human habitation. This is because habitation on the Moon requires many physical resources, which are very expensive to transport. Gathering data about the physical characteristics of Compton Pit is also important as the size of the pit can determine how many humans can be supported by the structure. In addition, HELP will also determine whether Compton Pit exhibits blackbody behaviour, which will save on insulation costs during the habitation phase. Radiation measurements will also determine how much radiation shielding is needed to protect humans.

To accomplish the first objective, identifying water, oxygen, hydrogen, and hydroxyl inside the Compton pit, HELP will use the NSS to scan for hydrogen signatures. Once a drilling area has been determined by the concentration of hydrogen signatures in the area, the ProSEED will drill to collect samples of the lunar regolith at a depth of 100-120 cm. The samples from the drill are then analyzed through the NIRVSS system, which will determine the levels of water, oxygen, hydroxyl, and hydrogen in the sample. The NIRVSS system will also be able to determine the concentration of volatiles such as Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicates, and Anorthite Plagioclase.

To determine the characteristics of the pit, the RIEGL VZ-400 V-Line 3D Terrestrial Laser Scanner will be used to create a point cloud mapping the interior of the pit, which can be processed to create a 3D model of Compton Pit. This can also be used to determine ease of access to the pit. To characterize the temperature of the pit, the REMS will be used. Radiation will be measured using the M-42.

3.2 Experimental Logic, Approach, and Method of Investigation

The payload subsystem has been intricately designed to operate amongst other spacecraft components to ensure science measurements are successfully obtained from the lunar surface and the Compton Pit. The Interface Control section does well to visualize how these payload instruments might function in relation to important concepts to science acquisition, such as data storage, data transmission, temperature control, and power maintenance. These concepts can be further analyzed at specific instances in which payload instruments will be expected to obtain the measurements necessary to make this mission successful.

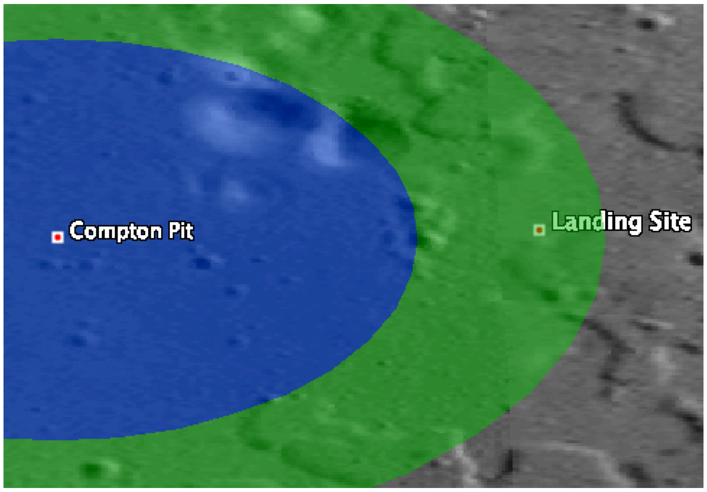

Figure 29: JMARS Visualization of Distances Between Compton Pit and Landing Site

In Figure 29, two colored radii are used to represent distances between the Compton Pit and the landing site selected for the HELP mission. The green shaded area has a radius of 5 km to represent the required range established by the customer required for landing site location[6]. The blue shaded area has a radius of 3 km to visualize when lunar surface measurements will begin to be taken. This boundary was specified previously in the HELP Science Traceability Matrix as an ideal range to obtain science recordings. Measurements taken at this point will assist in determining how the area surrounding the Compton Pit might play a role in providing in-situ resources for lunar habitation of the pit.

Throughout the entirety of mission operations, an onboard fault detection system and a multi-layered damage detection system will monitor the state of subsystem components continuously. The onboard fault detection system will utilize point-to-point (P2P) connections between components present throughout the payload, CDH, thermal control, power, and mechanical subsystems to track the status of these subcomponents. Whenever these components return irregular transmissions, the onboard fault detection system will send an alert signal to the OBC to alter the state accordingly, or relay a transmission to ground control that a spacecraft component has become faulty. The multi-layered damage detection system is applied to the mechanical structure and will operate similarly (Williams et al. n.d.). Together, these two components maintain operation of the spacecraft and ensure payload instruments are communicating data efficiently to the OBC and electronic data storage bank.

Immediately after exiting the primary spacecraft, the HELP rover will seek a shaded area to test and calibrate its scientific instruments. It's necessary for the rover to conduct these preliminary measures under these shadowed conditions due to guidelines placed on the Imaging System (IS) of the ProSEED drill (Trautner et al. 2024). The rover will utilize the primary spacecraft as an asset in locating this shaded

[6] This distance of 5 km was established in the MCA Mission Task Document by the customer as the furthest distance a landing site can be from the chosen pit.

area. The Mastcam-Z will locate shade provided by the body of the primary spacecraft, and the mechanical drive-train will map the rover's traversal some known distance from the primary spacecraft. The OBC will keep track of this known distance to assist with RIEGL calibration. While the HELP spacecraft will not begin drilling at this time, strategies outlined in the Testing and Calibration Measurements section see many of the payload instruments initialized at this site. The Rover Environmental Monitoring Station (REMS) and M-42 radiation detector will be calibrated during traversal instead.

The spacecraft rover will continue its traversal towards the Compton Pit until it reaches the 3 km range signified in Figure 29. At this time, the rover will stop and wait until the area becomes shaded so as to allow the IS to run smoothly. The ProSEED will then begin drilling into the lunar surface. The device will drill for a thirty minute interval while the ProSEED Control Electronics Unit (CEU) and Local Electronics System (LES) ensures power is supplied to the drill and data will be recorded electronically from the ProSEED (Trautner et al. 2024). During this timeframe, the IS will record multispectral images of the surface and the Near-Infrared Volatile Spectrometer System (NIRVSS) and Neutron Spectrometer System (NSS) will analyze spectral signatures in the lunar soil. The data returned by NIRVSS and NSS will be handled by the OBC and further stored in the electronic storage bank or transmitted to ground control. In examining the measurements returned, the amount of minerals and readily available hydrogen and oxygen molecules will be quantified. Evaluating the amount of these volatiles will allow mission Planetary Scientists to gauge the extent to which the Compton Pit might host an environment suitable for future human exploration.

Moving forward, once HELP has reached the determined edge of Compton Pit, it will use the REIGL system to determine whether the entry ramp for the pit is sufficient for access. When it has found an edge of the pit that is the right angle, it will descend into the pit. Then, it will travel to the south-east edge of the pit, where there is a permanent shadow. When at the edge, HELP will use REIGL to further characterize the bottom of the pit and to determine whether there are areas in the pit that can be traversed beneath the surface. HELP will use its LiDAR readings and visible light cameras to navigate within the pit. During this time, the REMS will be checking the local area for blackbody behaviour, and the M-42 will record the radiation as HELP moves toward its targe The NSS will scan the ground for hydrogen signatures, and will determine a drilling location. Once a drilling location has been determined, the ProSEED drill will collect a sample from the area. The sample will then be deposited near the drilling site, where NIRVSS will gather data from the sample.

In recording data from both the lunar surface surrounding the Compton Pit and from within the pit itself, not only will the surplus of in-situ resources be quantified in the vicinity of the pit, but its habitability will be determined too. The habitability of the pit will incorporate factors such as the pit's regular temperature, radiation, and structural dimensions. By evaluating these variables in accordance with resources that may be of use for humans settling in this cave, future plans for human exploration.

3.3 Payload Success Criteria

To record meaningful data on water and other volatile species, NIRVSS must be able to measure signatures of volatiles such as H, O_2, H_2O, OH, CO, CO_2, and CH_4. NIRVSS must analyze data on the surface, and subsurface to a depth of up to 1m from soil excavated from the ProSEED drill. To acquire subsurface samples the ProSEED drill must be operational to extract samples and bring them to NIRVSS for analysis. H_2O and OH can give information about potential for water in the lunar pit, while CO_2 and CH_4 concentrations would give information about soil composition and chemical processes that have occurred in the lunar pit. NIRVSS needs to operate across a wavelength range for each molecule in order to differentiate between the molecules and determine their concentrations in soil samples. NIRVSS must operate at a high spectral resolution to minimize noise and give accurate readings on volatiles. Data collected by NIRVSS is crucial to the HELP mission in order to determine surface composition of the Compton Pit and predict if there is water ice in the Pit. The information the NIRVSS system would gather would be useful in determining the Pits condensed gases, minerals, and subsurface composition and predict if water ice could be found in the Compton Pit.

3.4 Testing and Calibration Measurements

Establishing plans for preliminary testing and calibration is absolutely necessary for the rover to verify the efficiency of its science instruments on the lunar surface. Calibration involves comparing the readings returned by an instrument with standard reference values (“What Is Instrument Calibration and Why Is It Important?” 2023). Conducting these processes reduces measurement uncertainty, improves component reliability, and allows the spacecraft system to evaluate subsystem statuses and respond accordingly (“What Is Instrument Calibration and Why Is It Important?” 2023). While pre-launch testing will most definitely be completed at facilities in an attempt to replicate the Moon’s environment and calibrate each instrument, each device’s measurements are subject to change given that simulated environments cannot perfectly recreate extreme lunar conditions (Madigan 2023). Therefore, procedures have been identified that will gauge the accuracy and precision of each instrument when the rover first reaches the lunar surface.

In order to effectively outline calibration strategies for each science measurement, efficient methods of metrology and calibration must first be defined. NASA hosts a comprehensive Metrology and Calibration Program that establishes these methods that verify data accuracy and reliability (“Metrology and Calibration” 2024b). The Measuring and Test Equipment (MTE) used for this process is essentially the instruments themselves, and the process will incorporate metrology to confirm data quality and accuracy (“Metrology and Calibration” 2024b). Since accurate science measurements will have been recorded prior to launch in test facilities, the obtained preliminary testing measurements on the Moon will be compared to these values to determine accuracy. Regarding the spacecraft’s calibration system, the rover’s Onboard Computer (OBC) will handle the computation and transmission of the calibration readings, and will subsequently coordinate component responses based on these comparisons (“Metrology and Calibration” 2024a). Since recovery and redundancy techniques have been established with regards to each science instrument, these strategies will be considered by the OBC as it analyzes the status of the payload subsystem.

There are a total of six science instruments included in the payload subsystem, so approaches to testing and calibration have been outlined for each. When considering the RIEGL VZ-400 V-Line 3D Terrestrial Laser Scanner, it's critical that the device is capable of emitting and receiving laser readings that calculate the robot's distance from obstacles in its surrounding environment. The device must be able to record these values and subsequently generate an image that may include a 360° display of its surroundings (Szwarkowski and Moskal 2018). Therefore, once the robot reaches the lunar surface, it will drive some known distance away from the primary spacecraft, and the laser scanner's optical head will complete several 360° rotations while emitting and receiving laser readings to verify its functionality (Szwarkowski and Moskal 2018). Figure 30 observes how these data recordings can be represented (Szwarkowski and Moskal 2018).

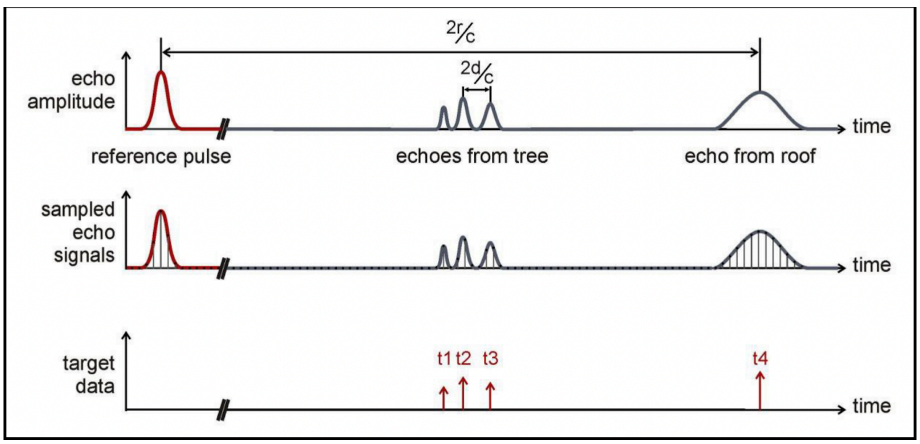

Figure 30: RIEGL VZ-400 V-Line 3D Terrestrial Laser Scanner Data Readings

Since LiDAR devices often require a couple of days to process recorded data into images, the reading values will instead be compared to readings obtained via experiments conducted at testing facilities, rather than waiting for an image to formulate (Marino 2023). The rover initially travels a known distance from the rover, so an experiment will be conducted at a testing facility that sees the rover travel this distance before recording laser readings. The OBC will respond accordingly by comparing these simulated measurements with those recorded on the lunar surface.

In addition, this traversal location must be located within a shaded area of the Moon shortly after landing in order to calibrate the PROSPECT Excavation and Extraction Drill (ProSEED) (Trautner et al. 2024). ProSEED incorporates an Imaging System (IS) that obtains multispectral images of the surface (Trautner et al. 2024). However, the IS is incapable of operating under extreme heat conditions, so for ProSEED calibration procedures the rover must be positioned in a shadowed area (Trautner et al. 2024). Regarding calibration of the entire ProSEED instrument, calibration samples will be obtained from lunar surface maria. Functional checks will be performed that evaluate the operability of the ProSEED Control Electronics Unit (CEU) and Local Electronics System (LES) to ensure power is supplied and data will be recorded electronically from the ProSEED (Trautner et al. 2024). Both the internal and external Hold Down Mechanisms (HDMs) included with the ProSEED will be initiated to maintain instrument operation during surface drilling as well (Trautner et al. 2024).

All mechanisms and sensors associated with the ProSEED will be initialized for calibration at this stage. The ProSEED will utilize the IS to align the Solids Inlet System (SIS) with the drill, so it can analyze the samples obtained by the drill (Trautner et al. 2024). The IS will also evaluate the working environment, which includes quantifying lunar dust that may have become disrupted due to landing procedures (Trautner et al. 2024). Based on the recordings returned by the IS, the exposure time of the IS will subsequently be tuned to sufficiently function on the lunar surface (Trautner et al. 2024). The permittivity sensor positioned along the body of the drill will assess measurements of noise with respect to the drill as well (Trautner et al. 2024).

The Near-Infrared Volatile Spectrometer System (NIRVSS) is used in coordination with the ProSEED to analyze spectral signatures of hydrogen, oxygen, hydroxyl, and water molecules that surface from drilling procedures. Therefore, the three subcomponents of this system must be calibrated efficiently to prepare the entire device for data collection. The Near-Infrared Volatile Spectrometer (NIRVS) will measure light reflected from the surface beneath the rover (Roush et al. 2015). Light will be emitted by a lamp included in the NIRVSS system, and measurements will be recorded surrounding LED, spectral, and Longwave Calibration Sensor (LCS) observations (Roush 2021). A drill observation camera (DOC) will assist with recording images of the precise drilling location once every fifteen seconds (Roush et al. 2015).

While this calibration setup will take place specifically at the preliminary testing location for drilling, NIRVSS calibration will also occur during rover traversal to this location as well. The NIRVSS is capable of continuously collecting spectral signatures while the robot is traveling (Roush 2021). Therefore, this operational feature must also be calibrated in preparation for data collection. The NIRVSS system’s functionality has previously been tested in Mauna Kea, Hawaii to assess its ability to measure the amounts of water and hydroxyl molecules in the surface soil located there (Roush et al. 2015). The values returned from this experiment will be compared with those initially obtained from the NIRVSS device during calibration testing to guarantee its accuracy and increase confidence of measurements.

For calibrating the Neutron Spectrometer System (NSS), there are two major variables that must be considered: the device’s lower-level discriminator threshold and its high-voltage bias (Peplowski et al. 2023). The discriminator takes care of filtering out faulty spectral measurements from recorded data, and the voltage bias increases gas gain, which subsequently improves the magnitude of spectral signals without increasing noise (Peplowski et al. 2023). In conducting experiments previously in the Mojave desert and at the NASA Johnson Space Center estimations have been provided for both of these variables (Peplowski et al. 2023). The high-voltage bias is recommended to be at a value of 1600 V (Peplowski et al. 2023). However, higher voltage values may cause the neutron capture peak to approach the sensor’s overload channel, which threatens the sensor's ability to record data (Peplowski et al. 2023). As thermal and epithermal neutron rates are initially evaluated to quantify hydrogen molecules, the spacecraft's OBC will work in coordination with its battery source to adjust this specified value if necessary.

It's been established in lab testing that the lower-level discriminator threshold of channel 3 works sufficiently in accordance with simulated gamma rays (Peplowski et al. 2023). Although, it's clarified that this instrument will respond differently to the lunar rays present on the Moon due to additional background information (Peplowski et al. 2023). The NSS will initially be programmed to channel 3 owing to these experiments, but will respond accordingly to measurements obtained via preliminary testing, likely leading to a threshold change to either channel 0 or 1 (Peplowski et al. 2023). Further analyzing neutron capture peaks can also reduce efficiency loss of cosmic-ray measurements (Peplowski et al. 2023). The OBC will sum the information provided through these peaks and evaluate how they change with respect to temperature (Peplowski et al. 2023). Consequently, the count rate of recorded signals will be altered depending on the values the OBC encounters.

In order to ensure temperature values are sufficiently recorded the Rover Environmental Monitoring Station (REMS) will be calibrated upon landing in the lunar environment. The REMS instrument has been programmed in the past with the Mars Science Laboratory (MSL) to record data once every hour at a frequency of 1 Hz for a five minute period (Mischna 2014). As the rover traverses to its drilling location, an air temperature sensor (ATS) available through the REMS device will record the lunar air temperature in Kelvin as a function of time (Mischna 2014). Temperature measurements are expected to be incredibly low, seeing as the rover will be in a shadowed region to conduct preliminary testing for the ProSEED. The ground temperature system (GTS) will be deployed and calibrated once the spacecraft travels into the Compton Pit. Seeing as the GTS is capable of obtaining surface pressure and ground brightness temperatures as a function of time, it'd be somewhat difficult for the spacecraft to recollect this device without the use of a robotics arm (Mischna 2014). Therefore, the GTS will be calibrated inside the Compton Pit itself, and will be used in accordance with the Mastcam-Z to assess the lighting conditions of the surface area (Mischna 2014). Values returned by the ATS and GTS will be compared to those previously found by MSL in order to assess the operability of the REMS system as a whole.

The M-42 radiation detector must also be calibrated to guarantee accuracy of radiation data collected both on the lunar surface and in the Compton Pit. This detector is responsible for collecting energy data within a range from 0.06 MeV to 18 MeV (Berger 2019). The device will then store this data between two nonvolatile flash memories and utilize a sleep mode for lower-power consumption (Berger 2019). This sleep mode will be deactivated upon reaching the landing site on the Moon, and the M-42 will begin collecting radiation measurements concerning energy in coordination with the ATS device included with REMS. Similar to REMS, the M-42 has been programmed previously to record energy measurements for five minute intervals (Berger 2019). Preliminary testing will involve documenting energy signals in relation to protons, helium, carbon, oxygen, and neon with respect to the count of which they're obtained (Berger 2019). This data will further be compared to measurements from a similar calibration study at the National Institute of Radiological Sciences (NIRS) in order to validate functionality of the M-42 under lunar surface conditions (Berger 2019).

In defining these calibration procedures for each science instrument on the HELP spacecraft's payload subsystem, calibration systems have sufficiently been established, further justifying this mission's correspondence with protocols outlined by NASA's Metrology and Calibration Program.

3.5 Precision and Accuracy of Instrumentation

ProSEED does not have strict accuracy and precision parameters. Depth and positional accuracy are most important to ensure the drill works properly and the depth of extracted samples are known. The drill is expected to extract subsurface samples within a range of 100 - 120 cm, which is sufficient for data to be analyzed by NIRVSS.

NSS has a sensitivity of 80 cm^2. This allows the NSS to find small areas of high concentration of volatiles. This allows the drill to extract samples from an area that has a high volatile concentration, leading to soil samples that we wish to analyze with NIRVSS to determine what volatiles are present and their concentrations.

RIEGL VZ-400 has a precision of 3mm, an accuracy of 5mm, and spatial resolution of 4mm. ± 3mm precision is ideal for repeatability, leading to a consistent image of the LiDAR cave mapping. The accuracy increases the quality of the cave mapping. This ensures the LiDAR mapping of the cave is useful to 3D model what the Compton Pit interior looks like for lunar rover navigation and finding suitable areas for human habitation in the Compton Pit.

REMS Ground Temperature Sensor (GTS) is a set of thermopiles that can measure data and survive in a range of 150 - 343. REMS has an absolute accuracy of 10K, with a resolution of .1 - 2K. REMS GTS increases accuracy as the temperature of the data it is measuring increases. This is a property of thermopiles. REMS has ±4.5 K when measuring data at 213 K, increasing to ±1 K accuracy when measuring data at 273 K. This accuracy as a function of temperature can be modeled to ensure accurate measurements when the lunar rover is on site.

NIRVSS has 2 spectrometers that operate in different wavelength ranges, with different spatial resolutions. The first spectrometer operators from 1300 - 2500 nm, with a spatial resolution of <15-20 nm. The second spectrometer operates from 2200 - 4000 nm, with a spatial resolution of <50 nm. A high spatial resolution is needed for NIRVSS in order to analyze small soil samples. This leads to more accurate concentration data of volatiles being analyzed, with the goal of analyzing concentration percentage of volatiles more accurately. There are necessary wavelengths to accurately measure each volatile, as outlined on the STM.

M-42 requires a small sensitivity in order to detect dosimetry on the lower end of the energy detection range. With a sensitivity of .5MeV, M-42 satisfies the mission requirement detection range, allowing it to detect low energy incident rays and secondary particles.

3.6 Expected Data & Analysis

Data analysis is arguably the most important aspect when closing out a space mission. Conducting effective measurements analysis during a mission will likely yield new scientific discoveries that lead to an improved understanding of the solar system, which subsequently outlines potential plans for future space exploration ("The Role of Data Science in Astronomy and Interstellar Exploration" 2024). Therefore, data storage and analysis strategies have been defined for each science instrument present on the HELP spacecraft.

Several databases have been identified as spaces to store collected data. The NASA Planetary Data System (PDS) website allows user access to recorded data, data analysis tools, and information in relation to planetary science research (Thompson 2022). The HELP R&D Team will be able to connect with readily available website staff, so the full bandwidth of tools and resources on this software can be put to use (Thompson 2022). The Science Discovery Engine (SDE) will also be used to store and analyze data returned by the HELP mission. SDE has resources and data available from Astrophysics, Biological and Physical Sciences, Earth Science, Heliophysics, and Planetary Science ("Science Discovery Engine (SDE)" 2024). This website offers accessibility to datasets, documentation, and specific instruments ("Science Discovery Engine (SDE)" 2024). SDE will also be used in coordination with Science Explorer (SciX) Digital Library Portal to confer with previously published papers that might be relevant to HELP's mission science (Hill 2024). The CDH Team will work with the R&D Team and Planetary Science Team to compile data returned to ground control via transmission, publish it to SDE, and subsequently publish papers drafted by mission scientists once data is successfully analyzed.

Each payload instrument must be examined to determine the type of data it must record. Examples will also be provided to sample what data returned by each device should generally look like. The RIEGL VZ-400 V-Line 3D Terrestrial Laser Scanner emits infrared light, which often reflects across several objects in its environment before returning as an "echo" optical signal to the device's receiver (Szwarkowski and Moskal 2018). This optical signal must then complete a series of conversions that sees the optical transmission converted into an electrical signal to then be amplified, sampled, and digitized in order to convert from an analog to a digital signal (Szwarkowski and Moskal 2018). Finally, this digital signal will be visualized as an online waveform using the system controller - this waveform representation can be visualized in Figure 30 (Szwarkowski and Moskal 2018). Output data relates these waveforms to specified timestamp intervals and the speed of light (Szwarkowski and Moskal 2018).

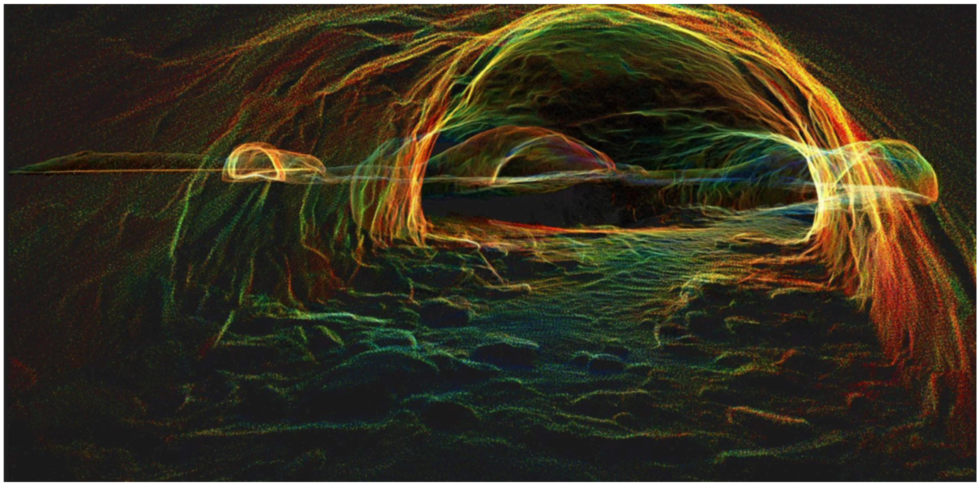

Figure 31: Lava River Cave Generated from KnacK Measurements

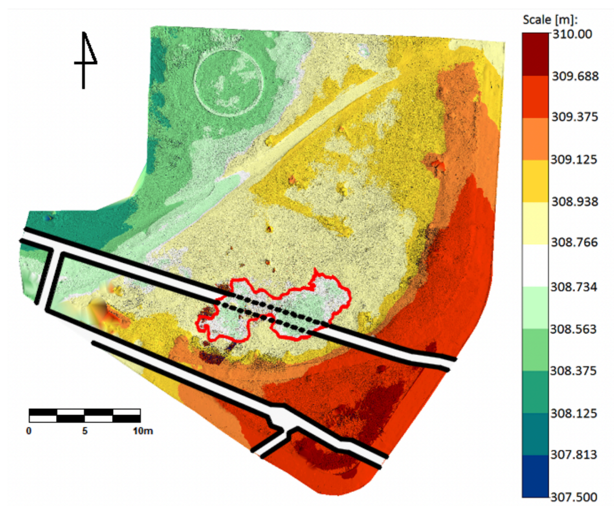

Figure 32: Terrain Surface Model Generated from RIEGL Data

Laser scans will then be transformed to represent a grayscale image similar to that seen in Figure 31 (King 2023). In comparing this image with the data returned by this payload device, terrain surface models can be generated that are representative of the image seen in Figure 32 (Szwarkowski and Moskal 2018). The scale seen in this model will likely vary depending on the part of the lunar surface the rover is exploring. Exploring the Compton Pit will likely require a larger scale, or include a wider variety of colors, in comparison to the landing site since its topographical features are higher in magnitude (Wagner and Robinson 2022). Due to the large amounts of data returned by this LiDAR device, the scans must be interpreted and pruned to only include necessary data at a given location (Szwarkowski and Moskal 2018).

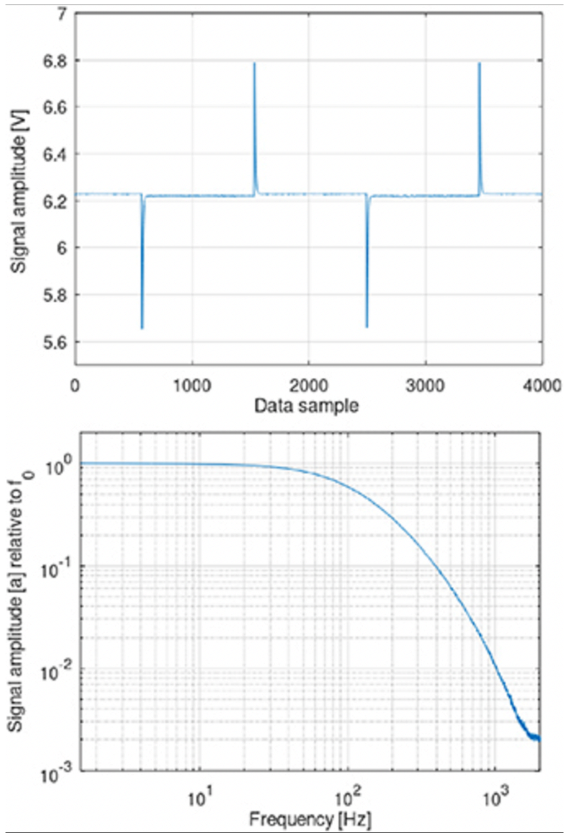

Figure 33: Permittivity Sensor Signal Amplitude vs. Sampling Rate and Frequency

The ProSEED drill will rely heavily on its permittivity sensor to obtain spectral values in relation to Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicate, and Anorthite Plagioclase (Trautner, Reiss, and Kargl 2021). The permittivity sensor utilizes an electrode carrier assembly and a printed circuit board carrier assembly (PCA) to generate frequencies within a range between 1.5 Hz and 200 Hz using a digital oscillator (Trautner, Reiss, and Kargl 2021). The amplitude of this signal is transmitted as a square wave signal, and is further compared with time and frequency (Trautner, Reiss, and Kargl 2021). On the lunar surface, these signals will be modeled similarly to those represented in Figure 33 (Trautner, Reiss, and Kargl 2021). Mission-specific results will vary depending on the sampling rate and frequency chosen for the permittivity sensor - two variables that are dependent on the sensor calibration readings that occur on the lunar surface.

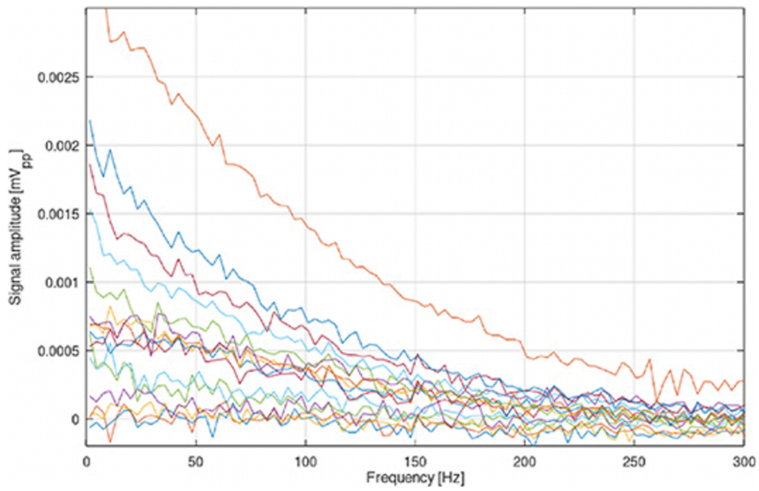

Figure 34: ProSEED Electrode Spectral Signal Amplitude vs. Frequency

Spectral measurements will be obtained while the sensor's electrode is located at or below the lunar surface. The ProSEED Imaging System (IS) will monitor soil build up at the surface of the lunar regolith, estimating its volume and density (Trautner, Reiss, and Kargl 2021). The permittivity sensor is capable of recording azimuth scan measurements of drilled soil as the drill remains active (Trautner, Reiss, and Kargl 2021). The permittivity sensor will subsequently apply its time/temperature mode of operations to compare its dielectric constant between measurements taken at periodic intervals of drilling (Trautner, Reiss, and Kargl 2021). Analyzing the change in frequency between intervals will allow the soil characteristics of the lunar regolith to be determined (Trautner, Reiss, and Kargl 2021). This data will be modeled similarly to that seen in Figure 34. Since this data has been recorded in evaluation of ice detection beneath the surface, spectral signatures obtained on the Moon in relation to the in-situ metals defined previously will likely produce different signal amplitudes in response to other frequency magnitudes. ProSEED and permittivity sensor testing will identify frequency values to use for spectral detection in this case, as well as examine common signal amplitudes returned by each material.

The Near-Infrared Volatile Spectrometer System (NIRVSS) will assist the permittivity device with analyzing spectral signatures of these metals, as well as spectral signatures of hydrogen, oxygen, hydroxyl, and water (Roush et al. 2015). The spectrometer integrated into the NIRVSS design is capable of recording spectral measurements in relation to two types of wavelengths: shortwave (SW) and longwave (LW) (Noe Dobrea 2024). Since the required spectral threshold for this mission is 1600-3400 nm, the both spectral modules will be necessary[7]. SW records spectral measurements from 1.3-2.5 μm, and the LW records measurements from 2.2-4.0 μm (Noe Dobrea 2024). These spectral modes can run independently of each other, but cannot be run simultaneously (Noe Dobrea 2024). Therefore, they will record data serially to ensure all relevant data is collected in a certain instance at a traversal site.

[7] The threshold requirement for NIRVSS is established in the HELP Science Traceability Matrix.

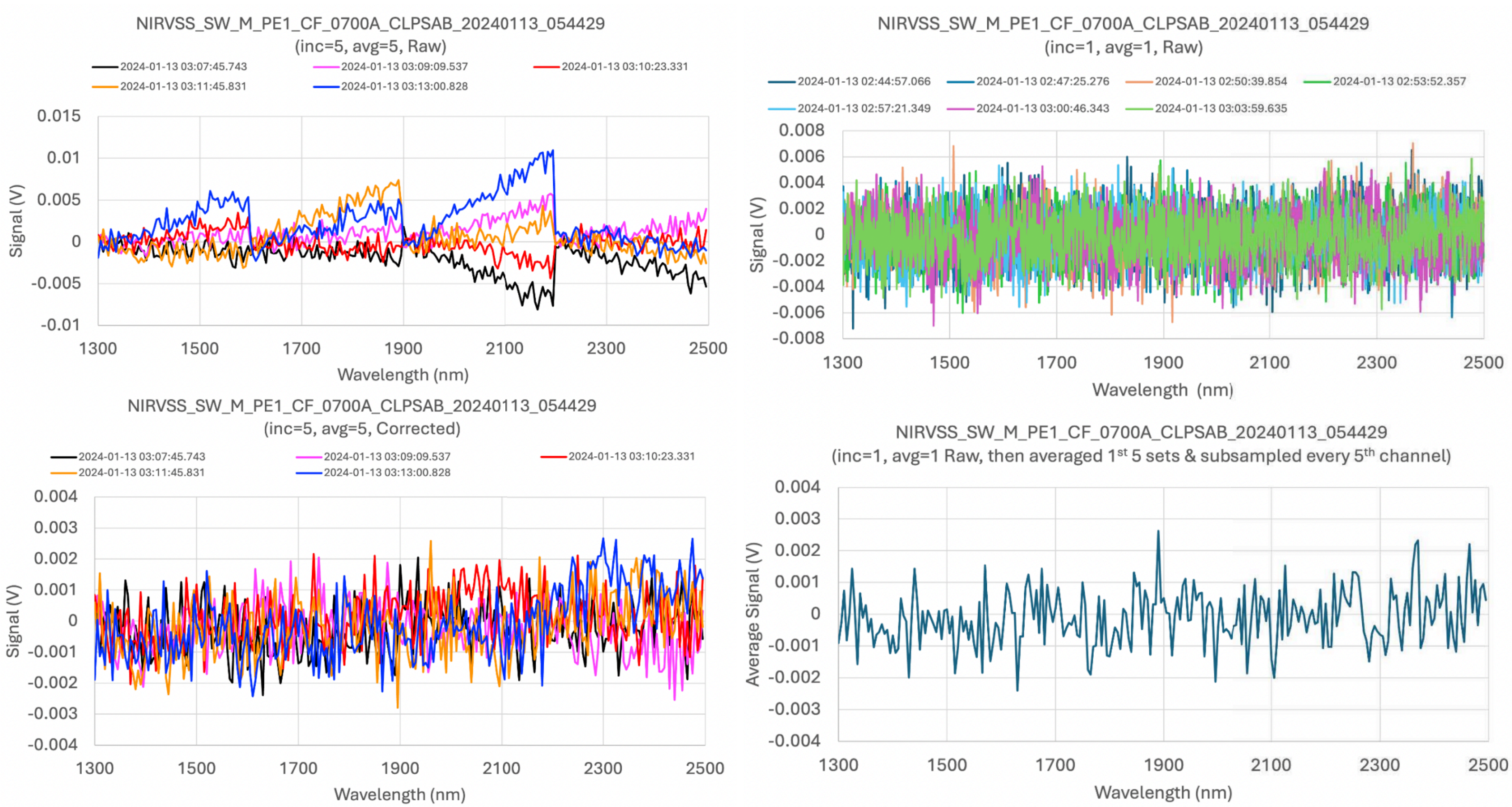

Figure 35: NIRVSS Shortwave Spectral Readings

Sample spectral values obtained via the SW module of the NIRVSS are visible in Figure 35. Wavelength values are examined with respect to signal voltage (Noe Dobrea 2024). The graph located in the top left-hand corner of the figure introduces raw data initially obtained via an incorrect background subtraction (Noe Dobrea 2024). The graph directly below has incorporated a correction factor that adjusts the values obtained through the present channel of the NIRVSS device (Noe Dobrea 2024). Fortunately, this correction is not necessary for the LW module (Noe Dobrea 2024). The following graphs on the right-hand side of Figure 35 observes a total of seven spectral signatures, all recorded within a day (Noe Dobrea 2024). These signatures are then condensed into an everage to better visualize spectral values. Considering the range of molecules and materials NIRVSS is measuring, spectral wavelength values and voltage signals will likely vary in graphs returned from this device in the HELP mission.

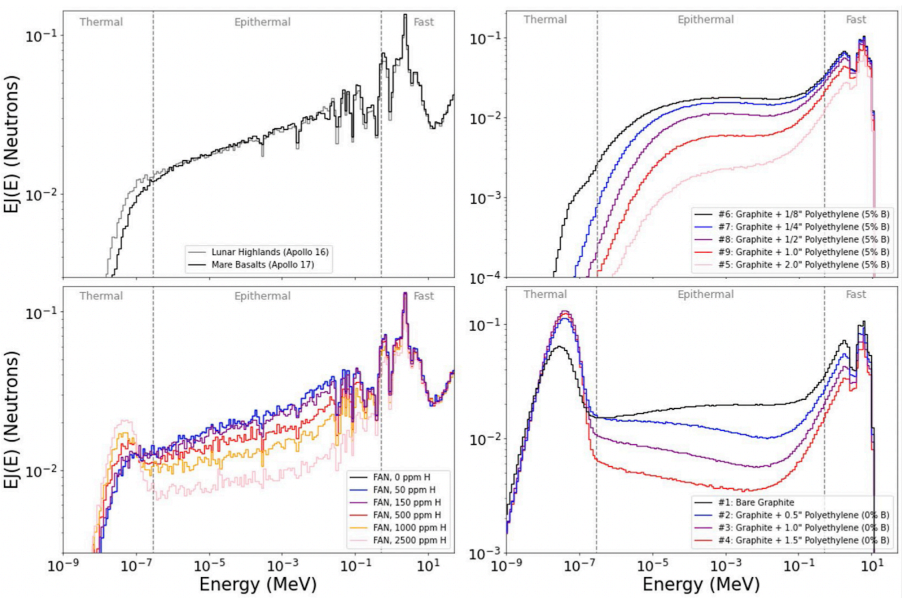

Figure 36: NSS Neutron Detection Given Energy Values

The Neutron Spectrometer System (NSS) will acquire spectral signatures in relation to hydrogen, oxygen, and water molecules, as well as other volatiles within an energy range from 1 eV to 1 keV[8]. Seeing as this spectrometer system will collect neutron signatures in relation to cosmic rays present on the lunar surface, it's somewhat difficult to replicate what spectral signatures will look like in a lab setting (Peplowski et al. 2023). In an attempt to replicate these environmental circumstances, spectral signatures recorded by the NSS were observed in a simulated cosmic ray environment as well as in a one with a generated Americium-Beryllium (AmBe) neutron source (Peplowski et al. 2023). These experiments are represented in Figure 36, with the cosmic ray data examined on the left and the AmBe neutron data on the right. The spectral graphs visible on the left of Figure 36 do well to consider maria surface regions of the Moon. This factor is beneficial to the HELP mission, seeing as the rover will

[8] This energy range is defined in the HELP Science Traceability Matrix as an ideal set of values that'll return useful data with regards to in-situ resources.

remain within maria terrain for the entirety of the mission. The spectral readings on the right specifically analyze readily available graphite signatures. This data will be useful for the HELP mission, but spectral magnitudes will likely vary across neutron amounts, seeing as a variety of materials and molecules are to be observed.

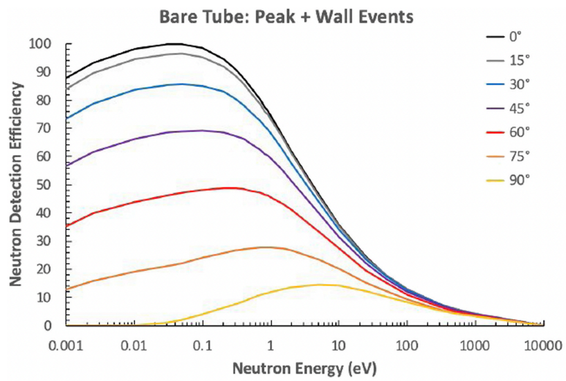

Figure 37: NSS Neutron Detection Efficiency vs. Neutron Energy

Another important variable to consider when recording NSS spectral readings is the efficiency at which the device is acquiring this data. Depending on the positioning of the NSS device with respect to the sample site being examined, spectral uncertainty will be more or less reliable (Peplowski et al. 2023). The effect of this angle is visible in Figure 37. In interpreting this graph, it can be concluded that the lower the degree between NSS placement and sample location, the more reliable the neutron energy is detected at that specified site (Peplowski et al. 2023). This is yet another factor to weigh when determining the available amounts of in-situ resources present in the lunar regolith.

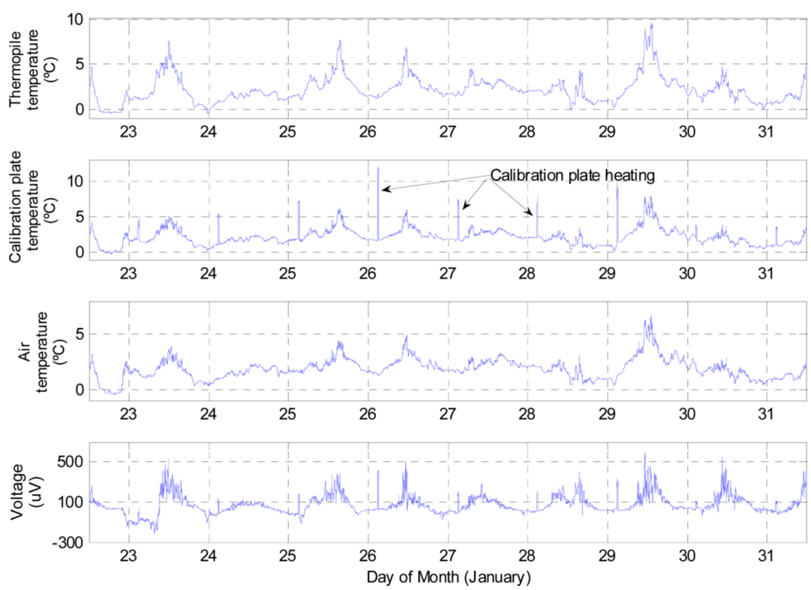

Figure 38: REMS GTS and ATS Scientific Measurements vs. Time

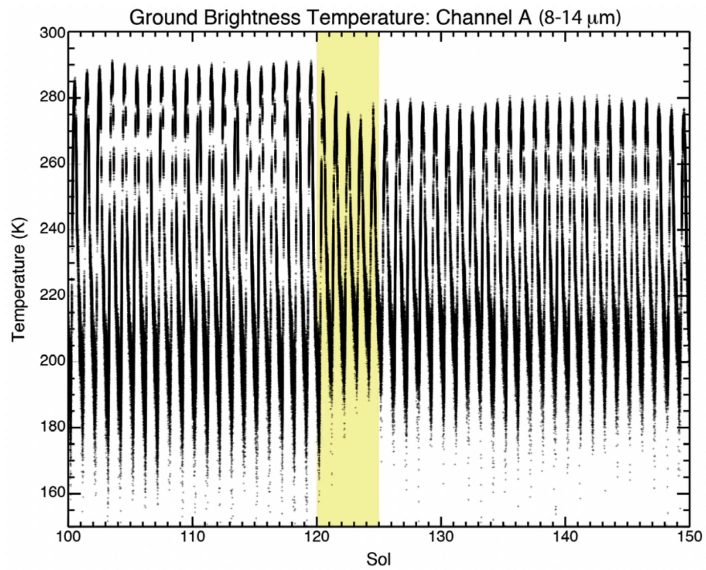

Figure 39: REMS GTS Ground Brightness Temperature Measurements vs. Time

The Rover Environmental Monitoring Station (REMS) is responsible for obtaining temperature measurements between 273 K and 373 K in the Compton Pit[9]. Following a study conducted at the Gale Crater landing site, scientific data was recorded and reconstructed into graphs useful for reference when anticipating what data will look like for this mission (Mischna 2014). In Figure 39, it's apparent that the GTS device included with REMS is capable of recording temperature measurements within the established threshold (Mischna 2014). However, it should be noted that these temperature values are recorded with respect to sols. One sol refers to one solar day on Mars, which is approximately forty minutes greater than the length of a 24-hour day on Earth (Allison and Schmunk 2023). For the HELP mission, temperature readings will be recorded within only a few days, as opposed to the 50 sols seen in Figure 39. As a result, the spectral signature will be more similar to the timeline seen in Figure 38, allowing for better visualization of the peaks and valleys of temperature values over this shorter amount of time (Sebastián et al. 2010). On the other hand, this data reflects temperatures that generally remain within 0-10°C. While these temperature values may be present temporarily on the Moon, lunar surface temperatures can range from -183°C to 106°C ("What Is the Temperature on the Moon?" n.d.). Ideally, Compton Pit temperatures will remain within the 273 K to 373 K range to increase the site's potential for habitability, however, it's difficult to predict the temperatures it will host at this time. Especially considering the drastic variation in temperature value depending on the permanently shaded and shadowed regions of the room in comparison to those that receive direct sunlight (Beale n.d.).

[9] This science requirement is established in the HELP Science Traceability Matrix seen in Figure 1.

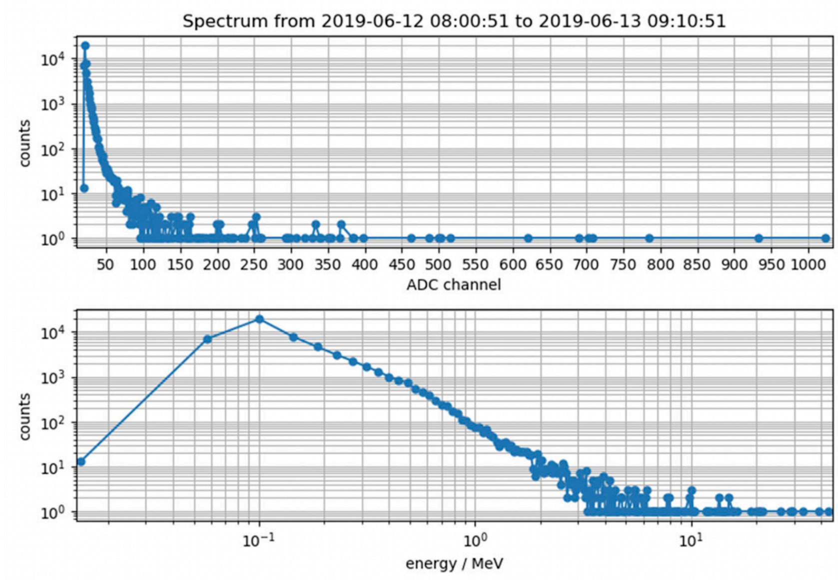

Figure 40: M-42 Real-Time Data Collection

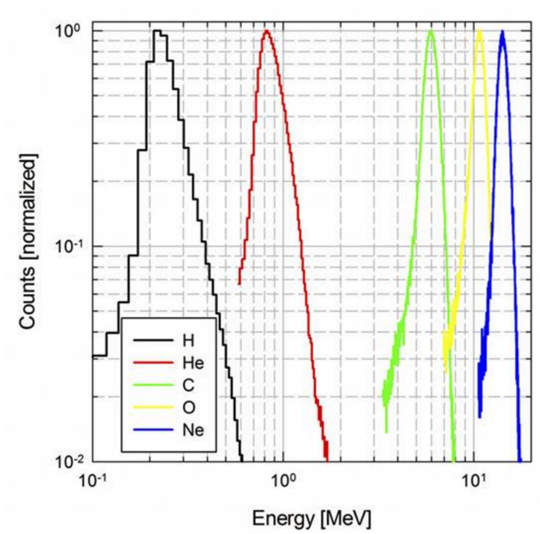

Figure 41: M-42 Spectral Signatures

In order to determine the varying levels of radiation present within the Compton Pit, data returned from the M-42 radiation detector must be properly stored and analyzed. As mentioned previously in the Testing and Calibration Measurements section, the M-42 device uses two nonvolatile data flash memories for data storage (Berger 2019). Measurements are stored every five minutes, and each considers depositions in energy between 0.06 MeV and 18 MeV (Berger 2019). These energy depositions are summed and divided by the mass of the M-42 device to find the absorbed dose of each spectra (Berger 2019). Finally a conversion factor of 1.23 is applied to the absorbed dose to make it relative to water rather than Silicone instead (Berger 2019). In Figure 40, the count, or sampling rate, can be adjusted and is observed with regards to ADC values as well as the measured energy deposition (Berger 2019). Figure 41 also displayed how spectra can be obtained in relation to protons, helium, carbon, oxygen, and neon (Berger 2019). Acquiring the dose rate and count rate in relation to protons is incredibly important in order to detect magnitudes that surpass the 25,000 millirem threshold specified in the HELP Science Traceability Matrix. Dose rate can be converted to millirems using the conversion factor of 1.23 previously established for the M-42 (Baes 2013). Therefore, by recording spectra readings in relation to protons, the amount of radiation present in the Compton Pit can be quantified.

Data acquisition principles and data analysis are critical steps that are absolutely necessary to successfully match science requirements set forth by the HELP mission. The importance of this stage is further stressed in the abrupt increase in science personnel in the Planetary Science and R&D Teams during Phases E and F of the mission. Therefore, strategies for storing and interpreting data returned by each payload instrument have been established so scientific conclusions and discoveries can be made.

4 MISSION RISK MANAGEMENT

4.1 Safety and Hazard Overview

A variety of risks threaten the safety and success of the HELP mission. These risks represent the probability that an event or scenario negatively impacts either the technical, safety, cost, or schedule aspects of this mission. Baselining strategies to identify, research and mitigate these risks is absolutely necessary for minimizing the risks present within each subsystem. In order to conduct risk management efficiently, the HELP team will abide by a handful of steps outlined by Risk-Informed Decision Making (RIDM) and Continuous Risk Management (CRM) protocols. Interpreting these protocols and integrating necessary processes into HELP's risk management system will foster sufficient risk mitigation techniques that will hopefully lead to eventual risk acceptance.

The first steps taken to effectively identify and mitigate risks relate specifically to RIDM[10]. This process can be divided between several key milestones. The first milestone involves reviewing stakeholder and mission expectations to derive performance measurements for the mission, which are further used in trade studies that evaluate multiple decision alternatives. Constraints were established by consulting the MCA Mission Task Document and assessing stakeholder constraints[11]. The HELP STM further formatted these constraints with performance measurements and requirements that abide to stakeholder criteria and mission science objectives. Various decision alternatives were then found by the science and engineering teams to be used in trade studies. This step is sufficiently completed by outlining risks in a Risk Summary Table based on the components considered in trade studies and other risks considered for the mission.

The second milestone of the RIDM process involves mitigating the risks outlined in Figure 42. Strategies used to estimate these performance expectations included similarity or analogous estimation methods, parametric estimation methods, and testing estimation methods. The testing methods have and will prove especially effective for improving a component's Technology Readiness Level[12] (TRL) in preparation for the mission. If a risk is deemed too costly to address given the mission timeline and budget, or seemingly has no solutions to addressing the problem, then previous decisions made in the earlier stages of the RIDM process will be reconsidered to better advance this mission.

As tests are completed for the technical subsystems and instrumentation,

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[10] The RIDM process involves evaluating a set of established performance measurements to help decision-makers make informed decisions (Homayoon Dezfuli et al. 2011).

[11] Stakeholder constraints are outlined in the MCA Mission Task Document. These constraints provide limits for mass (350 kg), dimension (2m x 1.25m x 1.25m), and design (must explore a lunar cave and get surface science measurements).

[12] The HELP team recognizes the importance of raising the TRL level of every subcomponent of the mission system, given the standard that the lowest TRL often represents the TRL of the entire system, and TRL plays a crucial role in risk evaluation and uncertainties in relation to the mission.

probability density functions[13] (pdfs) will be created in coordination with Monte Carlo shells to better understand uncertainties surrounding the performance parameters of each alternative. These strategies will address both aleatory[14] and epistemic[15] uncertainties. This process will be incredibly important for RIDM and pruning alternatives and for CRM when risks are further reconsidered, testing is repeated, and this process is iterated.

The third major milestone that will complete what HELP's RIDM process looks like includes establishing risk tolerances for the performance measurements and risks being considered and finally making a decision following the trade study process outlined previously. The risk tolerances assigned to the various performance measurements heavily impacted whether or not an alternative was selected. The size of these tolerances depended on the priority ranking of the measurement being evaluated. Measurements that are critical to the science objectives, especially ones spectrometer related, were given lower risk tolerances in order to eliminate components that generated the most uncertainty in relation to meeting necessary requirements. Customer constraints and failures that impacted larger pieces of the mission system were also considered when establishing these ranges of acceptance. A Risk Matrix helps visualize what risks have higher uncertainty ranges. A risk's probability of success directly affects the risk's place in the matrix by judging the risk's likelihood and consequence. This matrix is further inspected to assign priority for addressing one risk over another.

Completing this RIDM process allows the HELP team to move forward with necessary CRM protocols. The CRM strategies used are responsible for managing the risks that have been outlined in the RIDM process, and can be broken down into five critical steps. These steps are continuously repeated throughout the timeline of this mission concept to constantly check for new risks, mitigate ones already researched, and eventually accept risks once they've been mitigated sufficiently. It's important to note that no risk can be completely eliminated - accepting a risk implies that its likelihood of occurring has been reduced significantly to the point where other options present higher likelihood and the probability of the related scenario recorded has been minimized to the greatest degree possible.

The first step implemented from CRM involves identifying mission concerns based on the selected alternatives from RIDM. Next, the Risk Summary Table analyzes the likelihood of each risk scenario occurring, and the rated consequence of its impact on the mission system. The HELP team's Mission Assurance Specialists have assigned values to these two variables, L and C, in Figure 43. These values were determined based on several uncertainties potentially observed by the risks outlined in Figure 42.

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[13] A probability density function (pdf) is a figure, or graph, that displays the probability of outcomes that occur for a given performance measurement when assessing an alternative (Homayoon Dezfuli et al. 2011). These figures are normally used to compare uncertainties in the success of a component being compared in a trade study.

[14] Aleatory uncertainties are random and can't be alleviated by completing testing and analysis (Homayoon Dezfuli et al. 2011).

[15] Epistemic uncertainties are not random and can be reduced by learning more on a topic through testing (Homayoon Dezfuli et al. 2011).

These uncertainties consider the uniqueness of the risk in relation to other missions, the cross-cutting character or impact the risk will have on other system components, the complexity of the component being considered for the risk, the propagation potential of the risk to segway into greater faults in the mission concept, and the detectability of the risk if it were to occur. The severity assigned to likelihood and consequence is restricted to a number 1 to 5, with 1 being low likelihood or low consequence, and 5 being high likelihood or high consequence. Risks with the highest likelihood and consequence levels will be prioritized throughout this mission, whereas risks of lower value will be addressed secondhand and won't be represented in the Risk Matrix seen in Figure 43.

The third step of CRM involves addressing each of the risks established in Figure 42. These risks are either being actively researched, mitigated, accepted, or watched. The current status, or plan, of each risk is represented in the eighth column of Figure 42. At this current stage of the mission timeline, the newly established risks are being researched to better understand the circumstances that might bring about the risk scenario and what can be done to minimize the uncertainty in relation to each risk. After this process, mitigation strategies will begin to be implemented for each risk.

The fourth step will see the severity and progress of each risk tracked continuously throughout the mission timeline. The Mission Assurance Specialists have and will communicate with the engineering, science, and programmatics subteams to monitor and receive updates on risks to individual mission components. New risks will be appended to Figure 42, major priority risks will be addressed in Figure 44 to lower the likelihood of risk scenarios occurring, and the progress of these risks will be monitored until the point where it might be deemed possible to accept a risk as is in preparation for the mission.

Every NASA mission must additionally adhere to planetary protection (PP) regulations (Bishop 2024d). Maintaining planetary protection (PP) for this mission requires certain guidelines be met to ensure the HELP rover does not contaminate the lunar environment. The HELP spacecraft is categorized as a Category IIa mission by Committee on Space Research (COSPAR) policy standards, therefore risks are present in relation to the spacecraft's bioburden, probability of contamination, and organic inventory ("Editorial to the New Restructured and Edited COSPAR Policy on Planetary Protection" 2024). In order to properly address these potential issues of concern, strict guidelines and documentation will be developed that clarifies strategies for quantifying HELP's probability of contamination and chemical impact on the Moon. Researching and devising control plans for each of these areas of concerns will minimize the uncertainty in relation to planetary protection risks.

Regarding documents that will be formalized to ensure these procedures are efficiently executed, a PP Mission Categorization Proposal will be issued to specify that the HELP mission is a Category IIa mission, given that it will be completed below the 86°N latitude line at the Compton Pit (DeLoach 2022). A PP Requirements Document will then be formatted with requirements and relevant compliance, non-applicable, and non-compliance statements that clarify the mission's plans for abiding to the requirements. In addition, a scheduling system will be clarified for providing necessary planetary protection documentation. Next, a PP Implementation Plan will be developed that follows guidelines for a Category IIa mission. This document will follow the HELP mission across the entire project life-cycle; it will include how the mission abides to requirements and considers necessary risks (DeLoach 2022).

A Pre-Launch PP Report will also be filed that quantifies the spacecraft's volatile organic materials, propellent residuals, and combustion products that may be emitted by spacecraft systems (DeLoach 2022). Similarly, a Post-Launch PP Report will be conducted that will include any alterations to the previously quantified amounts due to launch. An End-of-Mission PP Report will be conducted during the decommissioning phase of the mission to again assess the spacecraft system's emitted or stored amount of volatile organic materials, propellent residuals, and combustion products to ensure it remains at a viable amount (DeLoach 2022).

Risk management directly impacts mission success. Practicing efficient, comprehensive risk analysis strategies will lead to reduced risks and uncertainties surrounding the mission outcome. Minimizing uncertainty boosts confidence that the mission will succeed and run according to plan. In following the RIDM and CRM protocols outlined previously and adhering to planetary protection regulations, risks and hazards will be identified, analyzed, and addressed, thereby improving the probability that the HELP mission will succeed.

4.1.1 Risk Analysis

The risk analysis process involves identifying risks following RIDM guidelines[16] and subsequently mitigating these risks to reduce the magnitude of threats to the HELP mission. The procedures followed by this mission to continuously track and alleviate these mission-specific risks are completed by adhering to the CRM process defined previously[17]. CRM will continuously be conducted throughout the entirety of HELP's mission timeline, especially leading up to mission launch[18]. Risks may be present in the lunar environment, they may jeopardize the success of the HELP rover, negatively impact the mission budget and schedule, or threaten planetary protection protocols. Several strategies have been identified and applied to mitigate the risks outlined in Figure 42. In implementing these methods, uncertainties will be minimized in relation to the likelihood and consequence of each risk, and the system's Technology Readiness Level[19] (TRL) will be improved in preparation for the mission. The likelihood and consequence, L and C, assigned to each risk can be visualized and interpreted in Figure 43.

The CDH subsystem is subject to multiple risks, one of which involves the passivation process necessary to complete HELP's decommissioning plan. This particular risk is outlined in Figure 42, as well as several other CDH-related risks. Point failures in communication and standard procedures present opportunities for the

[16] The RIDM guidelines mentioned here are further detailed in the Safety and Hazard Overview section.
[17] A detailed description of this CRM process is provided in the Safety and Hazard Overview section.
[18] The HELP mission launch date is on March 1, 2030.
[19] The HELP team recognizes the importance of raising the TRL level of every subcomponent of the mission system, given the standard that the lowest TRL often represents the TRL of the entire system, and TRL plays a crucial role in risk evaluation and uncertainties in relation to the mission.

passivation process to either default early and disrupt the mission timeline or prevent this energy depletion process from ever occurring due to autonomous recovery systems (Hull n.d.). This single point of failure will be mitigated by including redundant hardware and thorough software programs that ignore a passivation initiation message that occurs prior to the disposal phase of the mission (Hull n.d.). To further test scenarios in which message faults might occur, a series of software implemented fault injections (SWIFI) will be conducted. This procedure involves simulating typical faults that would cause system passivation to fail at the end of the mission (Arlat et al. n.d.). In addition, the CDH subsystem will be programmed using a disposal mode of operations to disable any autonomous recovery systems during the final decommissioning phase (Hull n.d.). Once a component's disposal mode has been initiated, it's impossible for that component to recover its autonomous recovery systems (Genevieve Warren 2023). Therefore, SWIFI procedures will also verify that this disposal mode of operations functions without fail.

Communication continues to be a point of concern for spacecraft interaction due to alternative spacecraft and satellite interferences. The surplus of space systems that separate the Earth from the Moon carry individual radio-frequency waves, as specified in Figure 42, meaning there is potential for those signals to override messages received from the HELP spacecraft. This risk is being addressed by obtaining frequency licensing and allocation, which takes approximately two to three years to confirm (Bapna, Martin, and Whittaker n.d.). The CDH Team outlined in Figure 45 is actively working to address this potential issue. In addition, the X-Band High-Gain Antenna will use phased arrays to address failure modes that might occur in communication (Hong 2023). These phased arrays utilize time delays to vary the emission and transmission of data (Delos, Broughton, and Kraft 2020). Based on the wavefront angle of data input and output signals, time delays allow the frequency of transmissions to be tuned (Delos, Broughton, and Kraft 2020). Data and commands can therefore be received sequentially within timed intervals, or all at once. This adaptability in communications further reduces the likelihood that there will be transmission interference between ground controls and the mission rover.

The payload subsystem carries several instruments of which operation is crucial to the success of the HELP mission. Furthermore, there are a variety of risks related to this subsystem outlined in Figure 42 that will be continuously expanded on and addressed. The LiDAR device is a complex device that returns large amounts of mapping data to be analyzed. The data it collects relies on laser technology to map surrounding areas. When alternative light sources interfere with this technology, the LiDAR detector may become damaged or incorporate these faulty light signatures into an incorrectly mapped representation ("Advanced Techniques for LiDAR Interference Avoidance" 2024). An ultra-narrow interference filter is being implemented to address this issue, due to its durability and ability to ignore certain wavelengths of light ("Thin-Film Interference Filters for LIDAR" 2017). Tuning lasers will be used to evaluate the reliability of this filter. These lasers will be set up in a filter test station that validates the filter's center wavelength, Full Width Half Maximum (FWHM), and out-of-band blocking width (Johansen et al. 2017).

Additionally, the massive amount of data that the LiDAR returns presents potential issues with data handling procedures. To ensure the data is efficiently recorded and analyzed, an Onboard Computer (OBC) will work with an electronic data storage bank to ensure data is efficiently stored ("Onboard Computers" n.d.). A wired connection transmits data obtained from the payload devices to the OBC and the data bank. The OBC further overlays this data to the x-band transponder, which utilizes a high gain antenna to send corresponding signals to ground control (Bolles 2024b). This sequence of data transmissions can be visualized in Figure 28, which addresses all interfaces on the HELP spacecraft.

Micrometeoroid and orbital debris (MMOD) presents potential concern to the payload subsystem as well. Despite there being a low possibility that the spacecraft is struck by a micrometeoroid, the resulting consequences from the impact are severe. Major injuries to the payload subsystem may prevent the necessary science measurements from being recorded. In order to address these scenarios, a system similar to Markov and Kalman State Identification (MAKSI) will be implemented to make continuous state estimations (Washington 2000). This onboard fault detection system actively evaluates any damages sustained by impacts, and then transmits a point-to-point (P2P) signal containing subcomponent state estimations to the OBC (Arnold et al. 2009)[20]. In transmitting these estimations to Earth and redistributing commands to each of these components, system accommodations can be made that might see redundant features of the spacecraft system utilized.

These sensors and redundant protocols are also important for addressing instrument failures that don't occur due to MMOD. Payload devices and optical features are susceptible to extreme conditions on the Moon such as temperatures and lunar dust too. In order to reduce uncertainties of failures that might occur due to these conditions, the instruments must be tested and analyzed under similar environmental conditions to raise TRL levels. These experiments will run at facilities such as NASA's Ames Research Center (ARC), which hosts Lunar Lab and Regolith Testbeds (Hoover 2023). These testbeds accurately recreate lunar lighting conditions as well as incorporate dust particles intricately designed by hand to replicate the lunar dust present on the Moon's surface (Hoover 2023). These lighting conditions can be interpreted to represent varying temperatures that can affect the spacecraft's components operability at different intervals of lunar surface and pit traversal.

Mechanical subsystem risks are prevalent in relation to MMOD, obstacles impeding navigation, and lunar dust. Impacts from micrometeoroids can potentially impact the HELP spacecraft, leading to significant damages to the mechanical subsystem that may prevent it from being able to travel to the Compton Pit. In order to mitigate this concern, a multi-layered surface damage detection sensory system is being applied to the mechanical structure. This system utilizes software to pin-point surface damage on the rover and its extent (Williams et al. n.d.). As damaged hardware is identified, a P2P signal is transmitted to the OBC, which handles the implementation of redundant protocols if they're necessary.

[20] This system of P2P signals is represented in Figure 28 in Interface Control.

Impact craters and resulting debris present additional concerns to navigating across the lunar surface. During the HELP spacecraft's trek from the landing site to the Compton Pit, it may encounter meteoroid debris or impact craters that represent significant obstacles to its traversal system. In unfortunate scenarios, these obstacles may cause the robot to become stuck, preventing it from visiting the pit. In order to address this navigation risk outlined in Figure 42, mire mesh wheels are utilized on the HELP rover to effectively traverse the lunar regolith. These wheels are flexible, allowing them to conform to lunar surface features while still being durable (Kilkenny 2017). Simulations will be run at the NASA Glenn Research Center Lab to test drive the wheels on a simulated lunar surface ("Designing Rovers for the Moon's Extreme Environment" 2022). This facility features a Simulated Lunar Operations lab (SLOPE) with simulated lunar soil on tilt beds that test wheel traction against large surface rocks (Matter 2021). Not only will these tests help justify the robot's traversal ability, but they'll also raise the TRL of the wheels.

The mechanical subsystem can also be potentially affected by lunar dust. Lunar dust threatens many subsystem failures. This dust has an electrostatic charge, and is incredibly sharp due to the Moon's lack of water and air, substances that are responsible for smoothening rocks on the Earth's surface ("Designing Rovers for the Moon's Extreme Environment" 2022). The electrostatic property of the dust causes it to settle on mechanical hardware and seals, potentially causing severe degradation (Kaczmarek 2021). To mitigate these risks, dust-resistant seals and materials are being studied and compared. The aluminum alloy being used in the spacecraft design is durable and will be molded tightly to hardware to prevent dust intervention. Additionally, labyrinth seals are to be applied to system motors, and Teflon seals to the wire mesh wheel motors in order to protect these components from dust. These seals can also withstand extreme temperatures, and will further be tested at the Kennedy Space Center (KSC) to simulate lunar dust and temperature conditions (Tabor 2020). The KSC hosts Swamp Works and its Electrostatics and Surface Physics team. This team studies the electrostatic properties of lunar dust, and is capable of testing the particles' electrostatic properties on the HELP spacecraft's mechanical body (Ryan 2024). These tests will subsequently raise the TRL levels of the mechanical system components interfaced with these seal solutions.

The power subsystem is also heavily impacted by lunar dust and other lunar environmental extremes. The dust's electrostatic property allows the dust to latch onto power components such as the HELP system's solar panels. As particles layer these power components, the signals of these components become muffled, lowering the magnitude of any energy provided via the power devices ("How Dangerous Is Lunar Dust for Humans and Equipment? And Can It Also Be Put to Good Use?" 2021). A photovoltaic effect of lanthanum-modified lead zirconate titanate (PLZT) dust removal ceramic is being applied to these system components to help remove attached dust. The PLZT emits electrostatic traveling waves to clear dust that has settled on solar panels after consuming ultraviolet light (Jiang et al. 2019). This device will further be examined by the Electrostatics and Surface Physics team at KSC in order to effectively evaluate its ability to remove lunar dust from power components.

Several other environmental characteristics of the Moon pose major risks to the power subsystem. Due to the Moon's orbital relationship with the Sun, some areas of the Moon are lit while others remain in darkness. The HELP spacecraft relies on solar panels for energy, therefore spending long periods of time in these dark regions is not possible since it will eventually run out of power. This concern limits the amount of time the HELP spacecraft can travel in these areas, which includes dark, secluded areas of the Compton Pit. Given that the allotted time for rovers to remain in permanently shadowed areas is 50 hours (Wetzel, 2021), a plan outlined in Concept of Operations clarifies how the HELP spacecraft charges for enough time in sunlight and has limited, estimated movement while in permanent darkness. Surface lighting conditions will also be replicated at ARC to examine how the rover will be impacted in a simulated lunar environment. This environment can be adjusted to recreate lighting scenarios at different instances in the mission Concept of Operations (Hoover 2023).

The Moon's thin exosphere also causes severe radiation due to its lack of a consistent magnetic field. This radiation has the potential to cause severe damage to HELP's power subsystem. Cosmic radiation has been known to wipe the memory of computer chips, cause electrical systems to fail, and lead to brittle wires that break easily ("Designing Rovers for the Moon's Extreme Environment" 2022). In order to address issues of radiation in the power subsystem, electrical wires are shielded with Specification 44* insulation to prevent them from becoming brittle ("Designing Rovers for the Moon's Extreme Environment" 2022). This type of insulation will be layered with a polyvinylidene fluoride jacket to prevent its irradiation, which may have affected other system components (Krueger 1968). Specification 44* resists radiation efficiently without degrading and carries a later weight in comparison to other insultations, such as Novathene and Teflon (Krueger 1968). In the event that wires do become faulty, the system's electrical flow has been programmed to be rerouted around damages and still reach its required destination (Beale n.d.). Preemptive shielding is also applied to the solar panels and other hardware components to protect them from degradation induced by cosmic rays (Beale n.d.). Using Corning type 7940 artificial fused silica, a thickness of 6 thousandths of an inch is layered over these components (Waddel n.d.). This specific thickness has been identified due to its greater power protection and lesser tendency to limit energy production from light (Waddel n.d.).

The thermal subsystem is also subject to major threats imposed by the lunar environment. The surface temperature on the Moon varies immensely depending on a region's lighting conditions. Due to the thin atmosphere on the Moon, known as the exosphere, the lunar surface is minimally insulated (Sharp and Urrutia 2023). This leads to temperatures that range from 121°C in the light to -133°C in the dark (Barry, n.d.). In the Compton Pit, permanently shadowed areas might reach extreme temperatures up to -246°C. This extreme flux in temperature may induce severe stresses and strains on the spacecraft's thermal technology, which heavily impact the functionality of thermal, electrical, and payload components (Beale n.d.). The Thermal Management Team is integrating a type of Kapton electrical heater known as the Omega Polyimide Heater Kit to address colder temperatures. To address the extreme heat, thermoelectric coolers and fluid loops are also included in the spacecraft design. These solutions are compact, and help monitor the temperature of system components and maintain operable temperatures (NASA, 2024). Heat pipes will be used to handle these thermal control components on the spacecraft, as well as high-resistance wiring[21]. Integrating several solutions in regards to temperature control will improve system redundancy as well.

Similar to the mechanical and power subsystems, the thermal subsystem is also threatened by lunar dust and its tendency to settle on spacecraft components. The layers of dust that build up on thermal devices reduce the spacecraft's ability to maintain insulation across the system body ("How Dangerous Is Lunar Dust for Humans and Equipment? And Can It Also Be Put to Good Use?" 2021). This scenario may eventually lead to robot systems failing, an event that would certainly prevent science measurements from being recorded. The PLZT technology used for the power subsystem will similarly be integrated with thermal components to mitigate this significant lunar dust issue. Its functionality will further be tested by the Electrostatics and Surface Physics team at KSC as well in order to evaluate its efficiency with the spacecraft's thermal components. Applying this technology across multiple spacecraft subsystems allows the Thermal Management and Power Maintenance Teams to follow similar testing protocols to raise the TRL of this lunar dust mitigation technique.

Since planetary protection (PP) involves protecting solar system bodies from contamination by Earth life, the HELP rover presents a threat to the lunar environment, especially to that contained within the Compton Pit (Bishop 2024d). One significant concern outlined in Figure 42 is that intensive organic inventories on the HELP spacecraft will lead to contamination of the Compton Pit. This risk will be addressed by working in sterile facilities for the entirety of spacecraft production. Personnel will be required to follow sterilization procedures and planetary protection guidelines will be followed (Greicius, Jackson, and Hartono 2020). A procedure known as controlled contamination will verify that sterilization protocols have been implemented sufficiently. Controlled contamination involves placing some known number of living organisms on spacecraft components and ensuring these organisms are killed once sterilization processes are completed (Quinn 1969). In this case, alcohol sporulation will be applied to incorporate bacterial spores that have increased longevity for the experiments and are safe to use in regards to health concerns (Quinn 1969). A PP Organic Inventory will be conducted to monitor organic materials on the HELP spacecraft that exceed 0.1 kg in mass (DeLoach 2022), as well as estimate the extent to which organic materials may be released into the lunar environment.

In addition, completing an End-of-Mission PP Report[22] involves carrying out the HELP Decommissioning Plan and ensuring planetary protection guidelines are followed. Without thorough plans for decommissioning, a risk arises as seen in Figure 42 that potentially sees the spacecraft exploding due to energy build-up (Hull n.d.). Passivation appears to be an efficient strategy that relieves onboard sources of energy and disables sources of energy generation (Hull and Schonberg 2022). While there are no propellant systems present on the HELP rover, the spacecraft's solid-state battery energy must be depleted during the decommissioning phase (Caldwell 2024b). However, initiating the

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[21] These interface techniques are further described in the Interface Control section.

[22] The End-of-Mission PP Report was outlined in the Safety and Hazard Overview section as an important document to file to ensure planetary protection.

passivation process might introduce interferences with the spacecraft's autonomous recovery systems in place. Therefore, a disposal mode of operations solution has previously been outlined with the CDH-related risks to counter this potential concern.

Risks considering budgeting and scheduling must also be addressed to ensure this mission is carried out successfully. For one, the mission schedule can potentially be impacted by severe testing delays. This mission's budget descope has led to several descoping processes in relation to the mission payload instruments and cost evaluation of the HELP mission. The payload changes signify more testing must be completed to confirm the addition of these new components, as well as raise the corresponding TRL of each component too. Testing facilities have been identified to confirm the integration of subsystem components onto the spacecraft[23]. However, setbacks in testing may still build upon each other to the point where the mission launch date is unachievable. Reevaluating and retesting procedures are necessary in case instruments fail under lunar conditions or are discovered to not meet system requirements. The completed testing procedures will follow guidelines outlined by NASA while maintaining risk control protocols ("NASA Systems Engineering Handbook" 2007).

In order to avoid setbacks in testing, the HELP team has already conducted trade studies for new instruments implemented since the budget descope, and has developed plans to travel to testing facilities to monitor the manufacturing and testing process. The Mars Science Laboratory is a good example as to why it's important to not underestimate the technical difficulty of a project, to incorporate margins that handle abrupt funding changes, and to organize an experienced, dedicated mission team (Martin 2018). A timeline of major milestones and a Gantt Chart have been created and revised to help alleviate concerns that the mission might overrun its schedule in relation to the mission launch date[24]. The major milestone timeline seen in Appendix C does well to display when and how each mission phase should be completed, with deadlines set for each significant task. The Gantt Chart displayed in Figures 48 and 49 provides a more in-depth schedule overview that includes margin to anticipate scheduling mishaps.

The Program Analyst Team has been working extensively with the Cost Budgeting and Schedule Management Teams to conduct mission cost and budget evaluations to continuously monitor the status of the mission and enforce the mission constraints regarding the budget and mission schedule[25]. In addition, an in-depth budget revaluation was conducted to alleviate descoping concerns, therefore the budget available now is considerably more accurate. Margin percentages mentioned in the Budget Basis of Estimate allow room for uncertainties in relation to cost and budgeting risks too. Mission budget and schedule is also tied hand-in-hand, with every one percent increase in mission schedule approximately causing a one percent or greater increase in cost growth (Majerowicz and Shinn 2016). This relationship further justifies the importance of the Cost Budgeting and Schedule Management teams in this mission, and the responsibility each team has to communicate concerns with sub-team members

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[23] These testing facilities are more explicitly stated and explained in each component's corresponding subsystem section of this PDR document.
[24] Mission launch is set for March 1, 2030.
[25] The mission cost cap is $300 million, and a hard launch date has been set for March 1, 2030.

and team leads.

In the event that personnel are not prepared to undergo testing, or there are equipment availability issues, there is a risk for the mission schedule to be impacted. These resource constraints may lead to significant milestones being missed throughout the mission timeline. To mitigate this particular risk, resource allocations will continuously be monitored by the Program Analyst Team, and mission tasks will be assigned priorities in order to coordinate the distribution of resources. These priorities are clarified in the FMEA section and the corresponding FMEA chart seen in Figure 44. When procuring components and contacting facilities to complete manufacturing procedures, secondary points of contact have been identified to anticipate situations in which contractors are unavailable. Mission deadlines have also been outlined in Figure 48. Sub-teams in Figure 45 should feel comfortable voicing concerns regarding the deadlines in this major milestone timeline, so accommodations can be made quickly and accordingly. Strategies to navigate this process will be implemented from NASA's Scheduling Management Handbook, which provides advice on how to adapt to changes and unforeseen circumstances ("NASA Schedule Management Handbook" 2011).

Scenarios that heavily impact mission schedules likely induce a similar effect on mission costs (Majerowicz and Shinn 2016). If technical difficulties were to occur, or devices or materials suddenly become higher in demand, the mission cost may threaten to surpass the descoped mission budget constraint of $300 million. This concern is why it's incredibly important to establish margins early on in the mission life-cycle - these boundaries anticipate issues and add leeway to handle cost increases should they occur. In order to further manage these unexpected costs, budget assessments and emergency funds will be allocated. The margins specified in the Budget Basis of Estimate will help accommodate any unexpected expenditures that occur throughout the mission. The importance of procedures like these becomes clear when consulting situations such as that of the James Webb Space Telescope, a device that experienced cost growth due to unforeseen challenges ("The Role of Satellites in Enabling Emerging Technologies" 2015). Cost risks are further defined by conducting proactive risk assessments such as failure modes and effects analyses (FMEA). The HELP FMEA section clarifies the highest priority risks that threaten the success of the HELP mission, and outlines how these risks impact technical and programmatics mission processes. The corresponding Figure 44 outlines the individual spacecraft systems and components that are affected by each risk as well.

Personnel variability in professional experience also presents opportunities for risk throughout the HELP mission. Staff turnover may occur and skill gaps may be present throughout mission personnel. To alleviate these risks, a program similar to Mission Support Future Architecture Program (MAP) has been implemented to address workforce availability concerns in this mission's Project Management Approach. Employees and contractors will be awarded when cost and schedule requirements are met ("NASA's Management of the Space Launch System Booster and Engine Contracts" 2023). Satisfaction surveys will be distributed and analyzed, and individual accomplishments will be celebrated consistently to create a healthy working environment (Manning 2019). The Space Launch System program outlines lessons learned that help to prioritize certain techniques over others in relation to this MAP program (“NASA’s Management of the Space Launch System Booster and Engine Contracts” 2023).

Personnel safety is also a major concern regarding personnel and testing procedures. Since personnel will be working often with HELP instruments to raise TRLs and assess a device's ability to withstand harsh environmental conditions, component failure is certainly a possibility. Safety protocols regarding Personal Protective Equipment (PPE) will be followed at testing facilities, safety equipment will be up-to-date, and safety guidelines will be strictly followed in order to address these risks (“Occupational Safety and Health” 2024). The Personnel & Safety Protocols section provides an in-depth overview of the entirety of safety procedures to be put in place for this mission. The HELP team is implementing a safety plan that aligns with safety strategies and procedures outlined in the NASA Systems Safety Handbook (Dezfuli 2014).

Mission outreach risks must also be considered when evaluating concerns of the entire mission. Risks are present in relation to foreign engagement and garnering public support. To address potential limits placed on international engagements, virtual conferences have been organized with foreign countries to discuss lessons learned and significant mission discoveries. These virtual conferences will provide informational pre- and post-launch mission updates as well. An Outreach Plan has been formalized that involves sending mass amounts of informational emails to contributors, customers, and general public subscribers. These emails will include brief mission updates as well as information, branding, and merchandise advertisements. The Mars Perseverance mission followed similar steps successfully using virtual outreach to induce greater mission interaction worldwide (Cook and Good 2021). Public support also plays a critical role in mission exposure and budgeting support. The benefits of prioritizing public support are prevalent when analyzing the Apollo Program and its proactive approaches for outreach and mission awareness (Ostovar 2024). The HELP Outreach Team will schedule educational events monthly with school systems across the nation. These events will include hands-on activities for students across all ages leading up to high school graduation to engage in (Smith et al., 2023). Televised mission updates and broadcasts are planned to provide the public with inside perspectives of the mission and view mission progress in real-time.

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Safety - Planetary Protection	1	3	↓	M	Given that the Moon is sensitive to extraterrestrial disturbances, organic inventories might contaminate potential lunar habitation sites visited by the HELP spacecraft, thereby impacting the habitability of the Compton Pit and the nearby landing site.	The spacecraft will be manufactured in sterile facilities, and controlled contamination will be used to verify that the spacecraft is sterile. A PP Organic Inventory report will also monitor the mass of organic materials on the spacecraft. (12/1/24, CA)
2	Safety - Decommissioning	1	5	↓	M	Given that a spacecraft stores residual energy over long periods of time when left running a spacecraft explosion may occur due to energy build up impacting the Compton Pit, thereby damaging a potential habitability site on the Moon.	Passivation processes are being implemented that address premature passivation messages, and a disposal mode of operations will disable autonomous recovery protocols that might prevent passivation from occurring during this stage of the mission. (12/1/24, CA)
3	Power - Lighting Conditions	1	4	↓	M	Given that the Moon has permanently shaded areas that receive zero light from the Sun, solar power cannot be continuously stored by the robot in these areas impacting the robot's solar panels negatively to limit the extent to which the robot can remain in these areas.	The HELP mission Concept of Operations clarifies how long the rover remains in potential permanent darkness regions of the Moon, and lighting conditions will be simulated using the lunar regolith testbeds found at the Ames Research Center. (11/30/24, CA)
4	Power - Radiation	2	4	↓	M	Given that the Moon has a very thin atmosphere, the lunar surface has little protection from cosmic radiation which can cause significant damage to electrical systems thereby wiping computer chip memory and short-circuits in system wiring.	Specification 44* insulation layered with a polyvinylidene fluoride covering will protect wires and computer chips from being significantly affected by radiation, and rerouting electrical connections addresses faulty wiring issues. (11/30/24, CA)

5	Power - Lunar Dust	1	4	↓	M	Given that lunar dust is present on the Moon and it carries an electrostatic charge, it will stick to objects not electrically grounded on the Moon such as the HELP spacecraft, which might damage system assemblies carrying electronics and reduce energy generated from solar panels.	The photovoltaic effect of lanthanum-modified lead zirconate titanate (PLZT) device will remove dust from energy sources using electrostatic traveling waves. This device will be tested by the Electrostatics and Surface Physics team at Kennedy Space Center. (11/30/24, CA)
6	Thermal - Lunar Dust	1	4	↓	M	Given that lunar dust is present on the Moon and it carries an electrostatic charge, it will stick to objects not electrically grounded on the Moon such as the HELP spacecraft, thereby covering thermal radiators and causing them to produce less heat for other subsystems.	The photovoltaic effect of lanthanum-modified lead zirconate titanate (PLZT) dust removal device will remove dust from thermal components using electrostatic traveling waves. This mechanism will be tested by the Electrostatics and Surface Physics team at Kennedy Space Center. (12/1/24, CA)
7	Thermal - Temperature	2	4	↓	M	Given that lunar surface temperatures vary from 40K to 250K, an object on the Moon may be subject to two polar opposite temperatures depending on the location of the Sun, impacting spacecraft components, by creating large heat fluxes that induce thermal stresses, strains, and distortions on science instrumentation and other components.	An Omega Polyimide Heater Kit will be used to address colder temperatures, and a thermoelectric cooler will be used with fluid loops to address the extreme heat. Heat pipes and high-resistance wiring are responsible for handling these thermal control processes. (12/1/24, CA)
8	Mechanical - Lunar Dust	1	3	↓	M	Given that lunar dust is present on the moon and it carries an electrostatic charge, it will stick to objects not electrically grounded on the Moon such as the HELP spacecraft and might erode mechanical components that haven't been properly sealed.	Dust-resistant seals such as the labyrinth and Teflon seals will protect mechanical components from lunar dust. These components will be tested at the Kennedy Space Center by the Electrostatics and Surface Physics team. (11/30/24, CA)

9	Mechanical - Navigation	2	3	↓	M	Given the heavily cratered and uneven terrain present on the Moon, there may be significant obstacles such as rocks and craters between the identified landing site and the Compton Pit impacting the HELP rover's wheel traction, thereby leading to problems with path planning and issues of getting physically stuck in one place on the lunar surface.	A wire mesh wheel design is being used to account for steep slopes and jagged regolith. These wheels will be tested in the SLOPE lab at NASA Glenn Research Center. (11/30/24, CA)
10	Mechanical - Micrometeoroid and Orbital Debris (MMOD)	1	3	↓	M	Given that the Moon has a very thin atmosphere, micrometeoroid and orbital debris may impact the lunar surface in and around the Compton Pit potentially threatening the HELP spacecraft's mechanical architecture by striking the spacecraft directly.	A multi-layered damage detection system is being applied to the robot architecture to locate damage and assess its magnitude. This system sends P2P signal updates to the OBC to respond to damages (11/30/24, CA)
11	CDH - LiDAR Data Handling	1	3	↓	M	Given the large amount of data returned by LiDAR simultaneous localization and mapping (SLAM), the LiDAR system used on help may produce a surplus of data information while mapping the Compton Pit overloading the CDH subsystem, thereby making it difficult for the subsystem to handle and record all the necessary data.	An Onboard Computer and electronic data storage bank will be used to handle data recorded by the RIEGL LiDAR device. This data will be transmitted using a x-band transponder and a high gain antenna. (11/30/24)
12	CDH - Communication Interference	1	2	↓	M	Given the variety of active communication systems that remain active in the space between the Earth and the Moon, there may be communication interferences that impact the radio-frequency waves emitted by the CDH subsystem, thereby interfering with the data being recorded by HELP's payload subsystem.	Frequency allocation and frequency licensing are being addressed by the CDH Team well before mission launch. Phased arrays will utilize time delays to control the transmission of messages. (11/30/24, CA)
13	CDH - Passivation Communication	1	4	↓	M	Given that passivation processes are controlled via communications systems one single erroneous line due mission operations initiating passivation would impact the HELP mission collection entirely thereby relieving the spacecraft of its power and preventing it from completing the mission.	The CDH Team is programming protocols into the HELP system that ignore early passivation messages. These protocols will be tested using SWIFI procedures. (11/30/24, CA)

14	CDH - Passivation and Autonomous Recovery Systems	1	2	↓	M	Given that autonomous recovery systems are in place on the HELP spacecraft, they may constantly default the system to an active state preventing passivation procedures, and thereby preventing the HELP mission from completing its end of mission protocols.	The CDH Team is programming a disposal mode of operations that disables autonomous recovery systems past a given mission milestone. This implementation is being tested using SWIFI procedures. (11/30/24, CA)
15	Payload - LiDAR - Light Interference	1	4	↓	M	Given the severe difference in lighting conditions on the Moon based on the location of the Sun, light will be reflected and received at different angles on the lunar surface impacting the light received by LiDAR, thereby damaging the LiDAR's light reception system or creating confusing data that affects LiDAR's mapping techniques.	An ultra-narrow interference filter is being integrated into the RIEGL LiDAR device to filter out unnecessary wavelengths of light. This filter will be tested using a filter test station with tunable lasers. (11/30/24, CA)
16	Payload - Micrometeoroid and Orbital Debris (MMOD)	1	3	↓	M	Given that the Moon has a very thin atmosphere, micrometeoroid and orbital debris may impact the lunar surface in and around the Compton Pit potentially threatening the HELP spacecraft by striking the spacecraft directly or impeding its path from the landing site to the pit.	A system similar to MAKSI is being implemented that continuously estimates the state of the payload devices. This system will help identify and assess MMOD damage of many subsystem components. (11/30/24, CA)
17	Payload - Instrument Failure	2	5	↓	M	Given that the lunar environment presents extreme conditions such as severe temperatures, radiation, and lunar dust, these conditions are difficult to replicate on the Earth impacting the trade studies conducted for payload instruments thereby causing failure uncertainties as to how instruments will function on the Moon.	Lunar regolith testbeds at the Ames Research Center can help raise the TRL of payload instruments in simulated lunar environments that replicate surface lighting conditions and lunar dust terrain. (11/30/24, CA)
18	Budget - Schedule Delays	3	4	↓	M	Given that scheduling often goes hand-in-hand with cost planning, major setbacks in scheduling due to instrument scrapping and retesting will heavily increase the HELP mission estimated cost, thereby pushing this mission's necessary allocated value to over the cost constraint.	While budget descoping has caused increased risks in testing, new component trade studies have been completed, and schedule timelines have been revised to raise confidence that the mission schedule will go ahead as originally planned. (12/1/24, CA)

19	Budget - Unanticipated Cost Increases	2	3	↓	M	Given the complexity of our space mission, unanticipated cost increases may happen due to unexpected technical challenges, delays, or resource demands in the HELP mission, leading to exceeding the budget and compromising the mission's ability to be completed within financial limits.	Periodic financial evaluations are to be completed and enforced to monitor and control unforeseen expenses. The Cost Budgeting and Schedule Management teams have incorporated margins in estimations to address this concern as well. (12/1/24, CA)
20	Schedule - Testing	3	4	↓	M	Given that testing will have to be completed on the spacecraft's instruments, setbacks may occur when a device is reevaluating to not be sufficient enough to be used in the HELP mission, leading to deadline delays thereby affecting the launch date of the mission.	Descoping has caused changes in payload instrumentation, so some delays have occurred in relation to testing. However, testing and manufacturing facilities have been identified and timelines have been reevaluated to help alleviate scheduling concerns. (12/1/24, CA)
21	Schedule - Resource Constraints	2	3	↓	M	Given that scheduling depends on the resources available for testing and development phases, resource constraints can lead to delays and restrictions on equipment readiness or facility access. This would delay key milestones in the HELP mission's timeline and push the launch date back, affecting the mission objectives.	Resource allocations are being handled by the Program Analyst Team to make sure there is sufficient personnel, time, and equipment for each mission task. Mission deadlines have been clarified, tasks have been assigned priorities in the FMEA table, and manufacturing and procurement facilities have been identified. (12/1/24, CA)
22	Outreach - Lack of Support	1	2	↓	M	Given that mission success and lessons learned relies on public and shareholder support of the mission failing to stress the importance and impact of the HELP mission for space exploration impact data recorded by the spacecraft in that the subsequent lessons learned won't be efficiently documented and shared across school systems and major shareholders.	Educational programs held monthly will help raise awareness of the HELP mission in school systems, publicly broadcasted conferences will help raise public awareness, and informational emails will allow the public to subscribe to additional mission updates. (12/1/24, CA)

23	Outreach - International Engagement Limitations	1	2	↓	M	Given the global interest in the HELP mission, limited international outreach efforts may restrict the HELP missions's ability to create a global engagement and learning, thus affecting international partners by reducing the HELP mission's collaborations.	Virtual sessions will be scheduled with foreign entities to provide pre- and post-launch mission updates as well as lessons learned post-mission, and informational emails will be sent with important mission-related content. (12/1/24, CA)
24	Personnel - Testing	1	5	↓	M	Given that personnel will be testing system components in extreme conditions, risks are present in relation to system failure and lack of safety protocols impacting personnel safety thereby threatening the health of any engineering or science professionals conducting testing procedures.	Protocols are being employed at manufacturing and testing facilities to address personnel health and safety hazards. These procedures consider both mental and physical concerns, and are explicitly defined in the Personnel Hazards and Mitigations section. (12/1/24, CA)
25	Personnel - Staff Turnover & Skill Gaps	1	3	↓	M	Given the specialized skills needed for critical tasks, high staff turnover or skill gaps may result in operational delays or knowledge loss, leading to a decrease in the quality and continuity of mission outcomes and increasing training costs and loss of time.	Mitigation strategies similar to MAP are being implemented that ensure personnel are efficiently appropriated, mission contributors are awarded for successful work, and employees feel comfortable reaching out with concerns. (12/1/24, CA)

Figure 42: HELP Mission Risk Summary Table

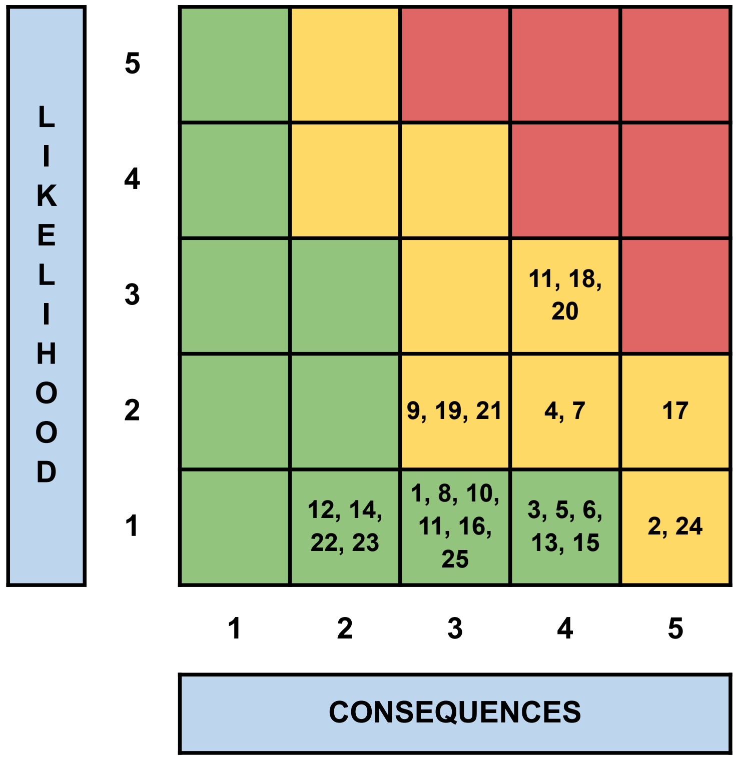

Figure 43: HELP Mission Risk Matrix

4.1.2 Failure Mode and Effect Analysis

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Safety	Planetary Protection: Contamination of lunar habitat	Damage to habitability and ecosystem	8	Improper containment of organic inventories	2	Assess spacecraft organic materials and containment	5	80	Examine the effects of contamination, carry out emergency sterilization, and update safety procedures.
	Decommissioning: Energy buildup causing explosion	Damage to lunar environment and assets	9	Residual energy during decommissioning	3	Develop passivation techniques	6	162	Update passivation techniques, implement robotic decommissioning, and carry out an emergency energy release.
Power	Lighting Conditions: Inability to store solar power	Reduced operational capacity	7	Permanently shaded areas on the Moon	4	Design long-duration storage systems	4	112	Increase battery capacity, look into adding more solar panels, and switch to backup energy sources.
	Radiation: Electronics damage due to radiation	Loss of communication and control	8	Lack of adequate shielding	3	Research and integrate shielding materials	5	120	Install emergency shielding, swap out damaged parts, and incorporate adaptive radiation systems.
	Lunar Dust: Short circuits and panel damage	Loss of power generation	7	Electrostatic attraction of dust	4	Add dust removal technologies	6	168	Replace broken parts, improve dust repulsion techniques, and use dust removal systems to clean the impacted components.
Thermal	Lunar Dust: Heat dissipation inefficiency	Overheating of systems	8	Dust accumulating on and inside the thermal radiators	5	Develop dust repelling techniques	6	240	Upgrade thermal materials, implement alternative cooling systems, and clean dust frequently.
	Temperature: Structural stress and distortion	Failure of critical systems	9	Extreme temperature fluctuations	4	Apply thermal insulation and heaters	5	180	Redesign critical systems, put active temperature regulation in place, and fix stressed components.
Payload	Instrument Failure: Inability to replicate lunar conditions	Unreliable instrument performance	8	Harsh lunar environment conditions	5	Establish robust testing protocols	4	160	Use backup instruments, increase redundancies, and validate alternative ground-testing simulations.
Budget	Schedule Delays: Cost overrun due to rescheduling	Exceed project budget and timeline	7	Instrument scrapping and resetting	4	Develop contingency budget plans	5	140	Reassess the scope of the mission, allocate emergency funds, and renegotiate contracts with stakeholders.

Schedule	Testing: Missed deadlines for mission launch	Compromised mission timeline	8	Insufficient time for testing	4	Streamline testing procedures	4	128	Prioritize critical tests, implement streamlined testing protocols, and request timeline extensions
Personal	Testing: Failure in maintaining safety protocols	Compromised testing integrity	7	Inexperienced or insufficient staff	3	Cross-train personnel for critical tasks	4	84	Rotate experienced personnel, provide intensive training, and enforce stricter safety checks.

Figure 44: Failure Mode and Effect Analysis Table

The Failure Mode and Effect Analysis (FMEA) is a strategy used for keeping track of major influences on the mission's success. Conducting FMEA allowed the HELP team to locate and assess risks so that the team can work towards reusing this essential tool for locating, evaluating, and reducing risks that could have an impact on the mission. This section will focus on failure modes for important mission tasks, such as safety, power, thermal management, payload performance, and scheduling. In order to improve mission dependability, the comprehensive analysis guarantees that possible failures are carefully assessed and that suitable mitigation techniques are put into place.

Safety Risks

The mission's habitability and scientific integrity are directly threatened by contamination of the lunar habitat (RPN: 80). Future habitation plans and lunar ecosystems may be jeopardized if inventories are not kept under control. Emergency containment and sterilization must be put into place right away if this risk continues. Furthermore, if unchecked, the energy buildup during spaceship decommissioning could result in catastrophic explosions (RPN: 162). To ensure safe decommissioning, this calls for a strong passivation system that includes remote robotic intervention and emergency energy release.

Power Management Risks

Solar power restrictions are caused by constant lunar shade (RPN: 112). This can lead to possible operational downtime if this risk is not addressed. Including energy storage devices, adaptive solar technologies, and backup power sources will help mitigate this issue. Additionally, radiation-induced damage to electronics could cut off control and communication lines (RPN: 120). The mission must switch to emergency electronic replacement and implement adaptive radiation-resistant components in the event that radiation shielding fails.

Two major hazards are increased by lunar dust: power system short circuits (RPN: 168) and thermal radiator overheating (RPN: 240). Essential hardware can experience irreversible damage if the dust accumulation is not controlled. For the mission to continue, it requires proactive measures such as installing dust removal equipment, improving protective coatings, and starting real-time hardware diagnostics.

Thermal Regulation Risks

Spacecraft systems are under tremendous thermal stress due to the Moon's drastic temperature swings (RPN: 180). Instrument failure and structural deformation may result from these situations if left unchecked. It will require the use of active heating systems, sophisticated thermal insulation, and regular hardware checks to make sure systems stay reliable and functional. Structural elements need to be modified and verified with simulated stress testing in order to withstand these harsh conditions.

Payload & Schedule Risks

The scientific goals of the mission may be jeopardized if instruments fail due to the inability to replicate lunar conditions in testing facilities (RPN: 160). There needs to be improved instrument testing procedures, alternate simulations, and thorough redundancy strategies in place. In addition, schedule delays brought on by testing or rescheduling mistakes might cause expenses to rise and the mission timeline to be derailed (RPN: 140). In order to prevent these setbacks, emergency funds, quicker processes, and stakeholder renegotiations need to be set in place.

Personnel & Safety Protocols

Personnel not following safety protocols during testing is another major risk that must be closely monitored and prevented (RPN: 84). In order to reduce the chances of this risk, the HELP Team must have cross-functional staffing, constant employee training, and strict adherence to safety regulations. If this safety regarding personnel continues to be an issue, external consultants might be required.

Final Analysis of FMEA Risk Priority Numbers

The risks with the highest Risk Priority Numbers (RPN) represent the most important dangers to the mission's success and will address the risks that receive immediate attention. The maximum RPN for safety, which is related to energy accumulation during spacecraft decommissioning, is 162. The greatest RPN in the Power category, 168, is ascribed to panel damage and short circuits brought on by lunar dust. The maximum RPN for Thermal is 240, which is associated with inefficient heat dissipation brought on by dust buildup. The maximum RPN in the Payload category is 160, which is associated with instrument failure brought on by the inability to simulate lunar conditions. Last but not least, the Schedule category has the highest RPN at 140, which is the result of testing and rescheduling errors. These values highlight the areas that need the greatest focus in order to successfully reduce mission risks.

4.1.3 Personnel Hazards and Mitigations

Maintaining personnel safety is critical to the success of the HELP mission. Personnel hazards may occur in a variety of circumstances, and they threaten the mental and physical health of mission personnel. These hazards may occur in relation to physical, chemical, biological, ergonomic, and psychological circumstances. By applying protocols outlined by the Office of Safety & Mission Assurance (OSMA) and the Occupational Safety and Health Administration (OSHA), and understanding the breadth of hazards that put personnel at risk throughout this mission, mitigation strategies have been outlined to ensure safety and health are preserved.

Physical hazards can be described as any hazard that may cause physical harm or injury to an employee due to any physical factors or conditions present in mission facilities ("Physical Hazards and Risks" n.d.). These hazards include but aren't limited to tripping hazards, machine-related incidents, cranial injuries, noise exposure, prolonged vibration, radiation exposure, electricity exposure, and extreme temperatures ("Physical

Hazards and Risks” n.d.). For the HELP mission, physical risks are most certainly prevalent, especially in manufacturing and testing facilities. While completing testing procedures at KSC, ARC, and other facilities, spacecraft components will be examined under extreme conditions that mirror those present on the lunar surface. These tests are absolutely necessary to raise the TRL level of the system, but they also threaten employee safety. Being exposed to noise or machine vibrations over long periods of time can also lead to temporary or permanent disabilities in hearing and other functions of the body (“Physical Hazards and Risks” n.d.). These hazards especially exist in manufacturing facilities, where scientists, engineers, and technicians will work closely with machinery across long periods of time to monitor production.

Chemical hazards include any substance that may induce negative physical and health effects to either people or to the environment due to its chemical properties (Reyes 2024). These hazards are dangerous to the human body, especially if they make contact with the human eye and skin, or sneak into the human respiratory system. Unfortunately, chemical hazards will be frequent throughout Phases C and D of the HELP mission in manufacturing and testing facilities. Since HELP mission facilities are required to maintain sterilization protocols to meet planetary protection guidelines, disinfectants and cleaning materials pose dangers due to frequent exposure. In addition, welding fumes that emanate from spacecraft manufacturing processes may cause respiratory issues leading up to lung disease and cancer (Reyes 2024). Oil and gasoline are fluids often utilized in manufacturing machinery that present chemical hazards as well.

Hazardous waste is a common type of solid and/or liquid chemical waste that exhibits either ignitable, corrosive, reactive, or toxic qualities (Finch n.d.). These hazards damage the environment as well as threaten human health, causing increases in mortality and irreversible illnesses (“NASA’S Management of Hazardous Materials” 2020). The US Environmental Protection Agency (EPA) provides a comprehensive list that defines hazardous waste, many of which may be commonly found in manufacturing and testing facilities (“PART 261- Identification and Listing of Hazardous Waste” 2024). Since mission personnel may potentially be spending long periods of time in the vicinity of these hazards during Phases C and D, guidelines for tracking and removing these wastes must be outlined and enforced.

Biological hazards are hazards that threaten the health of people and all other living organisms. Common biological hazards include bacteria, viruses, molds, and fungi (“Biological Health Hazards” 2021). These hazards not only threaten the planetary protection protocols outlined in Risk Analysis, but they pose national threats similar to the COVID-19 pandemic that occurred just previously in 2020. Any viral hazard that reaches the severity of the Coronavirus disease threatens the entirety of the HELP mission, therefore precautionary measures must be in place to address those circumstances if they were to arise.

Ergonomic hazards consider workplace conditions that cause wear and tear to an employee’s musculoskeletal system. These particular hazards cause repeated strain on the human body, often involving heavy lifting, awkward posture, prolonged stationary positions, and forceful motion (“Identifying and Addressing Ergonomic Hazards

Workbook" n.d.). Employees subject to these ergonomic hazards often develop extremely uncomfortable conditions, including stiffness, swelling, sensitivity, weakness, and difficulty moving ("Identifying and Addressing Ergonomic Hazards Workbook" n.d.). Manufacturing equipment is not lightweight - workers that attempt to move or force around heavy objects during spacecraft manufacturing and testing will quite possibly be subject to ergonomic strain. In striving to meet mission deadlines, HELP administratives and technical employees might also feel inclined to work overtime. This may lead to employees spending extended periods of time in uncomfortable seated or working positions, or attempting to handle too much at once, leading to increased musculoskeletal stress.

Psychological hazards, also known as psychosocial hazards, include any factors in the work environment that cause stress to a person's physical or mental well-being (Manawis 2024). In a high-stress/high-stakes environment such as the one presented by the HELP mission, personnel might be subject to long shifts, fatigue, and anxiety. Allowing an unhealthy, toxic work environment to fester in which leadership positions are unreliable or work relationships involve bullying or discrimination may cause low morale, depression, Post-Traumatic Stress Disorder (PTSD), or other prevalent mental health issues (Manawis 2024). These types of hazards, especially those negatively affecting mental health, directly impact the health of mission personnel and are often the cause of employee turnover[26], job dissatisfaction, and decreased productivity ("Mental Health in the Workplace: Supporting Employee Well-Being" 2024).

It's important to understand the role that OSMA and OSHA play in improving workplace conditions in order to properly address personnel hazards. OSMA emphasizes the importance of abiding by NASA Safety and Mission Assurance (SMA) and Safety, Reliability, Maintainability and Quality Assurance (SRM&QA) protocols throughout the entirety of the mission timeline (Bishop 2024a). NASA's SMA system includes many safety disciplines and programs that will prove useful for mitigating the personnel hazards outlined for this mission. In addition, the NASA SRM&QA Office handles the standardization of policies regarding safety, problem reporting, software assurance, and system assurance and assessment ("IMPLEMENTATION of the RECOMMENDATIONS of the Presidential Commission on the Space Shuttle Challenger Accident" n.d.). HELP's Mission Assurance Team will work closely with this office to handle risk management policies in relation to personnel hazards.

Similar to OSMA, OSHA outlines specific guidelines that help address hazards present throughout the NASA Mission Life Cycle. These guidelines cover subdisciplines that range from monitoring hazardous energy to maintaining test operations safety (Bishop 2024b). By promoting OSHA techniques concerning training, outreach, education, and assistance, the HELP mission will minimize risks and resulting consequences ("About OSHA " n.d.).

One particular SMA system that will be implemented in the HELP mission is its comprehensive Safety Culture (Bishop 2024c). This program outlines five guidelines to

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[26] Personnel turnover was a risk outlined in Risk Analysis that sees a lack of employees present to complete the mission due to them leaving the mission team or improper planning and training.

be followed to promote an inclusive, comfortable environment in which employees feel comfortable voicing safety concerns and confident that safety and health are prioritized. As long as the criteria outlined below is continuously followed and prioritized throughout the mission, risks can be identified early by those actively working in manufacturing, testing, and other mission facilities.

The first piece of criteria involves reporting safety threats to the necessary authorities (Bishop 2024c). In order for this guideline to be met, leadership must establish a trust with sub-teams that sees members confident the safety concern will be properly addressed. The second guideline sees an award system established for bringing safety concerns to light (Bishop 2024c). Professionals will never be punished for voicing concerns, especially when an employee's intentions are to create a safer, healthier environment. The third criteria of flexibility ensures that early mitigation systems are put in place to address unexpected safety risks that occur along the mission timeline (Bishop 2024c). Implementing programs that take precautionary measures early-on in the mission will ensure major schedule setbacks don't occur given unfortunate events. The fourth piece of criteria considers learning, and the importance of mission personnel understanding helpful resources available to share experiences and learn from others (Bishop 2024c). The fifth and final guideline for following this Safety Culture system is employee engagement (Bishop 2024c). In order for this program to efficiently identify hazards and safety concerns, there must be employee buy-in from mission managers and sub-team personnel.

Guidelines outlined by OSHA are especially useful for managing the physical and chemical hazards associated with this mission. To protect employees from energy-inflicted injuries and other machine-related physical or chemical injuries, Lockout/Tagout procedures will be in place. The Lockout/Tagout system sees locks placed on faulty equipment to isolate their functionality within the production line, and tags used to inform employees as to why the lock was utilized (Bishop 2024b). Flammability hazards will be heavily monitored and assigned Flammable Hazard Levels (FHL) (Lewis 2023b). A Fall Protection Program will be implemented that ensures fall hazards are identified earlier and mitigated accordingly (Bishop 2024b). Regulations will be set in place that make Personal Protective Equipment (PPE) a mandatory requirement for personnel in manufacturing and testing work environments. PPE sees protective equipment such as safety goggles, ear-plugs, and head-gear used to protect the eyes, face, and head (Bishop 2024b). In addition, respiratory devices and protective clothing and shields will always be available, especially in areas of the workplace where physical, chemical, and biological hazards are prevalent (Bishop 2024b). Gloves and knee padding are but a couple PPE resources that will help prevent ergonomic hazards as well ("Ergonomics - Solutions to Control Hazards" n.d.).

While PPE acts as one mitigation solution to resolving physical and chemical hazards, it doesn't sufficiently mitigate it completely. The HELP mission will abide by the Hazard Communication Standard (HCS), which establishes guaranteed communication of potential chemical hazards to mission personnel by outlining plans to communicate these issues (Reyes 2024). An inventory of all chemicals involved in the mission will be documented, tracked, and assigned a Toxicity Hazard Level (THL) in order to ensure all grounds are covered (Reyes 2024). Enforcing employee training is critical in order for this system, as well as other mitigation techniques, to be as effective as possible. The HELP mission will follow OSHA's Safety Training and Certification procedures to develop employee knowledge on how to handle dangerous chemicals, production-line machinery, and how to use mitigation strategies such as PPE to improve mission safety (Bishop 2024b).

Another online training module will be enforced that covers hazardous waste management. This training includes content similar to that of the course provided by Goddard Space Flight Center's (GSFC) Medical and Environmental Management Division (MEMD), which requires the class be completed annually by any facilities with personnel generating or storing hazardous wastes (Finch n.d.). In addition, a waste tracking system will be implemented that utilizes durable containers designed specifically for waste storage, with labels that state "Hazardous Waste" and clarify the type of waste inside (Finch n.d.). A Hazardous Waste Report will also be filed annually by each manufacturing and testing facility that hosts any EPA hazardous wastes (Finch n.d.). This report will list and quantify hazardous wastes present at the corresponding facility. Strict guidelines will also be defined for waste disposal. It's critical that hazardous waste is not disposed of via sinks, storm drains, or the trash (Finch n.d.). Facility disposal divisions will instead be contacted to remove and properly dispose of accumulated hazardous waste. Using the containment and labeling procedure outlined previously, it'll be easier for these divisions to efficiently address this issue.

Regarding biological hazards, the HELP administrative team will work closely with NASA's Biosafety Review Board (BRB) to identify and control any biological concerns present in the HELP mission. The biological payloads present within manufacturing and testing facilities will be examined, and any biohazardous materials present will be assigned a NASA BioSafety Level (BSL) (Lewis 2023a). Similar to the system in-place to track chemicals across mission facilities, a tracking system will also be used to monitor biohazards. Together, the BSL, THL, and FHL combine to make a Hazard Response Level (HRL) used in coordination with a comprehensive Hazardous Materials Summary Table (HMST) (Lewis 2023b). This table will compile all of the chemical, biological, and flammable hazards present throughout the HELP mission (Lewis 2023b).

In terms of ergonomic hazards, workplace machinery and set-ups will be designed or rearranged to minimize ergonomic strain presented by awkward body positions and heavy lifting ("Ergonomics - Solutions to Control Hazards" n.d.). Requirements will be set in place to enforce machinery-use for any heavy lifting. A job rotation system will also be implemented, especially in manufacturing and testing facilities, that sees employees complete rotations around several tasks that target different muscle groups ("Ergonomics - Solutions to Control Hazards" n.d.). Personnel will have the variability to adjust work schedules and work pace, and will be provided with small periods of recovery time throughout the work time to relax strained muscles ("Identifying and Addressing Ergonomic Hazards Workbook" n.d.).

Psychological hazards will be mitigated by promoting mental health awareness, completing team-wide assessment surveys, and providing relative training modules that give instructions on how to identify and maintain good mental health. Digital training modules will be required for all mission personnel to complete. These modules will promote diversity and inclusivity, provide advice on how to manage mental health, and tips on how to identify symptoms of psychological hazards in the workplace (Manawis 2023). The HELP mission will conduct Organizational Risk Safety Assessments (ORSA) to receive discrete employee feedback. ORSA is a tool that utilizes on-site interviews and surveys to gauge the opinions of mission personnel regarding mission safety and well-being (Bishop 2024b). HELP personnel should feel comfortable utilizing this resource to voice safety and mental health concerns, whether it be regarding themselves or a coworker. The Substance Abuse and Mental Health Services Administration (SAMHSA) outlines Employee Assistance Programs (EAP) that the HELP administration will share with mission personnel and emphasize their importance. EAPs offer services that assist employees with addressing personal problems that might involve health, finances, social anxiety, or substance abuse ("Provide Support" 2023).

These mitigation strategies involving training, protection equipment, employee resources, surveys, and hazard tracking will be emphasized constantly throughout the entirety of the HELP mission. Similar to Risk Analysis, personnel hazards must be monitored continuously and updated accordingly as new hazards come to light. Personnel safety is of the highest priority, not just for ensuring mission success but for maintaining physical and mental well-being as well.

5 ACTIVITY PLAN

5.1 Project Management Approach

The HELP mission team can be divided amongst individual subteams, of which each plays a significant role in ensuring the mission is successfully completed. Understanding the connections and communication between these specialty groups and the responsibilities that employees carry in relation to their subteam is incredibly important for reassuring all necessary aspects of the HELP mission will efficiently be addressed.

After researching analogous discovery-class missions, it’s estimated that approximately 30-50 team members are necessary to complete the HELP mission (Yost, 2021). Further evaluating the HELP mission and its necessary subdivisions led to the establishment of the subteams outlined in Figure 45. A total of 37 team members are divided amongst five specific categories of personnel, including scientists, engineers, technicians, administration, and management. An additional 8 members are dedicated to completing outreach related expenditures. Therefore, the entire HELP mission carries a team of 45 members, and each team member plays a role outlined in the categories specified in Figure 46.

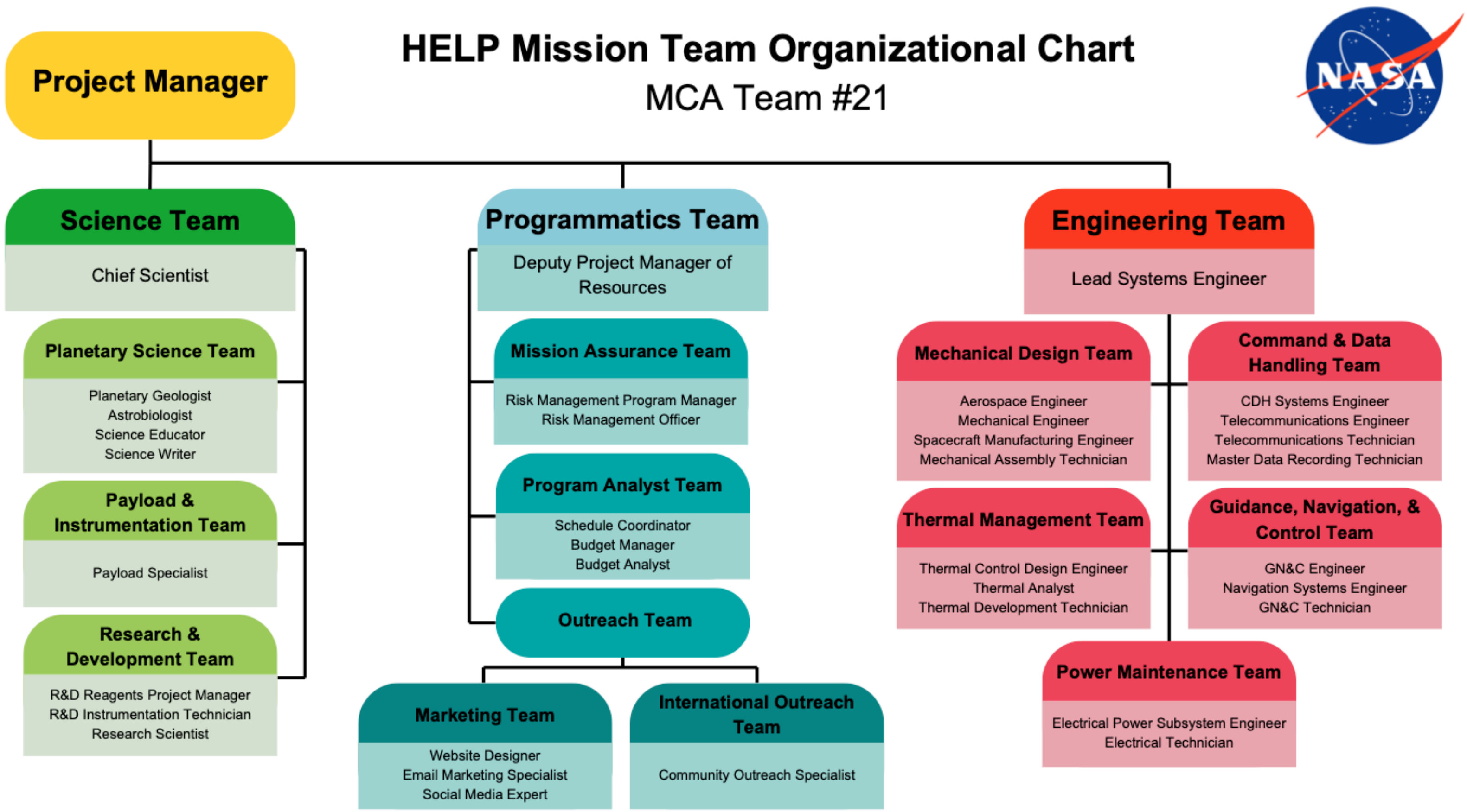

Figure 45: HELP Mission Team Organization Chart

	Phase C	Phase C	Phase C	Phase D	Phase D	Phase D	Phase E-F
Team	FY 1	FY 2	FY 3	FY 4	FY 5	FY 6	FY 7
Project Manager:	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management
Science Team							
Chief Scientist:	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management
Planetary Science Team:	3 - Scientist	2 - Scientist	1 - Scientist	1 - Scientist	1 - Scientist	0	5 - Scientist
Payload & Instrumentation Team:	3 - Scientist 1 - Technician	4 - Scientist 1 - Technician	4 - Scientist 1 - Technician	3 - Scientist 3 - Technician	3 - Scientist 3 - Technician	4 - Scientist 3 - Technician	2 - Scientist
R&D Team:	3 - Scientist	3 - Scientist	4 - Scientist	1 - Scientist	1 - Scientist	1 - Scientist	5 - Scientist
Engineering Team							
Lead Systems Engineer:	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management
Mechanical Design Team:	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	3 - Engineer 2 - Technician	3 - Engineer 2 - Technician	3 - Engineer 2 - Technician	0
Power Maintenance Team:	2 - Engineer 1 - Technician	2 - Engineer 1 - Technician	2 - Engineer 1 - Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	0
Thermal Management Team:	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	0
Command & Data Handling Team:	2 - Engineer 1 -Technician	2 - Engineer 1 -Technician	2 - Engineer 1 -Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	2 - Engineer 2 - Technician	1 - Engineer 1 - Technician
Guidance, Navigation, & Control Team:	2 - Engineer 1 - Technician	2 - Engineer 1 - Technician	2 - Engineer 1 - Technician	2 - Engineer 1 - Technician	2 - Engineer 1 - Technician	2 - Engineer 1 - Technician	1 - Technician
Programmatics Team							
Deputy Project Manager of Resources:	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management	1 - Management
Mission Assurance Team:	3 - Administration	3 - Administration	3 - Administration	2 - Administration	2 - Administration	2 - Administration	2 - Administration
Program Analyst Team:	3 - Administration	3 - Administration	3 - Administration	3 - Administration	3 - Administration	3 - Administration	2 - Administration

Figure 46: Personnel Mission Life Cycle Division Chart

Of the 37 total team members contributing to the HELP mission, 4 are dedicated to management, 9 are scientists, 10 are engineering, 8 are technicians, and 6 are administration. This division of labor is specifically outlined for Phase C, and can be further observed in Figure 46 to understand how each category is separated amongst the individual subteams. As the mission progresses, mission staff are redistributed to address more pressing concerns in some areas while others have a smaller workload. Since Phase D primarily focuses on the manufacturing and testing of the spacecraft and system components, an increase in engineering and technician personnel is necessary. Phase D also sees a drop in scientist personnel, since most of the planetary science and payload instrument research should be completed, assuming the engineering team is moving forward with established designs and verification and validation (V&V) plans.

By modeling Phase C and its distribution of personnel, the subteams outlined in Figure 45 can be further examined to identify the specific role an individual plays in the completion of the HELP mission. For example, the 10 engineering professionals are divided amongst the Engineering Team, the 9 science professionals are divided amongst the Science Team, the 6 administration personnel are divided amongst the Programmatics Team, and the 8 technicians are distributed between both the Science and Engineering Teams. These divisions are displayed in Figure 46. Understanding how each of these broad categories of subteams organizes its staff and designates authority helps one understand how the HELP mission is coordinated.

The Science Team carries the responsibility of ensuring instrumentation is implemented to meet the mission science requirements outlined in Figure 5. The Planetary Science Team consists of more staff towards the beginning of the mission under the first fiscal year of Phase C, since it’s responsible for researching the Compton Pit, risks associated with the pit, and environmental risks on the Moon. During Phase C, this team consists of two Planetary Geologists and one Astrobiologist. The Planetary Geologists will be allowed much autonomy to cover any necessary bounds in relation to mission hazards and environmentally-based risks (Wheeler 2024). However, they must also communicate their discoveries throughout the Science Team, Engineering Team, and Mission Assurance Team to ensure risks are continuously monitored and tracked throughout Phase D. The Astrobiologist will assist with planetary protection concerns to ensure the rover doesn’t contaminate the lunar environment to any extent (Wheeler 2024). The amount of Planetary Science Team personnel sees an increase in Phases E and F to draw lessons learned from the recorded data and the corresponding lunar environment. This team now includes a Science Educator and a Science Writer to assist with science measurement documentation and communication of lessons learned (Wheeler 2024).

The Payload & Instrumentation Team researches and implements solutions for integrating the instrumentation technology into the HELP spacecraft design. This team will consist primarily of Payload Specialists, who will be responsible for making sure the mission’s science requirements are met by using the selected payload devices (“Career Opportunities in Space Exploration: From Astronauts to Mission Specialists” 2024). Therefore, they will receive help from technicians when the time comes to manufacture and test payload instruments. This team coordinates its payload research and integration so recovery and redundancy protocols are thoroughly discussed between personnel regarding what each payload instrument contributes to the spacecraft.

The Payload & Instrumentation team heavily communicates with the Research & Development (R&D) Team. The R&D Team is also allowed a significant amount of autonomy regarding decision making and testing strategies. This team consists of one R&D Reagents Project Manager (PM) and two R&D Instrumentation Technicians during Phase C. The two technicians are responsible for raising the Technology Readiness Level (TRL) of system components, which subsequently will raise the TRL of the entire HELP mission rover, while the R&D PM will coordinate project implementation and alignment with science requirements ("Careers in Research & Development (R&D)" 2024). This team collaborates heavily with the Engineering Team, and will handle much of the V&V-related testing as well. The R&D Team plays a more significant role in Phase C, where it researches manufacturing plans for spacecraft equipment, as well as in Phases E and F to conduct research following the collection and analysis of science measurements. In these two final phases, the R&D Team is made up of Research Scientists in order to analyze and conduct studies concerning the data recorded by the mission rover (Wheeler 2024).

The Programmatics Team plays a significant role in the entirety of the HELP mission. The Mission Assurance Team is responsible for researching mission-related risks, tracking risks discovered by the Science and Engineering Teams, outlining and helping implement mitigation plans, and continuously monitoring risk status to ensure each is properly addressed. The Risk Management Program Manager and Risk Management Officers must have a comprehensive knowledge of mission processes and components for these positions, due to the heavy reliance of mission success on risk mitigation and acceptance. The Risk Management PM will be responsible for establishing requirements, or mitigation techniques, that must be completed to minimize risks and ensuring that the mission abides to Safety and Risk Management Protocols ("Risk Management" 2024). The Risk Management Officers will communicate risks throughout the entire mission team, track identified risks across the mission timeline, and oversee mitigation implementations ("Risk Management" 2024).

The Program Analyst Team is represented by two subcategories: the Cost Budgeting Team and the Schedule Management Team. One Schedule Coordinator will address the mission schedule, while one Budget Manager and one Budget Analyst will address the mission cost. These two teams will work closely together to monitor the mission's budget and scheduling, and ensure that they remain within range of the established customer constraints[27]. The Cost Budgeting Team holds most of the autonomy regarding budget distribution between other subteams. A consultative system is in place that sees subteams discussing their ideal budget with the Cost Budgeting Team, but ultimately the Budget Manager will have the final say as to how much money is allocated to a given subteam ("Budget Analyst Job Titles" 2024). Therefore, the Cost Budgeting and Schedule Management Teams must continuously monitor mission costs and scheduling setbacks that might impact the current standard, leading to significant changes that might involve descoping.

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[27] The total mission budget constraint is $300 million, and the mission launch date is March 1, 2030.

The amount of administration personnel remains consistent for the entirety of Phase C, however, throughout Phase D the amount of administrators in the Mission Assurance Team decreases to 2. Most of the risks that threaten the mission have already been established prior to Phase D, and mitigation plans should already be in place to help lower the likelihood of risk scenarios occurring. Therefore, it is fitting that a decrease in personnel is seen in this subteam. This transition can be visualized in Figure 46. In Phases E and F, the Program Analyst Team is downsized instead, since major cost and scheduling issues aren't as prevalent past mission launch.

The Outreach Team consists of 8 total members, and it has been split into the Marketing Team and the International Outreach Team. These members aren't included in Figure 46, but are still important factors associated with the HELP mission. The Marketing Team consists of 4 of these members, each of which have different programming and social media responsibilities in relation to formatting a HELP mission website, establishing HELP social media accounts across LinkedIn, Instagram, X, and Facebook, as well as sending informational emails. This team will travel for educational programs across the nation, so it is expected that marketing personnel work well with children. The International Outreach Team is composed of the other 4 members. Each member of this team will attend virtual and in-person conferences with representatives across the globe. It's preferable that these personnel are fluent in several languages, and are comfortable traveling and sharing mission-related information with a host of other cultures and regions.

The Engineering Team is the most complex in that it includes a variety of subteams, of which each is responsible for addressing a major subsystem of the HELP spacecraft and plans for subcomponent V&V. The Mechanical Design Team begins with four members, two of which are engineers and the other two technicians. One engineer is an Aerospace Engineer, while the other is a Mechanical Engineer. The two will work together to design and develop the spacecraft hardware and its various mechanisms ("The Role of Engineers in Space Missions: Key Skills and Pathways" 2024). These two engineers will work with two Mechanical Assembly Technicians to research and design mechanical-related components such as wheel treads, spacecraft mechanical structures, and material preference ("Mechanical Assembly Technician - Airbus Defence & Space" 2024). This team must examine these factors, estimate costs, and discuss them with the Cost Budgeting Team to receive an associated subsystem budget cap. Heading into Phase D, the personnel in this team is increased to include an additional Spacecraft Manufacturing Engineer to deal with the unique manufacturing design of the spacecraft architecture ("Manufacturing Engineer (Spacecraft)" 2024). This team must also communicate constantly with other Engineering Team subteams and the Lead Systems Engineer to organize the integration of other system subcomponents onto the mechanical hardware design of the spacecraft.

The Power Maintenance Team identifies sources of power for the rover to efficiently run on the lunar surface. This team begins with two Electrical Power Subsystem Engineers and one Electrical Technician, but gains an additional Electrical Technician during Phase D to address the testing associated with the solar panels and batteries. The Electrical Power Subsystem Engineers will be responsible for conducting

V&V of each spacecraft power component and developing the spacecraft's circuitry architecture design ("Spacecraft Electrical Power Subsystem Engineer" 2022). The Electrical Technicians rely on their knowledge of circuitry and wiring to integrate the established energy sources into the spacecraft design ("Electrical Technician" 2024).

The Thermal Management Team must recognize and analyze areas of heat transfer to address the extreme temperature range present on the Moon. The team's Thermal Analyst will consider conductive heat transfer, radiation heat transfer, and convection heat transfer if it's relevant and how each affects the system (Gilmore 2002). A Thermal Control Design Engineer will research thermal control solutions such as paint, multi-layer insulation (MLI), and radiators ("Spacecraft Thermal Control" 2024). These two engineers and two Thermal Development Technicians are designated to this subteam for the entirety of the mission. The Thermal Development Technicians will help execute the thermal control plan outlined by the Thermal Analyst and Thermal Control Design Engineer ("Thermal Development Technician" 2024). Similar to the Mechanical Design Team, the Power Maintenance and Thermal Management teams must coordinate their work amongst the other Engineering Team subteams and the Lead Systems Engineer, as well as discuss their related cost cap with the Cost Budgeting Team.

The Command & Data Handling (CDH) Team plays a significant role in that it ensures science data is properly recorded and stored once it is obtained from the lunar site. For Phase C, this team is composed of one Command & Data Handling Systems Engineer, one Telecommunications Engineer, and one Telecommunications Technician. The Telecommunications Engineer and the Telecommunications Technician will establish communication connection systems between the rover and ground control, and obtain the frequency licensing necessary to minimize interference (Bapna, Martin, and Whittaker n.d.). The Command & Data Handling Systems Engineer will ensure data is collected and properly stored to be transmitted via this communication ("Principal Engineer - Command and Data Handling Systems Engineer" 2024). Heading into Phase D, these two engineers and the one technician will be joined by a Master Data Recording Technician. This technician will be readily available to assist the team with rover transmissions during Phases E and F as well ("The 10 Top Types of Telecommunications Technician Jobs" 2024). Unlike many of the other mission teams in Phases E and F, the CDH Team continues to have the Telecommunications Engineer and the Telecommunications Technician in Phases E and F to ensure that data is transmitted and collected efficiently at this critical time.

The Guidance, Navigation, & Control (GN&C) Team also incorporates a communication aspect to receive ground system commands and navigate across the lunar surface. One GN&C Engineer and one Navigation Systems Engineer works with one GN&C Technician throughout Phase C. The Navigation Systems Engineer implements system commands to be utilized in system operations on the lunar surface ("Lead Engineer - Navigation Systems" 2024). Both engineers and the technician will work closely with the Payload & Instrumentation Team and other Science Team subteams to enforce the HELP Concept of Operations, involving an in-depth plan mapped out for when the rover reaches the lunar surface. This plan is outlined in Figure

6. Similar to the CDH Team, the GN&C Technician will be available in Phases E and F to address any critical issues that arise concerning system navigation ("Guidance, Navigation, and Control Engineer - Associate (Spring 2025)" 2024). Again, both the CDH and GN&C teams are also responsible for understanding the costs associated with their subcomponents and working below the cost cap assigned by the Cost Budgeting Team.

Verification and validation (V&V) involves confirming the requirements outlined by the customer and each of the other subteams are properly addressed and met throughout the mission timeline (Day n.d.). The V&V process is enforced by each of the engineering subteams outlined in Figure 45, as well as the Payload & Instrumentation Team. Mission validation is completed earlier in the Mission Life Cycle in Phase B in order to ensure requirements remain stagnant throughout the mission timeline. In Phase D, teams addressing this process will clarify verification protocols involving inspection, analysis, demonstration, and testing to each of the spacecraft subsystem components. In outlining these methods, the TRL of system subcomponents will be raised and mission uncertainties will be alleviated. Officials guaranteeing V&V are awarded much autonomy to outline V&V strategies, but they must also maintain constant communication and consider process costs with the Cost Budgeting Team before beginning the V&V process of a subcomponent.

Decision making is an important factor to consider when addressing mission task division and significant decisions in order to move forward with the mission. The 4 management positions consist of the Project Manager (PM), the Deputy Project Manager of Resource (DPMR), the Chief Scientist, and the Lead Systems Engineer. The PM is the decision-maker responsible for making these major decisions. Similar to the decision making process in-place with the Cost Budgeting Team, the PM will discuss major decisions with representatives from the Science, Engineering, and Programmatics Teams, but will essentially have the final say in an outcome[28]. The representative of the Science Team is the Chief Scientist, that of the Engineering Team is the Lead Systems Engineer, and that of the Programmatics Team is the DPMR. When conducting trade studies across subteams, the PM will delegate the decision to a deliberation lead instead. Deliberation leads will be one of these three team representatives, and they'll be responsible for having more knowledge in relation to the trade study being conducted. Therefore, these leads can make more informed decisions considering RIDM processes. These leads must also explain their decision to the PM, as well as communicate the necessary changes that must occur amongst the other subsystems for its integration to be conducted smoothly.

5.2 Mission Schedule

5.2.1 Schedule Basis of Estimate

There are several assumptions and restrictions that have been laid out in order to obtain an accurate schedule basis of estimate. A constraint made by the customer includes the budget of $300 million, the costs of staff, software, hardware, and science

[28] This decision structure can be defined as consultative decision-making.

is deducted from this budget. The spacecraft must be completed and be ready to launch by the deadline of March 1st, 2030. The time of travel, part of Phase C, will also be added on to the assumptions, which will be approximately four weeks, traveling from their respective locations to Cape Canaveral, FL. In order to obtain a time frame for how long each phase will last, another discovery class mission, the Lucy Mission, was used as an analogous mission and based on its template, several time estimations and assumptions were used for phase C and D of the HELP mission. The schedule will assume that Phases C and D will be longer compared to the analog mission because of a longer time of preparation for the launch date. This allows the Phases C and D for the HELP to be extended by 200% as the ratio from the Lucy mission was used to justify this. Based on the Lucy mission, it will also use the fiscal calendar in order to keep track of finances. After the completion of both Phases C and D, the HELP mission will then move onto Phase E, the Post-Launch Assessment Review (PLAR), which uses the Apollo mission as reference. The Apollo mission was used for this estimate to find out how long it takes to reach the moon. Phase F, finally, which allows the closeout to begin, meaning the rover is decommissioned and reports will be finalized, which will approximately take a day. Both Phases E and F require staff to travel which lands around a week's worth of time.

Thus, the following assumptions and restrictions are laid out:

1. The deadline of the completion of the spacecraft is March 1st, 2030.
2. The HELP mission will be using the fiscal calendar for financial tracking.
3. There will be a 200% increase for Phase C and D based on the Lucy mission.
    a. Approximately one year was given for Phase C and Phase D respectively from the Lucy mission.
    b. Three years is given for Phase C and Phase D respectively for the HELP mission.
4. Phase E's PLAR will take three days based off of the Apollo mission.
5. Time will be set aside for staff travel to Cape Canaveral, FL.
    a. Three weeks will be set aside for Phase C.
    b. One week each will be set aside for both Phases E and F.
6. Schedule margin will be 30 days for each phase.

All assumptions are based on these restrictions and analog missions such as the Lucy mission and Apollo mission have been used as references for the scheduling of the HELP mission.

5.2.2 Mission Schedule

The mission schedule can be broken down into four primary phases: Phase C, Phase D, Phase E, and Phase F. Each of these phases marks a significant milestone range of NASA's Mission Life Cycle past NASA's approval of this mission's implementation (Deiss, 2023). Understanding the task and subtask breakdown within each of these phases and the amount of time needed to efficiently complete each helped contribute to the creation of the schedule timeline depicted in Figures 10 and 11. These tasks are also specifically divided amongst mission life cycle phases, which can be observed in Appendix C, the Mission Life Cycle Phases Table.

The first major category specified in Appendix C is Phase C, otherwise known as Final Design and Fabrication. In evaluating the project breakdown of this phase, two major milestones must be considered and completed. The first of these two milestones for review is the Critical Design Review (CDR). The CDR is incredibly important in that it clarifies and finalizes robot architecture designs. This involves a complete explanation of how the instrumentation is manufactured, how individual subsystems of the robot are constructed, and how comparable instrumentation will be analyzed and considered for future robot implementation. The document must also specify how each subsystem will effectively interact with one another to allow the robot to collect all of its desired science measurements. It clarifies the interface between the mechanical, power, electrical, and computer hardware subsystems, and how each plays a role in getting the rover to traverse across the lunar surface and ensure the instrumentation functions according to plan.

Given the importance of this document and the role it plays in defining complete designs for robot architecture and instrumentation, other discovery-class missions were considered to evaluate an efficient time estimate for when this review should be drafted and submitted. The Lucy Mission, a discovery-class mission, played a crucial role in determining a time estimation for not only this particular document, but for the entirety of Phases C and D, which can be observed in Figures 10 and 11. While the Lucy Mission is still active, both of its Phases C and D are marked as complete. The timeline for Phase C was October of 2018 to August of 2020, and the timeline for Phase D was October of 2020 to October of 2021 ("Timeline", 2024). The end of Phase D marks the vehicle launch of the mission. For the Lucy Mission, both of these phases were approximately a year in length.

The set mission launch date for HELP is March 1, 2030. This launch date creates a Phase C and D completion timeline that extends six years in total. Using the phase split presented in the Lucy Mission as a template for when the phases will be completed for this mission, it is assumed that Phases C and D for HELP will each take approximately three years total in time. The ratio from Lucy Mission launch to this mission launch helped formulate this assumption. Further division within these phases was derived from both the Lucy Mission and documentation summarizing deliverables and expectations for missions completing the NASA Mission Life Cycle (Deiss, 2023).

Based on the life cycle timeline expectations for the CDR and its completion within Phase C, an estimate was generated not just for when the CDR takes place, but also for its individual subtasks, and those related to the System Integration Review (SIR) as well. The CDR is often completed at some point halfway into Phase C, therefore it was estimated that it should be completed over a year into Phase C, during January of 2026. Similar assumptions were made about its individual subtasks, as well as the SIR which is often much later towards the end of Phase C. In this case, it's estimated it will be done by January of 2027. Given that this is a rough estimate, a phase margin was specified that allows an extra 31 days for this phase to accommodate obstacles that inhibit progress in Phase C.

Next, Phase D is often referred to as System Assembly, Integration & Test, and Launch & Checkout. The task breakdown represented in Phase D was assigned timeline due dates using a similar assumption strategy to that used in Phase C. Considering this phase deals with the manufacturing, assembly, integration, and testing of the robot, many of the major task deadlines consider test and operational readiness. This is marked as a Key Decision Point since it determines the capabilities and how prepared the instruments are for the mission. The Test Readiness Reviews (TRRs) are set to have an estimated completion time in January of 2027, followed by a set Operational Readiness Review (ORR) deadline for February of 2029, and a Mission Readiness Review (MRR) deadline for January of 2030. The order of these documents is important, since each segways into the next, modeling a predecessor system. Again, the end of Phase D marks mission launch at Cape Canaveral, FL, on March 1, 2030. Therefore, the completion of these assignments beforehand is crucial to confirming spacecraft readiness regarding safety and capability.

Phase E marks Operations and Sustainment of the mission. This phase encompasses post-launch evaluation, and the most important piece of the mission: where the robot collects necessary data. The Post-Launch Assessment Review (PLAR) is given a rough estimate of nine days to be completed, which involves evaluating the efficiency of the launch and its completion and how it can be improved. The estimated travel time for the spacecraft to reach the moon and begin operation is three days, modeled after the time taken for the Apollo spacecraft to travel a similar distance ("Journey to the Moon", 2017). The process of HELP carrying out its mission once landing on the lunar surface is outlined in the Concept of Operations. Once the mission is complete, the robot then completes its decommissioning process outlined by the Decommissioning Review (DR), marking the closing stages of the robot's role in completing its mission.

In Phase F, otherwise known as Closeout, a Disposal Readiness Review (DRR) is conducted to construct the robot to dispose of itself based on the plans outlined in the document. This process should be very short, so it is given a day. Next, completing the final mission report is the final step in completing this mission. Approximately a month is given to baseline this report, draw conclusions from the data, document lessons learned from this mission, and draft areas for future exploration and improvement. This report will verify whether or not the Compton Pit is suitable for human habitation in the future, and will provide a surplus of information regarding the surface conditions adjacent to the pit. The final date estimated for this mission to be completed is June of 2030.

The major milestones are provided in the high-level overview below, and a Gantt chart outlining specific tasks follows this.

Major Milestone	Date Completed
Submit Critical Design Review	January 23, 2026
Submit System Integration Review	March 1, 2027
Complete Test Readiness Reviews (TRR) of Instrumentation and System	March 1. 2028
Submit Operational Readiness Review (ORR)	February 1, 2029
Submit Mission Readiness Review	January 1, 2030
Launch mission at Cape Canaveral, FL	March 1, 2030
Submit Critical Events Readiness Review	April 19, 2030
Submit Decommissioning Review	May 6, 2030
Submit Disposal Readiness Review and Conclude Mission	June 6, 2030

Figure 47: Major Milestones Schedule

ID#	TASK	START	END	DAYS	MARGIN
1	**Draft and submit Critical Design Review**	12/23/24	1/23/26	397	32
1.1	Develop detailed designs of necessary hardware and software	12/23/24	7/23/25	213	
1.2	Further explain how subsystems effectively interface	12/23/24	10/23/25	305	
1.3	Explain how the instrumentation is analyzed and considered for future implementation	12/23/24	10/23/25	305	
1.4	Continue updating plans for operations, risks, and anticipated procedures for manufacturing	12/23/24	1/23/26	397	
1.5	Key Decision Point: Submit Production Readiness Review (PRR) for necessary instrumentation	12/23/24	1/23/26		
1.6	Schedule Margin	12/23/25	1/23/26	32	
1.6	◆ Submit Critical Design Review	1/23/26	1/23/26	1	
2	**Draft and submit System Integration Review**	1/23/26	3/1/27	403	31
2.1	Finalize design plans and plans for integrating the subsystems and instrumentation	1/23/26	11/23/26	305	
2.2	Baseline how each subsystem will operate	11/23/26	1/30/27	69	
2.3	Begin outlining the process of Verification & Validation (V&V)	11/23/26	1/30/27	69	
2.4	Schedule Margin	1/30/27	3/1/27	31	
2.5	◆ Submit System Integration Review	3/1/27	3/1/27	1	
3	**Begin and Complete Test Readiness Reviews (TRRs) of**	3/1/27	3/1/28	367	30

	Instrumentation and System				
3.1	Manufacture system components and then assemble and integrate them	3/1/27	1/1/28	307	
3.2	Inspect instrumentation and system capability to obtain science measurements	1/1/28	3/1/28	61	
3.3	Key Decision Point: Assess instrumentation with prototypes to determine TRR	1/1/28	3/1/28	61	
3.5	Schedule Margin	2/1/28	3/1/28	30	
3.6	◆ Complete Test Readiness Reviews (TRRs) of Instrumentation and System	3/1/28	3/1/28	1	
4	**Draft and Submit Operational Readiness Review (ORR)**	3/1/28	2/1/29	338	32
4.1	Test instrumentation and instate confidence in its usage	3/1/28	5/1/28	62	
4.2	Key Decision Point: Begin V&V of subsystem and instrumentation results	3/1/28	5/1/28	62	
4.3	Finalize operations plans and procedures	5/1/28	2/1/29	277	
4.4	Baseline plans for decommissioning and disposing of the robot after mission completion	5/1/28	2/1/29	277	
4.5	Schedule Margin	1/1/29	2/1/29	32	
4.6	◆ Submit Operational Readiness Review (ORR)	2/1/29	2/1/29	1	
5	**Draft and Submit Mission Readiness Review (MRR)**	2/1/29	1/1/30	335	31
5.1	Baseline and verify V&V results	2/1/29	1/1/30	335	
5.2	Prepare launch and confirm spacecraft flight/launch capability	5/1/29	1/1/30	246	
5.3	Perform safety review assessing launch and mission safety	5/1/29	1/1/30	246	
5.4	Confirm spacecraft safety and capability readiness	5/1/29	1/1/30	246	
5.5	Schedule Margin	12/1/29	1/1/30	31	
5.6	◆ Submit Mission Readiness Review	1/1/30	1/1/30	1	
6	**Complete Launch Readiness Review (LRR) and Launch Vehicle (LV)**	1/1/30	3/1/30	60	29
6.1	Complete Launch Readiness Review	1/1/30	2/1/30	32	
6.2	Schedule Margin	2/1/30	3/1/30	29	
6.3	◆ Launch Mission at Cape Canaveral, FL	3/1/30	3/1/30	1	
7	**Draft and Submit Critical Events Readiness Review**	3/1/30	4/19/30	50	1
7.1	Key Decision Point: Conduct vehicle launch performance assessment	3/1/30	4/1/30	32	
7.2	Activate science instruments upon landing	3/4/40	3/4/30	1	
7.3	Collect data measurements concerning surface features	3/4/30	3/18/30	15	
7.4	Visit Compton Pit and cave map the pit dimensions and structural features	3/19/30	4/19/30	32	
7.5	Collect measurements concerning cave temperature and radiation	3/19/30	4/19/30	32	
7.6	Schedule Margin	3/19/30	4/19/30	32	
7.7	◆ Submit Critical Events Readiness Review	4/19/30	4/19/30	1	
8	**Draft and Submit Decommissioning Review**	4/19/30	5/6/30	18	6
8.1	Begin process of decommissioning the robot systems	4/19/30	5/1/30	13	
8.2	Outline potential upgrades for future missions	4/19/30	5/1/30	13	
8.3	Conduct safety review	4/19/30	5/1/30	13	

8.4	Key Decision Point: Compile and Document Collected Data Efficiently	4/19/30	5/1/30	13	
8.5	Schedule Margin	5/1/30	5/6/30	6	
8.6	◆ Submit Decommissioning Review	5/6/30	5/6/30	1	
7	**Complete Disposal Readiness Review (DRR)**	5/6/30	6/6/30	32	6
7.1	Conduct robot disposal according to outlined plans	5/6/30	5/7/30	2	
7.2	Ensure Organized Documentation and Draw Conclusions Based on the Collected Data	5/6/30	5/7/30	2	
7.3	Baseline and write up the mission final report	5/6/30	6/1/30	27	
7.4	Draft and capture lessons learned based on data collected (determine habitability of Compton Pit and the supply of resources available in the vicinity)	5/6/30	6/1/30	27	
7.5	Schedule Margin	6/1/30	6/6/30	6	
7.6	◆ Submit Disposal Readiness Review and Conclude Mission	6/6/30	6/6/30	1	

Figure 48: Mission Schedule Gantt Chart