

# System Requirements Review (SRR)

## 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
BRAILLE	Biologic and Resource Analog Investigations in Low Light Environments
CCB	Change Control Board
CDH	Computer and Data Handling
CDR	Critical Design Review
COSPAR	Committee on Space Research
CRM	Continuous Risk Management
DR	Decommissioning Review
DTN	Disruption Tolerant Networking
REMS	Rover Environmental Monitoring Station
FPGA	Field Programmable Gate Array
HELP	Habitability Explorer for Lunar Pits
ISRU	In-Situ Resource Utilization
LHDAC	Lander Hazard Detection & Avoidance Camera
LIBS	Laser Induced Breakdown Spectroscopy
LiDAR	Light Detection and Ranging
LND	Lunar Lander Neutron and Dosimetry Experiment
LRA	The Laser Retroreflector Array
LROC	Lunar Reconnaissance Orbiter Camera
LVPS	Low Voltage Power Supply
MCA	Mission Concept Academy
MCR	Mission Concept Review
MDR	Mission Definition Review
MMOD	Micrometeoroid and Orbital Debris
MOVE	Modal Optimized Vibration dust Eliminator
MPASS	Multi-Parameter Aerosol Scattering Sensor
NIRVSS	Near-Infrared Volatile Spectrometer System
NSS	Neutron Spectrometer System
PDF	Probability Density Function
PLAR	Post-Launch Assessment Review
PLZT	Photovoltaic effect of Lanthanum-modified lead Zirconate Titanate
PM	Project Manager
PP	Planetary Protection
RAD	Radiation Assessment Detector
RFA	Request For Action
RIDM	Risk-Informed Decision Making
SIR	System Integration Review
SSD	Solid State Detectors
SSR	System Requirements Review
STM	Science Traceability Matrix

TBD	To Be Decided
TBR	To Be Revised
TRIDENT	The Regolith and Ice Drill for Exploring New Terrain
TRR	Test Readiness Review
TRL	Technology Readiness Level
XRF	X-ray Fluorescence Spectrometer

# **1 SYSTEM REQUIREMENTS REVIEW**

## **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. 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 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. Therefore, the hope is that this cave will host habitable temperatures from day to night. The Rover Environmental Monitoring Station (REMS) and Lunar Lander Neutron and Dosimetry Experiment (LND) devices will be used to assess temperature and a Radiation Assessment Detector (RAD) will record critical radiation data from the pit. Regarding lessons learned from the Compton Pit, an advanced knowledge of lunar caves will be developed in terms of their conditions and what life can survive there. 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 within a short distance surrounding 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. Finding the presence of Silicon, Carbon, and Hydrogen will enhance understanding of the lunar environment in the vicinity of the Compton Pit. The presence of Oxygen and Hydroxyl will also be observed in regions outside the pit in order to decide if this area presents a suitable environment. Comparing data regarding temperature and radiation levels between these surface areas and the lunar pit itself will help draw differences that will 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 just might 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 Apollo Lunar Surface Drill (ALSD) would be a suitable instrument to complete this goal. The system's purpose of gathering core samples to extract soil column samples and to create holes for emplacement of two heat flow probes in the lunar surface (National Air and Space Museum, 2021). The ALSD 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 we can identify surface regions 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, PEREGRIN-1-02). Together, both of these instruments are able to identify the H, O<sub>2</sub>, H<sub>2</sub>O, 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 Oxygen and 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 Anorthitic Plagioclase.	Collect spectral signatures of Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicates, and Anorthitic Plagioclase present 10 cm below the surface in a 3km area.	Drilling Depth:	10cm - 30 cm below the ground	20 cm-30cm	Apollo Lunar Surface Drill (ALSD)	Identify and process lunar resources, including water and oxygen  Develop compatible hardware for extreme lunar environments
				Drilling Speed:	15:21 mm/ss - 23:40 mm/ss	10:43 mm/ss - 13:50 mm/ss		
				Control and Operation:	Cordless, 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:	70°F-530°F	350°F-530°F		
	Determine the amount of solar wind materials, water, and Hydroxyl molecules present in the lunar regolith located around	Identify Hydrogen (H) Oxygen (O <sub>2</sub> ), water (H <sub>2</sub> O), and Hydroxyl (OH) molecules measure the amount of hydrogen-bearing materials near the surface at the landing site	Collect spectral signatures of H, O <sub>2</sub> , H <sub>2</sub> O, and OH in the 10-30 nm range over a 3km area.	Wavelength range:	1600-3400 nm	1300-2500 nm	Near-Infrared Volatile Spectrometer System (NIRVSS) & Neutron Spectrometer System (NSS)	Map out the temperature and changes on the site  Measure subsurface and subsurface water, CO <sub>2</sub> , and CH <sub>4</sub>
				Integration time:	1 s <sup>-1</sup>	712 bits per sample		
				Sensitivity:	Thermal and epithermal neutrons	Thermal and epithermal neutrons		

	and inside the Compton Pit.	to determine the potential for water ice.		Spatial Resolution:	H <sub>2</sub> O: 20-30 nm NH <sub>3</sub> : 10-20 nm CO <sub>2</sub> : 10-20 nm CH <sub>4</sub> : 20-30 nm	<20 nm and <50 nm		Analyze the composition and structure of the surface and subsurface with the detection of neutrons.
<a href="#">Life Support &amp; 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)</a>	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	REIGL 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	Detects temperature measurements between 273K and 373K and radiation levels that exceed 25,000 millirems.	Temperature range:	273-373K	143-343K	Rover Environmental Monitoring Station (REMS)	Collect dosimetry and temperature data in the Compton pit to determine habitability
				Integration time:	TBD1	TBD6		
				Sensitivity:	TBD2	TBD7		
				Spatial Resolution:	TBD3	TBD8		
				Wavelength range:	<400 nm	TBD9	The Lunar Lander Neutron and Dosimetry	
				Integration time:	10s	3598.2s		

		variation.		Sensitivity:	TBD4	TBD10	Experiment (LND)	
				Spatial Resolution:	TBD5	TBD11		

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, we chose pits 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. 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.

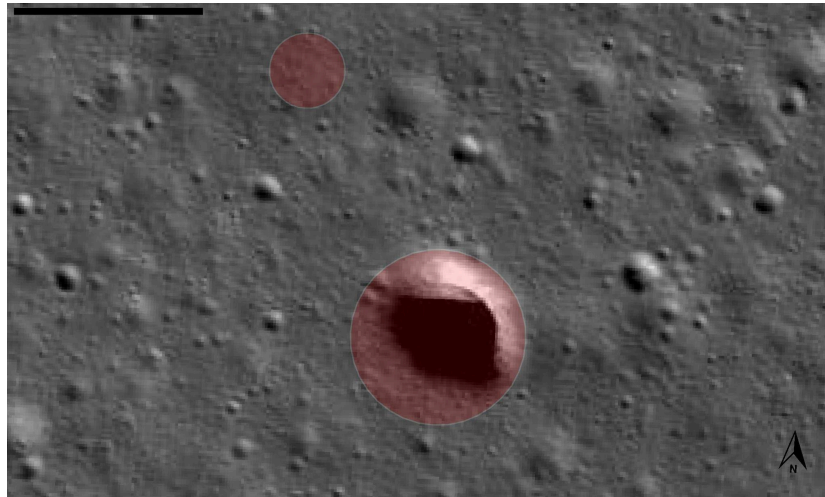


Figure 2: Aerial Compton Pit image.

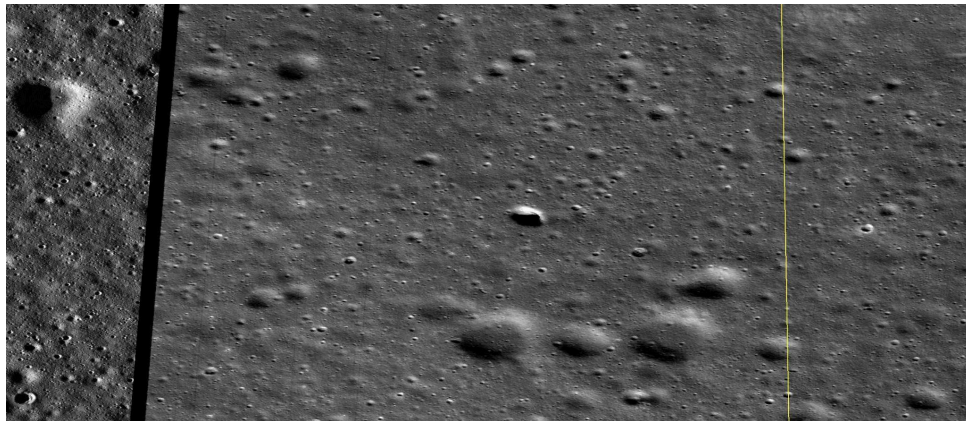


Figure 3: Side view of Compton Pit that shows relative surface area.

Could use more detail on where science data will be collected from -TF

## 1.4 Mission Requirements

The budget for the mission is \$425 million. The schedule for launch is March 1, 2030. The goals for HELP involve hydrogen sampling, mineral sampling, and mapping. HELP will search for hydrogen in rock, and 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, it will use its spectrometer to find other important minerals on the Moon, such as iron and pyroxene.

HELP will also evaluate Compton pit in terms of suitability for human habitation. It will determine whether Compton Pit exhibits a constant temperature throughout the day-night cycle, and whether it can protect humans from solar radiation. It will also map the inside of the pit and gather data to inform next steps in regards to habitation on the Moon.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method
MG.1	Develop precursor lunar robotic missions and define those scientific activities that astronauts will conduct on the Moon.			All	Demonstration
MG.2	Provide safe and enduring habitation systems to protect individuals, equipment, and associated infrastructure			All	Demonstration
PM.1	The mission shall follow all accepted given constraints by the customer while planning for future inspections		MG.1 MG.2	PM.1.1 PM.1.2 PM.1.3	Demonstration
PM.1.1	The mission shall have a cost cap of \$425 to expend		PM.1		Demonstration
PM.1.2	The spacecraft shall be ready for launch by March 1st, 2030		PM.1		Demonstration
PM.1.3	The mission shall prepare and progress through the program's required gate reviews		PM.1		Demonstration
SCI.1	The mission shall determine the readily available amount of Oxygen and metals in lunar regolith near the selected lunar pit/cave	To support in situ resource utilization (ISRU) efforts and prepare for future human missions by analyzing critical elements for life support and construction.	MG 1	SCI.1.1 SCI.1.2 SCI.1.3	Demonstration

SCI. 1.1	The spacecraft shall identify Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicates, and Anorthitic Plagioclase in the regolith.	To identify essential mineral resources needed for oxygen extraction and building materials.	SCI.1		Demonstration
SCI. 1.2	The spacecraft shall collect spectral signatures of Ilmenite, Pyroxene, Olivine, Anorthite, Mg-rich silicates, and Anorthitic Plagioclase.	To verify the presence of key minerals over a 3 km area, enabling resource mapping in the vicinity of the pit/cave.	SCI.1		Demonstration
SCI. 1.3	Spectral data must 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		Demonstration
SCI.2	The mission shall determine the amount of solar wind materials, water, and Hydroxyl molecules present in the lunar regolith near the pit/cave.	To evaluate the potential for extracting water and other essential materials for future missions and habitation on the Moon.	MG.1	SCI.2.1 SCI.2.2	Demonstration
SCI.2.1	The spacecraft shall identify Hydrogen (H), Oxygen (O <sub>2</sub> ), water (H <sub>2</sub> O), and Hydroxyl (OH) molecules in the regolith.	To map the availability of water and essential gasses in the surrounding area, critical for life support and fuel production.	SCI.2		Demonstration
SCI.2.2	The spacecraft shall collect spectral signatures of H, O <sub>2</sub> , H <sub>2</sub> O, and OH molecules 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		Demonstration
SCI.3	The mission shall characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves.	To assess the viability of lunar pits/caves for future human habitation, supporting exploration and habitation goals.		SCI.3.1 SCI.3.2 SCI.3.3	Demonstration

SCI.3.1	The spacecraft shall define the dimensions and deformations of the selected lunar pit/cave.	To create a detailed topographical map of the cave and surrounding area, ensuring it meets the criteria for human habitation and exploration.	SCI.3		Demonstration
SCI.3.2	The spacecraft shall collect and map the dimensions, deformations, terrain, overhangs, and stress points 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		Demonstration
SCI.3.3	The spacecraft shall measure temperature and radiation levels within the cave.	To ensure that the environment is suitable for human habitation, with acceptable levels of radiation and manageable temperature variations.	SCI.3		Demonstration
SCI.4	The spacecraft shall evaluate the viability of lunar caves for long-term human habitation.	To support NASA's Lunar Exploration objectives by exploring the feasibility of using lunar pits/caves as future habitat locations for astronauts.	MG.2	SCI.4.1 SCI.4.2	Demonstration
SCI.4.1	The spacecraft shall assess ease of access to the cave through entrance ramps or slopes.	To ensure that astronauts or robotic systems can access the cave with minimal risk, supporting long-term missions.	SCI.4		Demonstration
SCI.4.2	The spacecraft shall monitor environmental conditions, including potential hazards, in and around the cave.	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.	SCI.4		Demonstration

Figure 4: Mission Requirements Table

## **1.5 System Definition**

### **1.5.1 Spacecraft Overview**

Unfortunately, this section was not able to be thoroughly researched and completed, and must be designated TBR12. Going into the MDR, in-depth drawings will be developed for a top-level overview of the HELP spacecraft, as well as representations of what the individual subsystems will look like as well. These drawings will eventually be reformatted into CAD drawings using Siemens NX CAD software to better visualize the HELP spacecraft. Based on the requirements of the subsystems outlined below, higher-level requirements will be identified that specify the needs of the overall spacecraft. A table will be constructed that includes estimated mass, dimensions, and max power draw for all subsystems to ensure that the spacecraft will remain within customer constraints as well.

## 1.5.2 Mechanical Subsystem

### 1.5.2.1 Mechanical Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MECHANICAL-1	Rover shall meet required design constraints.	It should be able to fit on the transportation vessel.		MECHANICAL-1.1, MECHANICAL-1.2	Inspection	Mechanical	Met
MECHANICAL-1.1	Rover shall not exceed a mass of 350 kg.	It should not be too heavy as this can affect the success of the mission.	MECHANICAL-1		Inspection	Mechanical	Met
MECHANICAL-1.2	Rover shall not exceed the dimensions of 2 m x 1.25 m x 1.25 m.	It should be able to fit as a payload on the transportation vessel without taking up too much space.	MECHANICAL-1		Inspection	Mechanical	Met
MECHANICAL-2	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-2.1, MECHANICAL-2.2	Demonstration	Mechanical	Met
MECHANICAL-2.1	Rover shall be able to descend a slope of .667 degrees.	This is the slope of the lunar pit chosen.	MECHANICAL-2		Test	Mechanical	Met
MECHANICAL-2.2	Rover shall be able to move over different types of terrain.	The environment (rocks, dust, holes, etc.) should not affect the mobility of the rover.	MECHANICAL-2		Test	Mechanical	Met

Figure 5: Mechanical Requirements Table

The mechanical subsystem is still in the very early stages of development. However, many requirements have been defined as of now. The first parent requirement is that the rover shall meet the required design constraints that were given at the beginning of the mission. This is due to the fact that there is limited space on the transportation vessel, and it needs to be able to fit without taking up too much space. Child requirements of this are requirements acknowledging the mass and dimension constraints; the rover is not to exceed a mass of 350 kilograms or the dimensions of 2 m x 1.25 m x 1.25 m. These requirements can be verified by a simple inspection of the dimensions and mass. The second parent requirement is that the rover shall be able to navigate the chosen lunar pit efficiently. This is because it needs to collect both data and samples from the environment, and without being able to move efficiently, it will be unable to do so. The child requirements of this are that the rover should be able to descend a slope of at least .667 degrees as well as withstand many different types of terrain, including rocks, dust, holes, and more. While the JMARS tool is helpful in researching basic information about the Compton Pit, it is unable to recognize every single environmental hazard that exists on the moon, so it would be best to design for these hazards in advance in order to execute this mission to the fullest extent.

A requirements table regarding the aforementioned mechanical requirements and information is provided below.

### 1.5.2.2 Mechanical Subsystem Overview

Unfortunately, no mechanical subsystem overview can be provided at this time that further examines the mechanical subsystem of the HELP spacecraft, so this section must be designated TBR13. Heading into the MDR, hardware materials, protection equipment, seals, and wheels will be researched and outlined to complete HELP's mechanical subsystem design. A table will also be developed that includes a closer look at the mass, dimensions, and max power breakdowns of necessary mechanical subassemblies.

**Helpful sources I found that can help anyone design a mechanical subsystem, all major components can be found within these documents. Can be used for the overview or trade studies. I already completed a trade study for the wheels.**

#### Suspension system

<https://science.nasa.gov/mission/viper/rover-and-instruments/>

- Viper rover ( lunar rover )
- active suspension and independent steering

How to design a lunar rover : look specifically at page 19\* ( chart for mechanical ideas )

[https://www.nasa.gov/wp-content/uploads/2015/06/exploration\\_rover\\_concepts\\_grc.pdf](https://www.nasa.gov/wp-content/uploads/2015/06/exploration_rover_concepts_grc.pdf)

[https://www.nasa.gov/wp-content/uploads/static/history/alsj/a17/A17\\_LunarRover2.pdf](https://www.nasa.gov/wp-content/uploads/static/history/alsj/a17/A17_LunarRover2.pdf)

Lunar rover vehicle design. Lubricant and motor ideas/ trade studies/ examples

<https://www.eng.auburn.edu/~dbeale/ESMDCourse/Chapter6.htm>

Types of wheels ( used for wheel trade study below )

<https://ntrs.nasa.gov/api/citations/20100000019/downloads/20100000019.pdf>

- Types of wheels and trade study for different types of wheels

<https://www3.nasa.gov/specials/wheels/>

- New developments in wire mesh wheels

Sub Assembly	Description	Mass (kg)	Dimension	Max Power
Wire Mesh Wheels				

### 1.5.2.3 Mechanical Subsystem Trade Studies

Mechanical trade studies are unfortunately also TBR14 at this time. In preparation for the MDR and future engineering advancements, trade studies will be conducted for wheels, hardware materials, and seals that help protect spacecraft components from harsh environmental conditions.

Types of Wheels					
Criteria	Explanation	Grade	Weight	Solid Metal Wheels	Wire Mesh Wheels
Cost	The wheels must not exceed the allocated budget for this mechanical sub assembly.	10 = Inexpensive 5 = Medium 1 = Expensive 0 = Fail	25%	7	3
Durability	The wheels must be able to withstand the terrain changes, temperature changes, and obstacles that occur on the lunar surface and within the lunar caves.	10 = High 5 = Medium 1 = Low 0 = Fail	25%	3	8
Mass	The wheels must not exceed the mass specified for this mechanical subassembly.	10 = Low 5 = Medium 1 = High 0 = Fail	25%	4	7
Performance	The wheel must be able to efficiently support the combined loads of the spacecraft while maintaining stability.	10 = High 5 = Medium 1 = Low 0 = Fail	25%	3	9
		TOTALS:	100%	42.50%	67.50%

<https://ntrs.nasa.gov/api/citations/20100000019/downloads/20100000019.pdf>

- Types of wheels and trade study for different types of wheels

<https://www3.nasa.gov/specials/wheels/>

- New developments in wire mesh wheels

### 1.5.3 Power Subsystem

#### 1.5.3.1 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- 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
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 6: 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, we will utilize solar panels. These solar panels should be protected against points of failure caused by harsh environments, or power surges due to sudden increases of sunlight exposure. We will also maximize the amount of energy captured by allowing the solar panel to rotate to face the sun. These solar panels will be connected to numerous batteries throughout the power system. We must ensure these batteries have enough capacity to provide enough power to all components throughout the configuration. Additionally, we must also ensure that these batteries are protected from: overcharge, short circuits, power surges, and other points of failure. 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.

### **1.5.3.2 Power Subsystem 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 our mission. Among the components of this subassembly is the solar panels. 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, our mechanism for orienting the solar panel to face the sun will be a single axis tracking system. To ensure the safety of our solar panels, we will design our solar panels to be deployable. In the event that the surrounding environment is ruled dangerous and may compromise the safety of our 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. Our 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, we will install a vibration mechanism 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 our solar panels as efficient as possible for this mission, we will create these panels from lightweight materials, and utilize multi junction cells. Multi efficient cells are beneficial due to the fact that our 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 our spacecraft will experience times of permanent darkness, it is vital to the mission that our 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. 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 our 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 our 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, we will ensure that the battery satisfies all power requirements for the components that are connected to our 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 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 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. 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.

	Mass	Dimensions	Max Power Draw
Solar Panel	20 kg	1.65m x 1.0m	N/A
Single Axis Tracking Device	8.8 kg	1.2m x 0.115m x 0.2m	12 W
Solid State Battery	20 kg	50 x 30 x 20 cm	N/A
Dual Bus System	5 kg	30 x 20 x 10 cm	10 W

Figure 7: Power Subassembly Specification Breakdown

### 1.5.3.3 Power Subsystem Trade Studies

Criteria	Explanation	Grade	Weight	Solid State Battery	Lithium Ion Battery
Capacity	The capacity of the batteries has to be enough to store ample power to run all the subsystems in the event that the rover ventures into a permanent dark area, until it can navigate back to where it can collect solar energy	10 = high 5 = medium 1 = low 0 = Fail	30%	9	7
Efficiency	Optimizing the amount of power that is going to be usable for the amount that is being used to store it	10 = high 5 = medium 1 = low 0 = Fail	25%	8	8
Temperature Tolerance	Ability to withstand harsh temperature and not having performance inhibited by extreme temperatures	10 = high 5 = medium 1 = low 0 = Fail	25%	8	4
Stability	Fire Risk	10 = high 5 = medium 1 = low 0 = Fail	20%	8	3
		<b>TOTALS:</b>	<b>100%</b>	<b>86.00%</b>	<b>54.50%</b>

Figure 8: The trade study for batteries considered Solid-State and Lithium Ion batteries.

The Power Storage Subassembly needs to store the power collected by the panels for later usage and mitigate the risk of over/underconsumption of power.

The first criteria was capacity is crucial for this mission as our rover intends to venture into areas of permanent darkness, so it is very important to have a battery with high energy density and was assigned 30% weight. The solid state battery doubles the current with higher discharge rates than lithium ion batteries.

Efficiency was weighted at 25%, as the amount of payoff received for energy put in and stored must be efficient to streamline unnecessary expense of power in a risky environment. Both the solid state and lithium ion batteries are efficient batteries that have low self-discharge rates, holding onto the stored power for longer periods of time without losing power.

Temperature tolerance is a risky variable with batteries as it can affect its durability and efficiency, and is weighted at 25%. Lithium ion batteries are not stable under extreme temperatures and the performance would be inhibited unless precautions were taken to combat the temperature wearing on the batteries. While the solid state batteries are more stable when faced with extreme temperatures.

The stability of the battery is vital to the integrity of the power subsystem. To maintain the durability of the lithium ion battery, the system would have to be climate controlled so as to not limit the shelf life and maintain rechargeability, while lithium ion batteries are flammable and can self-ignite under the right conditions. While the solid-state battery mitigates this risk contains no flammable fluid.

## 1.5.4 Computer and Data Handling (CDH) Subsystem

### 1.5.4.1 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	Blank
CDH-1.1	The rover's subsystem should be able to communicate with satellite at 384,400 km and its lander	384,400 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	Blank
CDH-1.2	The rover's subsystem should deliver information at 8.495 GHz frequency	The satellite will be able to gather information from the rover because it has a different frequency and won't get interference	CDH-1		Analysis	CDH	Blank
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	Blank
CDH-2.1	The subsystem should be able to handle and manage the information its retrieved	Constant information 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	Blank

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	Blank
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	Blank
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	Blank

Figure 9: CDH Requirements Table

The computer data handling is in its early stages and helps relevant subsystems such as payload, data handling, and mechanical. The first parent requirement is to make sure the rover has an instrument in order to send and receive information in order to communicate with Mission Control. Without this subsystem working, there would be no way to know whether or not if subsystems are operational and receive data samples. This requirement can be verified via testing. The second parent requirement for the rover is its method of handling and gathering information in each of its respective subsystems. In order for subsystems to work interchangeably, it would need its child requirement, an Onboard Computer (OBC), responsible for tracking mission data and communicating with Mission Control. This parent requirement will be tested with demonstration. In addition, in case any subsystem gets compromised, a battery backup will also be installed to make sure it will be able to send what sample data it could've collected with the remaining power and inform Mission Control, this will be tested with demonstration.

The rover has its own sub-requirement: it has a storage unit for gathering data samples and retrieving information, which is required for collecting lunar samples. The rover will be equipped with a storage unit and the method will be tested through inspection.

There are several subsystems that interlink with computer data handling, but it is still in the early stages of development, there will be more relevant subsystems in the near future. The CDH requirements table is shown below with current relevant information.

#### **1.5.4.2 CDH Subsystem 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 High Gain (X-band) antenna 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.

#### **1.5.4.3 CDH Subsystem Trade Studies**

Unfortunately, at this time no trade studies have been conducted for the CDH subsystem, therefore this section has been designated TBD19. Heading into the MDR, studies will be conducted that consider communication pathways to be established between the rover and Mission Control, types of antennas to implement on the rover, and computer processing algorithms that help handle the surplus of data recorded from payload instruments.

## 1.5.5 Thermal Management Subsystem

### 1.5.5.1 Thermal Management Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
THRM- 1	Maintain a sufficient temperature range inside of the spacecraft in order for all electronics and equipment to properly operate	Any extreme temperatures may cause our electronics/ equipment to fail and put our 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, we will have a backup installed to replace the broken component	SYS-1.2		Test	////////	Met
RET- 1	Prevent the interior temperature of the spacecraft from dropping too low	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 we must adhere by	RET- 1	RET- 1.1.1, RET- 1.1.2	Inspection	Thermal	Met
RET- 1.1.1	The components of the spacecraft will be painted with a reflective coating	The components coated in a reflective painting will be able to reflect radiation and minimize heat loss	RET- 1.1		Inspection	Thermal	Met
RET- 1.1.2	Surfaces of the spacecraft will be covered with MLI	The surfaces of our 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 will have heating systems installed inside to heat the interior	Heaters will help balance the internal temperature of the spacecraft should the temperatures ever drop too low.	RET- 1	RET- 1.2.1	Inspection	Mechanical	Met
RET- 1.2.1	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 the amount of heat within the spacecraft in order to prevent overheating	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	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	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	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 radiators installed throughout	Assist in dissipating excess heat from within the interior	REL-1	REL- 1.2.1	Inspection	Mechanical	Met
REL- 1.2.1	The radiators located throughout the spacecraft should be retractable	Retractable radiators will assist in the flexibility required in maintaining balance in internal temperature	REL- 1.2		Inspection	Mechanical	Met

Figure 10: Thermal Requirements Table

The main requirement for the thermal management system is to maintain a specific temperature range 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 our 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. We can meet this requirement by utilizing reflective coating on our components, as well as applying MLI to the surfaces of the spacecraft. On the other hand, we also must ensure that the temperature does not climb too high. To meet this requirement, we will install a system of heat and fluid pipes to transfer heat away from hot spots within the spacecraft. We will also have radiators installed to complement the heat and fluid pipes. These radiators will serve as the end points of our pipes, where the radiators will help dissipate excess heat within the spacecraft.

#### **1.5.5.2 Thermal Management Subsystem Overview**

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

It is vital to the integrity of the mission that the thermal management system prevents overheating of components within the spacecraft. To combat this, we have several components that help disperse and release heat. 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. 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. 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. The radiators on our 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. As with other subsystems in the spacecraft, the cooling system must be fully autonomous and controlled by the spacecraft. We will also utilize reflective coatings and MLI on our components exposed to space. The goal of these coatings will be to reduce the amount of energy absorbed by these components. 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. We began by installing a heat exchanger to 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, we will also have numerous heaters installed throughout the spacecraft. 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 our 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, we must utilize sensors throughout the different systems. We will strategically place sensors in various parts of the interior, such as near our centralized power distribution unit, our 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. We will utilize thermocouples in order 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.

Within our thermal subsystem, an active heating and cooling system will be implemented to further guarantee mission success when it pertains to keeping the electronics and payloads within our 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 7-9 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  $1.56 \text{ W/cm}^2$  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  $-200 \text{ C}$  to  $200 \text{ C}$ . A closed loop temperature feedback will be implemented to help regulate the temperature within the spacecraft (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 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 (NASA 2024).

<b>Sub Assembly</b>	<b>Description</b>	<b>Mass (kg)</b>	<b>Dimension</b>	<b>Max Power</b>
MLI Coating	Passive Thermal System	3.0 kg	1.5 x 0.75 x 0.75	0 W
Adhesive Tape	Passive Thermal System	0.5 kg	-	0 W
Thermal Switch	Passive Thermal System	0.110 kg	10 x 5 x 3 cm	6 W
Omega Polyimide Heater Kit	Active Heating System	0.2 kg	-	1.56 W/cm <sup>2</sup>
Thermoelectric Coolers	Active Cooling System	0.2 kg	4 x 4 cm/ unit	7.7 W
Fluid Loops	Active Cooling System	1.5 kg	2m total	2.38 mW/cm <sup>2</sup>
Radiators	Passive Cooling System	2.5 kg	50 x 25 cm/unit	0 W
Thermocouples	Passive Thermal System	0.1 kg	2 cm/unit	0 W

Figure 11: Subassemblies of the Thermal Subsystem

### 1.5.5.3 Thermal Management Subsystem Trade Studies

Types of Coating for Thermal System						
Criteria	Explanation	Grade	Weight	Matte White Paint	MLI Coating	Adhesive Tapes
Cost	The thermal components of the rover cannot exceed the specified budget for the thermal subsystem.	10 = Inexpensive 5 = Medium 1 = Expensive 0 = Fail	15%	4	4	9
Lower IR Emissivity	Lower IR emissivity minimizes heat loss through radiation and allows for heat to be retained in cold lunar environments.	10 = Low 5 = Medium 1 = High 0 = Fail	35%	2	9	3
Low Solar Absorptivity	Low solar absorptivity minimizes how much heat is absorbed through solar radiation which can overheat the electronics within the spacecraft.	10 = Low 5 = Medium 1 = High 0 = Fail	35%	9	8	9
High Durability	High durability from thermal system assembly to operational use saves time and money while ensuring the system's success.	10 = High 5 = Medium 1 = Low 0 = Fail	15%	5	5	7
		TOTALS:	100%	52.00%	73.00%	66.00%

Figure 12: Thermal trade study that assesses different types of coating insulation for the thermal subsystem.

The trade study for different types of coating for a thermal subsystem include matte white paint, MLI coating, and adhesive tapes. Based on the requirements for this mission, the criteria selected to compare each type of coating was having low cost, low IR emissivity, low solar absorptivity, and high durability (NASA 2024).

Cost was given a weight of 15% because the thermal components cannot exceed the specified budget allocated for the thermal subsystem. However, passive cooling systems tend to be more on the inexpensive side when it comes to designing a thermal subsystem. Adhesive tapes were the most inexpensive option compared to the other types of coatings because they are typically easier to apply and remove making the application process significantly cheaper. Matte white paint and MLI coatings cost more due to the material itself and the process of applying them to the spacecraft (NASA 2024).

Having a lower IR emissivity was given a weight of 35% because having the ability to minimize heat loss through radiation is crucial when exploring the lunar cave where the temperatures tend to be colder than the surface temperature in direct sunlight. MLI coatings had the lowest IR emissivity due to its many layers of reflectors limiting radiative heat transfer. Matte white paint and adhesive tapes had high IR emissivity due to their ability to emit spacecraft thermal energy efficiently (NASA 2024).

Having a low solar absorptivity was also given a weight of 35% because the high fluctuations of heat from the direct sunlight can overheat the electronics and payloads within the spacecraft. This can jeopardize the success of the mission and prevent important data from being collected by the spacecraft. Each type of coating had a low solar absorptivity due to its ability to reflect sunlight efficiently (NASA 2024).

High durability was assigned a weight of 15% because maintaining durability from assembly to operational use saves time and money, while ensuring the thermal system's overall success. Adhesive tapes had the highest durability rating compared to the other types of coating and are easier to replace if they get damaged during the assembly process. However, some tapes are more susceptible to UV rays and atomic oxygen bombardment which can increase the solar absorptivity values. Matte white paint has less durability compared to adhesive tapes and slightly less than MLI coatings. MLI coatings have a durable outer layer, however, the inner layers are delicate and the performance drops drastically if the coating is compressed (NASA 2024).

Based on the trade study that compared different types of coatings for a thermal system, a combination of MLI coatings and adhesive tapes will be used to provide the best results for the requirements of this mission. MLI coatings are used as a thermal radiation barrier to both protect from solar and IR flux, while also preventing undesired radiative heat dissipation. Internal MLI blankets that are not exposed to solar radiation can be replaced with adhesive tapes that have a higher value-to-weight ratio, while also maintaining the same performance levels (NASA 2024).

Types of Kapton Electrical Heaters						
Criteria	Explanation	Grade	Weight	Polyimide Heater Kit	Polyimide Thermofoil HK Series	KPH, KPM Series
Size	The size of the heater must meet the size constraints allocated for the thermal subsystems. Multiple sizes and shapes can be beneficial when manufacturing the thermal subsystem.	10 = Within constraints and multiple shapes 5 = Within constraints 0 = Fail	10%	10	5	5
Power Consumption	The power consumption must be kept as minimal as possible to conserve power for the other electrical and payload components. Too much power consumption can also cause the system to overheat.	10 = Low 5 = Medium 1 = High 0 = Fail	30%	10	5	10
Internal Temperature Stability	Internal temperatures must be maintained at optimal operating temperatures (around 20°C) to prevent system failure.	10 = Maintains internal temperature 0 = Fail	30%	10	10	10
Structural Integrity	The heater must be able to withstand the different fluctuations of temperatures from the lunar surface at peak sunlight (121°C), night time (-133°C), and within the lunar cave (-17°C).	10 = Withstand all temperatures 5 = Withstand most temperatures 0 = Fail	30%	10	10	10
		TOTALS:	100%	100.00%	80.00%	95.00%

Figure 13: Thermal trade study that assesses different types of Kapton electrical heater for the thermal subsystem.

The trade study for different types of Kapton electrical heaters include the Omega Polyimide Heater Kit, the Minco Polyimide Thermofoil HK Series, and the Chromalox KPH, KPM Series. Based on the requirements for this mission, the criteria selected to compare each type of Kapton electrical heater was size, power consumption, internal temperature stability, and structural integrity (NASA 2024).

Size was given a weight of 10% because the size of the heater must meet the size constraints allocated for the thermal subsystem. All of the electrical heaters are relatively small compared to each other, therefore, the criteria was given a small weight percentage. Multiple sizes and shapes can be beneficial when manufacturing the thermal subsystem. The Polyimide Heater Kit received the highest score because it met the constraints for the system and it comes in various shapes to optimize the design in regards to the limited space within the thermal subsystem itself. Both the Polyimide Thermofoil HK Series and the KPH KPM Series met the constraints for the system, however, did not come in various shapes or sizes (NASA 2024).

Power consumption was given a weight of 30% because it must be kept as minimal as possible to conserve power for the other electrical and payload components. Too much power consumption can also cause the system to overheat. Both the Polyimide Heater Kit and KPH KPM Series had power ranges from 0.4 to 1.56 W/cm<sup>2</sup> which is on the low end of power consumption. The Polyimide Thermofoil HK Series had a higher power consumption range which was from 0.8 to 5.1 W/cm<sup>2</sup> (NASA 2024).

Internal temperature stability was given a weight of 30% because the spacecraft must maintain optimal operating temperatures ( around 20C ) to prevent system failure (NASA 2004). All three types of Kapton electrical heaters are able to maintain an optimal operating temperature for the spacecraft to function normally and efficiently (NASA 2024).

Structural integrity was given a weight of 30% because the heater must be able to withstand the different fluctuations of temperatures from the lunar surface at peak sunlight (121C), night time (-133 C), and within the lunar cave (-17 C) (Steigerwald 2022). All three Kapton electrical heaters had a temperature range from -200C to 200C which were able to withstand the different fluctuations of temperatures from the lunar surface and within the lunar cave (NASA 2024).

Based on the trade study that compared different types of Kapton electrical heaters, the Omega Polyimide Heater Kit produced a perfect score and will be used within the spacecraft's thermal subsystem.

Types of Active Cooling Systems						
Criteria	Explanation	Grade	Weight	Cryocoolers	Thermoelectric Coolers (TEC)	Fluid Loops
Size and Compactness	The size and compactness of the cooling system must meet the size constraints allocated for the thermal subsystems.	10 = Compact, within constraints 5 = Within constraints 0 = Fail	25%	5	9	5
Power Consumption	The power consumption must be kept as minimal as possible to conserve power for the other electrical and payload components. Too much power consumption can also cause the system to overheat.	10 = Low 5 = Medium 1 = High 0 = Fail	25%	3	10	5
Internal Temperature Stability	Internal temperatures must be maintained at optimal operating temperatures ( around 20C ) to prevent system failure.	10 = Maintains internal temperature 0 = Fail	20%	10	10	10
Cooling Capacity	The cooling system must have a cooling capacity greater than 5W.	10 = Withstand all temperatures 5 = Withstand most temperatures 0 = Fail	30%	10	10	10
		TOTALS:	100%	70.00%	97.50%	75.00%

Figure 14: Thermal trade study that assesses different types of active cooling systems for the thermal subsystem.

The trade study for different types of active cooling systems include cryocoolers, thermoelectric coolers, and fluid loops. Based on the requirements for this mission, the criteria selected to compare each type of active cooling systems include size and compactness, power consumption, internal temperature stability, and cooling capacity.

Size and compactness was given a weight of 25% because the cooling system must meet the size constraints allocated for the thermal subsystems. The thermoelectric coolers met both requirements of being compact and having a small mass. Both the cryocoolers and fluid loops met the requirement for meeting the size constraint, however, these systems are not as compacted as the thermoelectric coolers. Being able to fit all of the thermal subassemblies within the thermal subsystem is a high priority of this design (NASA 2024).

Power consumption was given a weight of 25% because it must be kept as minimal as possible to conserve power for the other electrical and payload components. Too much power consumption can also cause the system to overheat. Thermoelectric coolers had a significantly less amount of power consumption than the other two systems. Cryocoolers consumed the most power out of all three cooling systems averaging 5.5 W to 80 W (NASA 2024).

Internal temperature stability was given a weight of 20% because the spacecraft must maintain optimal operating temperatures ( around 20C ) to prevent system failure (NASA 2004). All three types of active cooling systems are able to maintain optimal operating temperatures for the internal system of the spacecraft (NASA 2024).

The cooling capacity was given a weight of 30% because the system must have a cooling capacity greater than 5W. All three types of active cooling systems are able to produce a cooling capacity greater than 5W and can range depending on the type and size of system used (NASA 2024).

The requirements for this mission are more focused on conserving heat than they are to increase cooling within the spacecraft. Based on the trade study that was conducted, cryocoolers are not needed for this thermal system. It consumes more power because it is producing more cooling for the system. The thermoelectric coolers and fluid loops are both compact and consume less power, while still producing cooling for the system when needed. Therefore, thermoelectric coolers and fluid loops will be used within this system (NASA 2024).

## 1.5.6 Payload Subsystem

### 1.5.6.1 Payload Subsystem Requirements

The Near Infrared Volatile Spectrometer System (NIRVSS) is designed to measure subsurface and surface water, carbon dioxide, and methane (NASA, PEREGRN-1-01). The system will map out the temperature and the changes occurring at the site. The primary purpose is to characterize the lunar composition of the Compton Pit. The instrument shall consist of a bracket assembly and a spectrometer box that holds one short-wave (1200-2400 nm) and one long-wave (2300-400 nm) that is connected by cables and mounted on the lander payload deck (NASA, PEREGRN-1-01). The short wave spectrometer shall have a spectral resolution  $<20$  nm and the long-wave  $<50$  nm. The total mass of the instrument is 3.57 kg and draws a nominal power of 30 W and will make measurements throughout the lunar day and night to monitor changes in the surface composition, solar illumination, surface thermophysical responses, and in the surface reflectance properties. NIRVSS shall continuously collect imaging, spectral, and surface temperature measurements during rover traverses between science stations (Roush, et. al.). The system should operate in various environmental conditions throughout the day to collect data and withstand expected radiation levels.

The NSS shall utilize a combination of local thermal and epithermal neutron flux to cover the specified energy range. The neutron spectrometer shall be capable of detecting and analyzing neutron flux in the energy range of  $<0.3$  eV for the local thermal neutron flux and 0.3 eV to 1 keV for the epithermal neutron flux (NASA, PEREGRN-1-02). A neutron spectrometer is designed to detect neutrons from three energy bands: thermal (average energy of about 0.025 eV), epithermal (between 0.025 and 1 eV), and fast neutrons (Falkner and Schulz, 2007). The instrument has two gas-proportional counter (GPC) sensors that are filled with helium-3, which gives the thermal neutron flux. The system shall have a minimum spatial resolution of 20 nm to collect CO<sub>2</sub>. The neutron spectrometer will be integrated into a larger payload and must meet size, weight, and power constraints defined in the overall payload specification. The sensor module is 21.3 x 32.1 x 6.8 cm, the data processing module is 13.9 x 18.0 x 3.0 cm and must have a mass of 1.6 kg and use 1.5W power (NASA, PEREGRN-1-02). The system should be operable in different environmental conditions, such as extreme temperatures and radiation levels.

The Lunar Lander Neutron and Dosimetry Experiment (LND) system uses a stack of 10 silicon SSD to detect energies from incident particles and waves. LND's sensor head uses gold and aluminum plating in order to absorb particles between certain detectors in order to determine at which detector each particle was able to pass through and where the particles were absorbed. Doing this, lets LND record information on the energy of particles, which is then put into an "xmas plot", the way LND stores data during data collection. The LND system is required to record dangerous radiation levels in order to determine the Comptons Pit potential for habitation. For this, LND needs to measure dangerous radiation spectra, which occurs  $< 400$  nm wavelengths. LND records data for thermal neutrons, fast neutrons, Gamma radiation, charged ions, and charged particles such as GCR and electrons. This spans the required set of

particles needed to measure to determine the habitability of Compton Pit. One of Chang E4's mission objectives was to determine radiation levels for human habitability, so this device is adequate.

Rover Environmental Monitoring Station (REMS) measures atmospheric pressure, temperature, and ultraviolet radiation levels. This system will measure the temperature in the Compton Pit, and providing UV radiation data will add extra redundancy in LND's measurements. REMS can work properly in a temperature range needed for Compton and record temperature data in the required temperature range.

The LiDAR system will have a range of 200m, will have less than a kilogram of mass, and will be able to take more than 100,000 measurements per second. This is due to the expected dimensions of the pit, velocity of the rover, and the expected deformations of the pit. The system should also be able to withstand unexpected temperature fluctuations given the little data collected about the temperature inside the pit.

Unfortunately, no payload requirements table is present at this time, so it must therefore be designated TBR33. These requirements will be outlined as soon as possible in order to base other system requirements based on what is needed to obtain the necessary science measurements. These payload requirements will be based on specifications outlined in the STM.

#### **1.5.6.2 Payload Subsystem Overview**

The Near Infrared Volatile Spectrometer System (NIRVSS) instrumentation system and the NSS system both aid to determine the amount of solar wind materials, water, and Hydroxyl molecules present in the lunar regolith located near or within the Compton Pit. The Near Infrared Volatile Spectrometer System (NIRVSS) uses near-infrared spectroscopy to detect and analyze volatile compounds in the environment. 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. 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). The system will provide critical data for exploration and understanding the potential habitability and understanding the geology of the Compton Pit.

During pre-launch NIRVSS will be powered to confirm system health and functionality but will not be powered during launch, orbital, or landing phases (Roush, et. al.). The real time data processing and spectral analysis will allow efficient data handling during missions. During cruise, NIRVSS will perform a full functional check and instrumental breakout and will observe a calibration plate before the rover leaves the lander (Roush, et. al.). The system is engineered to withstand environmental conditions during launch and operation, ensuring the continuous collection of imaging, spectral, and surface temperature measurements during rover traveling between space stations. The TRL scale ranges from 1 (basic principles observed) to 9 (system proven successful through mission operations). Currently, NIRVSS is at TRL 6 meaning that the

technology has been demonstrated in the relevant environment, such as during the VIPER lunar mission and a prototype is being tested to confirm its performance.

The Neutron Spectrometer 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). It is designed to analyze the composition and structures of these bodies' surfaces and subsurfaces by detecting neutrons. Each sensor produces a 32-channel (1-byte deep) spectrum, once per second (NASA, PEREGRN-1-02). It will accurately measure thermal, epithermal, and fast neutrons to collect information of the composition of the surface and subsurface of the Compton Pit. Since the NSS has been used in other missions such as the Mars Odyssey mission, it has proven its ability to collect data, providing a TRL level of 7 (Falkner and Schulz, 2007). It has proven to be functional in other missions but has not been tested for this specific rover. The prototype was tested in a relevant environment and there are plans to continue testing and validation.

For HELP to complete its mission requirements, it must be able to define the dimensions and deformations of Compton Pit. To do so, it will use a LiDAR system to accurately measure the interior of the pit. After research, two candidates were chosen: the REIGL VZ-400 V-Line 3D Terrestrial Laser Scanner and a Frequency Modulated Continuous Wave (FMCW) LiDAR system, used in the backpack-mounted KNaCK system. The two options were chosen due to their high TRL and portability. A trade study was conducted between the two options, and the REIGL VZ-400 V-Line 3D Terrestrial Laser Scanner was chosen due to a higher TRL, need for less modifications, weight, and resistance to environmental conditions (Miller et al.).

The REIGL VZ-400 V-Line 3D Terrestrial Laser Scanner has a TRL of 6. The system has a nominal range of up to 450m. Set to the preset PAN20 and PAN40 scanning profiles, the TLS can achieve a precision of 3mm and an accuracy of 5mm, with horizontal point spacing of 4mm and 7mm at a distance of 100m respectively (Garry, et al.). The view of the TLS is 100 degrees vertically and 360 degrees horizontally. It also contains an on-board inclination sensor of  $\pm 10$  degrees, with an accuracy of  $\pm 0.008$  degrees. The minimum range of the scanner is 1.5m, and the laser beam divergence is 0.3 mrad. The effective measurement rate in high-speed mode is 122,000 measurements per second, while the scan speed varies in the vertical direction from 3 to 120 lines per second while the horizontal scan speed varies between 0 to 60 degrees per second .

The input voltage of the TLS is 11-32 V of DC current, while the power consumption is on average 65W, with a maximum of 80W. It is cylindrical in shape, with a radius of 90mm and a length of 308mm. It weighs approximately 9.6 N on Earth, which gives it a mass of approximately 0.97893 kg. It is considered dust-proof, and when in storage can endure temperature extremes from -10C to 50C, and can operate under standard conditions at 0C to 40C. At low temperature conditions, it can scan continuously at temperatures of -20C given an internal temperature of 0C or higher, and can operate at -40C for 20 minutes given an internal temperature of 15C or higher. This indicates that insulation will be necessary from landing until Compton Pit is reached (Garry, et al.).

LND 'The Lunar Lander Neutron and Dosimetry Experiment' is an radiation measurement instrument integrated on Chang'E lunar lander 4 during the December 2018 launch and recorded radiation on the dark side of the lunar surface in January 2019, when the lunar rover landed on the von Kármán crater.

LND consists of a sensor head containing a stack of 10 silicon SSDs labeled A-J, each detector of 500  $\mu\text{m}$  thickness, an electronics box which contains the LVPS, FPGAs, and other analog electronics necessary for the sensor head to be operational, and connected to the ICU of the rover to allow for data acquisition. The LND electronics box temperature lies in a range of -20 to 55  $^{\circ}\text{C}$  when actively taking data. The temperature of the sensor head circuitry is higher than in the electronics box.

The silicon detectors in the sensor head are sandwiched in order to capture radiation data of incoming particles from the telescope opening of the sensor head. This gives a full energy range for the penetrative flux of the particles incident through the SSDs in the telescope opening over the angle the detectors span. The telescope opening is  $29.4^{\circ}$  in which it can measure incident particle radiation, based on the edge lengths of the inner (A/B) outer (I/J) SSDs in the detector stack. 20  $\mu\text{m}$  gold (Au) plating is inserted between E/F and G/H respectively in order to absorb thermal neutrons between the detectors to accurately record data from thermal neutrons. A 500 $\mu\text{m}$  aluminum (Al) plating is similarly inserted in the midpoint of the SSD stack to shield from thermal neutrons incident from the opposite direction they are being measured in by either the E/F or G/H detectors stacks.

The sensor head is tilted 13 degrees with respect to the zenith direction while data is being recorded. The telescope is covered by a thin Kapton foil, 50.8  $\mu\text{m}$  Kapton, 25.4  $\mu\text{m}$  Al thickness, in order to protect the telescope device. This thickness leads to minimal energy loss in recorded data, although the shielding this provides can be accounted for in energy calculations. LND uses an "xmas plot" in order to quantify energy of particles incident on the detector stack. This plot is made by seeing how the individual detectors measure if a certain particle has penetrated or not, giving data in which detector particles were able to penetrate and where they were stopped.

Neutral particles (thermal neutrons, fast neutrons, gamma radiation) are measured individually in the detector stack. The LND SSD stack is capable of stopping ions based on how much energy they have and lose by interacting with each detector, as long as they have more energy than the first detector (B or J) in the SSD stack: i.e protons in a 9.0-34.5 MeV range, various  $^3\text{He}$  and  $^4\text{He}$  ions, CNOs, and heavy ions. The data will be recorded on the SSD stack depending on where the particles are stopped in the SSD stack. LND can also measure high penetration radiation (GCR, electrons) by detecting which particles are detected (penetrate) through the entire SSD stack. Electrons have a lower penetration ability than GCR, leading to some energy loss. SSD detects electrons based on energy loss in the detector stack, measuring electrons as long as they have 300keV to penetrate the first detector in the stack (B). From this information, dosimetry can be calculated from the energy of the particles incident on the detector stack and the frequency of measurements in time (dose rate).

LND has a very high TRL of level 9. LND was recently successfully used in the 2019 Chinese lunar rover on rover Chang' E4, recording radiation data on the moon over the course of 13 days. This mission provided radiation results for the particles and rays above. Change' E4 was the first mission to record the radiation on a lunar surface with a lunar rover and not an instrument equipped on an orbital satellite or while in space flight.

REMS is designed to collect 6 parameters of temperature on the martian surface. REMS is a subsystem of the Curiosity rover which landed on Mars in 2011. REMS includes 2 separate instruments, called 'BOOM 1' and 'BOOM 2', which are to be placed on the rover in order to collect wind speed and direction, atmospheric pressure, relative humidity, ground and air temperature, and UV radiation data. BOOM 1 has wind sensors and humidity sensors while BOOM 2 has ground temperature sensors. The 1st instrument which records wind data points to the left on the rover in order for the 3 wind sensors, equally spaced 120 degrees apart on the BOOM to record wind data. The 2nd BOOM records ground temperature using a thermopile which looks at the lunar surface. This thermopile can record temperatures in a range of 150 - 300K, with a resolution of 2K and an accuracy of 10K.

This thermopile can be replaced with a higher temperature thermopile in order to reach the desired temperature range of 273 - 373 K for the Compton Pit mission. BOOM 2's humidity sensor is protected by dust inside a thin cylinder. It can measure humidity data from 200 - 323 K with a resolution of 1%. The BOOMS are to be placed at least 1.5m above the ground on the rover, with an offset between BOOM placement in order to not have the sensors on the BOOMS interfere with each other. Additionally, the thermopile in BOOM 2 will have to extend to have the sensor able to gather information about the ground temperature of the lunar pit. Data is sent without the requirement of manual input in 5-minute intervals every hour at 1Hz while REMS is active. The UV sensor on REMS is optimized to record UV spectra data through 6 photodiodes optimized to record data along the UV spectra seen on Mars where the Curiosity rover employing Mars was deployed.

These photodiodes do not have dust protection and include redundancy through the intervals some of the photodiodes record data over. The photodiodes point in the zenith direction with a range of 60 degrees for data collection of incident UV waves. These photodiodes are monitored through imaging to determine degradation via dust overtime, although for the short term Compton lunar mission, long term preservation of the photodiodes is not necessary. The UV spectra range of the photodiodes can be altered to be optimized for a lunar mission. REMS has a high TRL 9. It has been used in previous missions, although these have been Martian missions and not lunar missions. This makes REMS a candidate, although optimization is required for parameters given in the lunar environment compared to the Martian mission of Curiosity. The thermistor and humidity sensor need their data collection range of data to be optimized for a lunar mission. The interval of recorded data can be changed to be shorter to reflect a short-term rover mission instead of a long term mission that the Curiosity rover performed to record more temperature, humidity, pressure, and UV radiation data over the rover's active period.

<b>Instrument</b>	<b>Dimensions: (mm)</b>	<b>Mass (g)</b>	<b>Power draw (W)</b>
REIGL VZ-400 V-Line 3D Terrestrial Laser Scanner	Cylinder: Radius 90mm, length 308mm	9789.3	65-80
NSS	Sensor Module: 213 mm x 32.1 mm x 68 mm Data Processing Module: 139 mm x 180 mm x 30 mm	1600	1.5
Apollo Lunar Surface Drill	580 mm x 240 mm x 120 mm	1340	430
NRVSS	Spectrometer: 180 mm x 180 mm x 85 mm Bracket Assembly: 204 mm x 130 mm x 151 mm	3570	30
LND	Sensor Head: 101mm x 115mm x TBD34 Electronics Box: TBD35	TBD37	TBD38
REMS	TBD36	1200	Thermopile: .33 over course of active period of a day

Figure 15: Subassemblies of Payload Subsystem

### 1.5.6.3 Payload Subsystem Trade Studies

Spectrometry Systems						
Criteria	Explanation	Grade	Weight	The Near-Infrared Volatile Spectrometer System (NIRVSS)	The Neutron Spectrometer System (NSS)	X-Ray Fluorescence (XRF)
Size	Less weight on the system decreases stress of vehicle	10 = high, 5 = medium 1 = low 0 = Fail	20%	7	7	6
TRL	Assess mass, environmental resistance, modifications, test performance	10 = high, 5 = medium 1 = low 0 = Fail	35%	6	7	6
Environmental Adaptability	Increases the longevity and reliability of the instrument.	10 = high, 5 = medium 1 = low 0 = Fail	30%	10	10	10
Calibration Needs	Indirectly relates to TRL level, the less need for calibrations, the higher the score	10 = high, 5 = medium 1 = low 0 = Fail	15%	6	8	2
		<b>TOTALS:</b>	<b>100%</b>	<b>74.00%</b>	<b>80.50%</b>	<b>66.00%</b>

Figure 16: Trade Study for Spectrometry Systems

For HELP to complete its mission requirements, the surface and subsurface water, CO<sub>2</sub> and CH<sub>4</sub> have to be measured and the composition and structure also need to be analyzed. To fulfill the requirements, a spectrometry system would be the most beneficial to analyze the surface materials and its composition. Given the research conducted, the Near-Infrared Volatile Spectrometer System (NIRVSS) and the Neutron Spectrometer System (NSS) were the most suitable for the mission. These systems are able to map out the changes on the site and measure and analyze the surface and subsurface material and water using near-infrared spectroscopy and the detection of neutrons. For comparison, the X-Ray Fluorescence (XRF) varies in size and has a lower TRL so it isn't the best option compared to the NIRVSS and NSS systems. The biggest downside of the XRF is the calibration needs. It would be difficult to continuously obtain data since it needs to be calibrated frequently. Given the research conducted, the most suitable candidates for this mission. A trade study was conducted for these two systems, assessing their size, TRL, environmental adaptability, and calibration needs. They have similar results; however, the NSS received a better rating for TRL and calibration, meaning it has been proven to be more reliable and functional during missions.

LiDAR Systems					
Criteria	Explanation	Grade	Weight	REIGL VZ-400 V-Line 3D Terrestrial Laser Scanner	FMCW LiDAR System
Mass	kg; less mass on craft decreases budget and stress on vehicle	10 = high, 5 = medium 1 = low 0 = Fail	30%	10	6
TRL	Encompasses mass, environmental resistance, and modifications, among other factors	10 = high, 5 = medium 1 = low 0 = Fail	40%	8	6
Environmental resistance	Increases long-term usability of instrument, measured through quality of parts added for rust and radiation resistance	10 = high, 5 = medium 1 = low 0 = Fail	20%	6	6
Need for modifications	Directly correlates to TRL level, inversely correlates to budget	10 = high, 5 = medium 1 = low 0 = Fail	10%	9	7
		TOTALS:	100%	83.00%	61.00%

Figure 17: Trade Study for LiDAR Systems

The rover must also be able to define the dimensions and deformations of Compton Pit. To do so, it will use a LiDAR system to accurately measure the interior of the pit. After research, two candidates were chosen: the REIGL VZ-400 V-Line 3D Terrestrial Laser Scanner and a Frequency Modulated Continuous Wave (FMCW) LiDAR system, used in the backpack-mounted KNaCK system. The two options were chosen due to their high TRL and portability. A trade study was conducted between the two options, and the options were weighed based on TRL, need for modifications, mass, and resistance to environmental conditions. This is because of a reduced budget and a flexible mission window. The REIGL VZ-400 V-Line 3D Terrestrial Laser Scanner won on all counts.

Trade studies are yet to be completed for all of the payload devices, however, potential devices have been outlined that will help meet the science requirements outlined in Figure 1. These potential devices have also been specified in Figure 1 for reference, including the Lunar Lander Neutron and Dosimetry Experiment (LND), Rover Environmental Monitoring Station (REMS), and Apollo Lunar Surface Drill (ALSD).

### **1.5.7 Recovery and Redundancy**

Unfortunately, not every system has established recovery and redundancy protocols. These subsystems include mechanical and computer and data handling. These have both been assigned TBR38 and TBR39, and will be addressed as soon as possible in order to ensure the success of this mission.

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.

Several redundancies have been installed into the power system in order to ensure that the integrity of the mission is not compromised. For starters, we will be implementing a dual bus system. The primary bus serves to provide power to the components, while the secondary bus serves as a backup in case the primary bus fails. We have also implemented redundancies on our 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. Because the spacecraft has the ability to operate the power system fully autonomously, a low power mode has been installed. Whenever the solar panels are not receiving adequate energy and the power storage begins to run low, the spacecraft may enter low power mode. This low power mode is designed to ensure that only critical loads are receiving power, such as communication technology and navigation.

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.

### **1.5.8 Interface Control**

While an N<sup>2</sup> chart has been provided that displays a top-level overview of the HELP mission subsystems interfacing with one another, no narrative or block diagram can be provided at this time that explains further in detail how the spacecraft will work. Hence, the narrative has been assigned TBR40, and the block diagram TBR41. Both of these will be further expanded on going into the future assignments to better an understanding of the rover as a whole, and be sure that it will function properly.

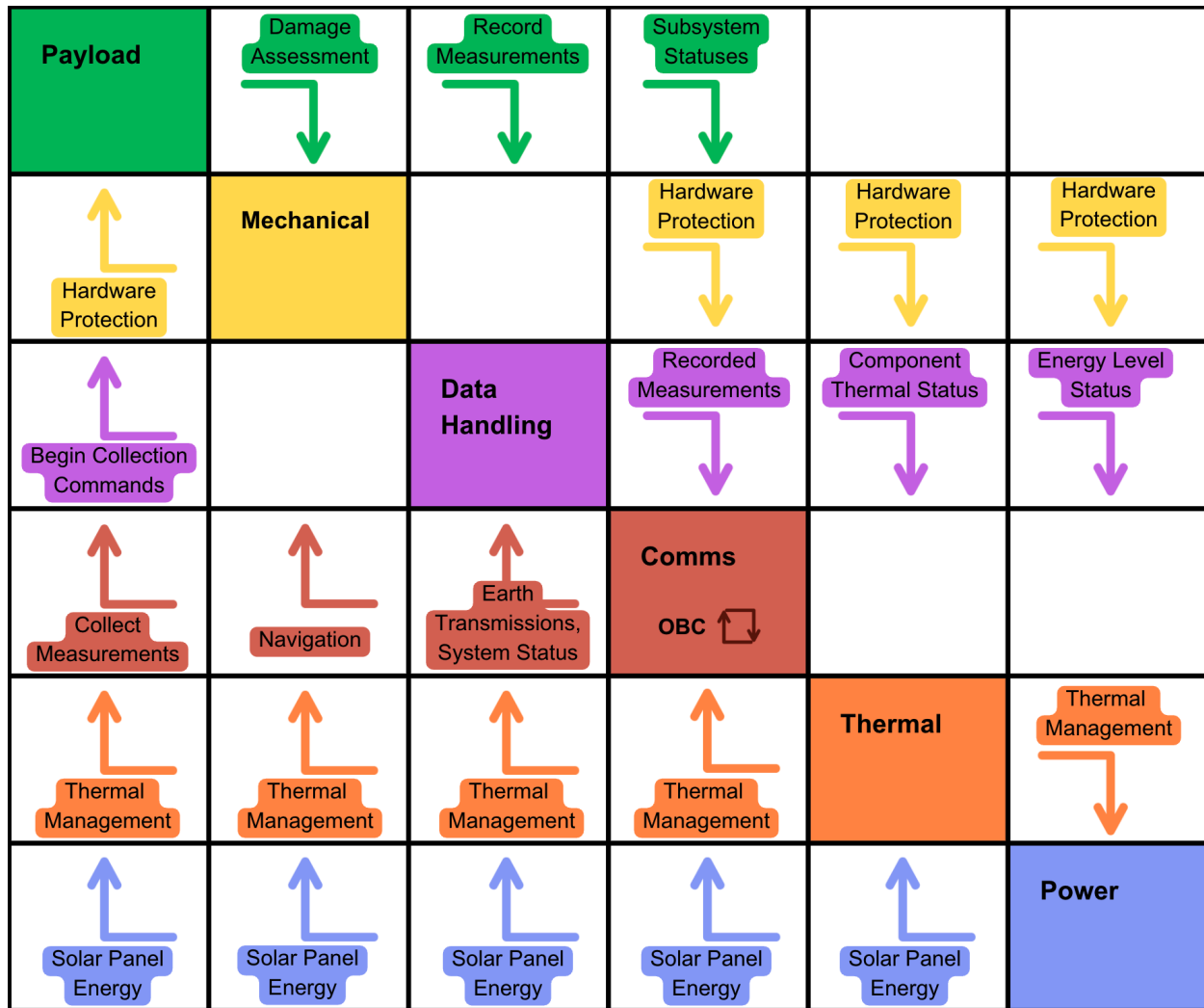


Figure 18: HELP Mission N<sup>2</sup> Chart

## 1.6 Risk Analysis

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. Baseline 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 their 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<sup>1</sup>. 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<sup>2</sup>. 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. For example, Figure 12 displays a thermal trade study conducted to evaluate thermal coating alternatives that can potentially provide help insulate the spacecraft. 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 previously. 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<sup>3</sup> (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.

To begin mitigating these risks, possible solutions must first be researched. 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 19, as well as several other CDH-related risks. Point failures in communication and standard procedures present opportunities for the 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.). 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 as well (Hull n.d.).

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 their own radio-frequency waves as specified in Figure 19, meaning there is potential for those signals to override messages received

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<sup>1</sup> The RIDM process involves evaluating a set of established performance measurements to help decision-makers make informed decisions (Homayoon Dezfouli et al. 2011).

<sup>2</sup> 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).

<sup>3</sup> 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.

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.). In addition, particular antennas such as the omnidirectional antenna are being researched to coordinate with phased arrays to address failure modes that might occur in communication (Bapna, Martin, and Whittaker n.d.).

The payload subsystem carries several instruments of which their operation is crucial to the success of the HELP mission. Furthermore, there are a variety of risks related to this subsystem outlined in Figure 19 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). Interference filters are being researched in order to address these concerns. Additionally, the massive amount of data that LiDAR returns presents potential issues with data handling procedures. To ensure the data is efficiently recorded and analyzed, point cloud editing software such as LiDAR360 and rock point cloud creation software are being researched and compared (Marino 2023).

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, system sensors are being researched that evaluate any damages sustained by impacts (Arnold et al. 2009). While 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. 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 their TRL. These experiments will be run at facilities such as NASA’s Ames Research Center, which hosts Lunar Lab and Regolith Testbeds (Hoover 2023).

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, low-weight protection hardware is being researched as an option that would minimize harm for the entire system. Impact craters and resulting debris present additional concerns regarding navigation 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 19, several wheel characteristics are being researched to further understand

how changing the tread, size, and durability of the wheel will affect the robot's ability to effectively traverse the lunar regolith. After certain alternative options have been outlined, simulations will be run to test drive the wheels on a simulated lunar surface ("Designing Rovers for the Moon's Extreme Environment" 2022). 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 types of seals being considered at the moment are metal and elastomer seals (Abernethy, Sheridan, and Barber 2020), both of which present different specifications that should be examined in a trade study to determine the preferred option. Vibration methods are also being considered to remove dust from the spacecraft, such as the Modal Optimized Vibration dust Eliminator (MOVE). This potential solution uses autonomous vibrations from modal frequencies and an anti-static coating to limit the extent to which dust particles affect the mechanical architecture (Packard, Hansen, and Stanley 2021). Other vibration technologies will be further examined to address this risk too.

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, their signals 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). There are a variety of mitigation strategies being considered in regards to this risk, including the vibration system mentioned previously for the mechanical subsystem, as well as the photovoltaic effect of lanthanum-modified lead zirconate titanate (PLZT) dust removal approach. The PLZT emits electrostatic traveling waves to clear dust that has settled on solar panels. These examples will eventually be examined through trade studies to decide on the best mitigation approach.

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 mission plan is being developed that sees the HELP spacecraft charge for enough time in sunlight and have limited, estimated movement while in permanent darkness.

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, several applications are being researched. Wires can be shielded with insulation to prevent them from becoming brittle ("Designing Rovers for the Moon's Extreme Environment" 2022). In the event that wires do become faulty, the system's electrical flow can be rerouted around damages and still reach its required destination (Beale n.d.). Preemptive shielding can also be provided for solar panels and other hardware components to protect them from degradation induced by cosmic rays (Beale 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.). A variety of solutions are being considered to address these conditions, including gold paint to prevent heat from being transferred via radiation, air insulation that remains lightweight, and thermally protected polymer seals ("Designing Rovers for the Moon's Extreme Environment" 2022). Integrating several solutions in regards to temperature control is being considered in order to improve system redundancy.

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. Multiple mitigation strategies are being considered for this risk, including vibration instruments and the Lunar Demonstration of Electrodynamical Dust Shield (Kaczmarek 2021). The Lunar Demonstration of Electrodynamical Dust Shield emits electric fields to clear dust from thermal components (Kaczmarek 2021). It hasn't been decided whether to move forward with one of these options yet, but similar strategies will be researched and compared via trade studies to confirm the best possible application.

As tests are completed for the technical subsystems and instrumentation, probability density functions<sup>4</sup> (pdfs) will be created in coordination with Monte Carlo

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<sup>4</sup> 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.

shells to better understand uncertainties surrounding the performance parameters of each alternative. These strategies will address both aleatory<sup>5</sup> and epistemic<sup>6</sup> 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 our 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 in Figure 19. These values were determined based on several uncertainties potentially observed by the risks outlined in Figure 19. 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

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<sup>5</sup> Aleatory uncertainties are random and can't be alleviated by completing testing and analysis (Homayoon Dezfuli et al. 2011).

<sup>6</sup> Epistemic uncertainties are not random and can be reduced by learning more on a topic through testing (Homayoon Dezfuli et al. 2011).

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 and 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 aren't be represented in the Risk Matrix seen in Figure 20.

The third step of CRM involves addressing each of the risks established in Figure 19. 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 19. 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 programmatic subteams to monitor and receive updates on risks to individual mission components. New risks will be appended to Figure 19, major priority risks will be addressed in Figure 20 to lower their likelihood of 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.

Maintaining planetary protection (PP) for this mission requires certain guidelines be met. 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).

One potential concern outlined in Figure 19 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 a sterile facility 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 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.

A Pre-Launch PP Report will also be filed that quantifies the spacecraft's volatile organic materials, propellant 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, propellant residuals, and combustion products to ensure it remains at a viable amount (DeLoach 2022).

Completing this End-of-Mission PP Report 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 19 that potentially sees the spacecraft exploding due to energy build-up (Hull n.d.). Passivation appears to be an efficient strategy to address this issue, and it will further be studied to develop an implementation plan. However, initiating the passivation process to relieve these concerns raises several risks in relation to the spacecraft system.

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. Setbacks in testing may build upon each other to a 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 Mars Curiosity Rover is a good example as to why it's important to begin this testing phase early. In order to mitigate this potential issue, the HELP team has already begun trade studies, and will continue to research testing facilities to begin to move further along this process as soon as possible. The completed procedures will follow guidelines outlined by NASA for testing while maintaining risk control protocols too ("NASA Systems Engineering Handbook" 2007).

In the event that personnel are not prepared to undergo this 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, and mission tasks will be assigned priorities in order to coordinate the distribution of resources. Strategies to navigate this process are being researched in NASA's Scheduling Management Handbook, which provides advice on how to adapt to changes and unforeseen circumstances ("NASA Schedule Management Handbook" 2011).

Many scenarios that heavily impact mission schedules also greatly affect mission

costs. If technical difficulties were to occur, or devices or materials suddenly become higher in demand, the mission cost may threaten to surpass the established mission budget constraint of \$425 million. This concern is why it's incredibly important to establish margins early on in the mission life-cycle - these boundaries allow for some leeway to occur in relation to cost increases. In order to further manage these unexpected costs, budget assessments and emergency funds will be allocated. The importance of procedures like these becomes clear when observing scenarios such as 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 will further be mitigated by conducting proactive risk assessments such as failure modes and effects analyses (FMEA). These assessments will be completed heading into the MDR.

Personnel safety and professional experience also present opportunities for risk throughout the HELP mission. Staff turnover may occur and skill gaps may be present throughout mission personnel. To alleviate these risks, cross-training and retention programs are being researched to reduce these areas of concern. The Space Launch System program outlines plans that prioritize workforce stability, so similar procedures will likely be replicated to enforce good protocols ("SLS (Space Launch System)" 2024). 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 must be followed at testing facilities, safety equipment must be up-to-date, and safety guidelines must be strictly followed in order to address these risks. The HELP team is developing 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, online resources are being researched as solutions to providing mission-relevant educational content. Outreach plans will also be formalized to reach out to foreign space agencies as well. The Mars Perseverance mission followed similar steps successfully, and their use of virtual outreach led to 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 team will plan similar events like televised mission updates and broadcasts that allow the public to view mission progress real-time.

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Safety - Planetary Protection	2	4	<b>NEW</b>	R	Given that the Moon is sensitive to extraterrestrial disturbances (Condition), organic inventories might contaminate potential lunar habitation sites (Departure) visited by the HELP spacecraft (Asset) thereby impacting the habitability of the Compton Pit and the nearby landing site (Consequence).	Actively researching processes that involve assessing the spacecraft's organic materials and completing a PP Organic Inventory in order to minimize the probability of contamination while in the Compton Pit.
2	Safety - Decommissioning	2	5	<b>NEW</b>	R	Given that a spacecraft stores residual energy over long periods of time when left running (Condition) a spacecraft explosion may occur due to energy build up (Departure) impacting the Compton Pit (Asset) thereby damaging a potential habitability site on the Moon (Consequence).	The process of passivation is being researched to better understand strategies to alleviate this energy build up and properly complete the decommissioning process.
3	Power - Lighting Conditions	4	4	→	M	Given that the Moon has permanently shaded areas that receive zero light from the Sun (Condition), solar power cannot be continuously stored by the robot in these areas (Departure) impacting the robot's solar panels (Asset) negatively to limit the extent to which the robot can remain in these areas (Consequence).	A plan is being developed that considers how long the HELP spacecraft can remain in permanently shaded areas and the robot's motion will subsequently be programmed.
4	Power - Radiation	3	5	<b>NEW</b>	R	Given that the Moon has a very thin atmosphere (Condition), the lunar surface has little protection from cosmic radiation (Departure) which can cause significant damage to electrical systems (Asset) thereby wiping computer chip memory and short-circuits in system wiring (Consequence).	Shielding equipment is being researched that insulates wires and protects computer chips from being significantly affected by radiation.
5	Power - Lunar Dust	4	4	<b>NEW</b>	R	Given that lunar dust is present on the Moon and it carries an electrostatic charge (Condition), it will stick to objects not electrically grounded on the Moon (Departure) such as the HELP spacecraft (Asset), which might damage system assemblies carrying electronics and reduce energy generated from solar panels (Consequence).	The photovoltaic effect of lanthanum-modified lead zirconate titanate (PLZT) dust removal technique is being researched among other strategies to use electrostatic traveling waves to remove dust from solar panels.

6	Thermal - Lunar Dust	5	4	<b>NEW</b>	R	Given that lunar dust is present on the Moon and it carries an electrostatic charge (Condition), it will stick to objects not electrically grounded on the Moon (Departure) such as the HELP spacecraft (Asset), thereby covering thermal radiators and causing them to produce less heat for other subsystems (Consequence).	The Lunar Demonstration of Electrodynamical Dust Shield is being researched as a technology to remove dust from thermal components using electric waves.
7	Thermal - Temperature	5	5	<b>NEW</b>	R	Given that lunar surface temperatures vary from 40K to 250K (Condition), an object on the Moon may be subject to two polar opposite temperatures depending on the location of the Sun (Departure), impacting spacecraft components (Asset), by creating large heat fluxes that induce thermal stresses, strains, and distortions on science instrumentation and other components (Consequence).	Thermal solutions are being researched such as gold paint, insulators, and heaters. Choosing which solution and how it will be implemented is yet to be determined.
8	Mechanical - Lunar Dust	2	4	<b>NEW</b>	R	Given that lunar dust is present on the moon and it carries an electrostatic charge (Condition), it will stick to objects not electrically grounded on the Moon (Departure) such as the HELP spacecraft (Asset) and might erode mechanical components that haven't been properly sealed (Consequence).	Dust-resistant materials and seals are being researched to be used in the spacecraft's mechanical subsystem, as well as vibration methods to remove dust.
9	Mechanical - Navigation	3	3	<b>NEW</b>	R	Given the heavily cratered and uneven terrain present on the Moon (Condition), there may be significant obstacles such as rocks and craters between the identified landing site and the Compton Pit (Departure) impacting the HELP rover's wheel traction (Asset) thereby leading to problems with path planning and issues of getting physically stuck in one place on the lunar surface (Consequence).	Wheel designs are being researched that account for steep slopes and jagged regolith, and any wheels implemented will be tested through simulations to model how they'll function on the lunar surface.
10	Mechanical - Micrometeoroid and Orbital Debris (MMOD)	1	5	<b>NEW</b>	R	Given that the Moon has a very thin atmosphere (Condition), micrometeoroid and orbital debris may impact the lunar surface in and around the Compton Pit (Departure) potentially threatening the HELP spacecraft's mechanical architecture (Asset) by striking the spacecraft directly (Consequence).	Shielding protection is being considered that refrains from surpassing the mass constraint for this mission.

11	CDH - LiDAR Data Handling	4	3	<b>NEW</b>	R	Given the large amount of data returned by LiDAR simultaneous localization and mapping (SLAM) (Condition), the LiDAR system used on help may produce a surplus of data information while mapping the Compton Pit (Departure) overloading the CDH subsystem (Asset), thereby making it difficult for the subsystem to handle and record all the necessary data.	Actively researching data algorithms and software that can handle complex and immense amounts of data returned by LiDAR systems.
12	CDH - Communication Interference	2	3	<b>NEW</b>	R	Given the variety of active communication systems that remain active in the space between the Earth and the Moon (Condition), there may be communication interferences (Departure) that impact the radio-frequency waves emitted by the CDH subsystem (Asset), thereby interfering with the data being recorded by HELP's payload subsystem (Consequence).	Frequency allocation and frequency licensing are being researched, as well as omnidirectional antennas and redundancy protocols, to ensure communication is established and maintained.
13	CDH - Passivation Communication	1	5	<b>NEW</b>	R	Given that passivation processes are controlled via communications systems (Condition) one single erroneous line due mission operations initiating passivation (Departure) would impact the HELP mission collection entirely (Asset) thereby relieving the spacecraft of its power and preventing it from completing the mission (Consequence).	Strategies for implementing proper software programming techniques and redundant hardware are being researched to better understand how to prevent this early passivation error.
14	CDH - Passivation and Autonomous Recovery Systems	1	2	<b>NEW</b>	R	Given that autonomous recovery systems are in place on the HELP spacecraft (Condition), they may constantly default the system to an active state (Departure) preventing passivation procedures (Asset), and thereby preventing the HELP mission from completing its end of mission protocols (Consequence).	The process of disabling the HELP's autonomous recovery system in order to prepare the system for this stage of the mission in which passivation must occur.
15	Payload - LiDAR - Light Interference	3	4	<b>NEW</b>	R	Given the severe difference in lighting conditions on the Moon based on the location of the Sun (Condition), light will be reflected and received at different angles on the lunar surface (Departure) impacting the light received by LiDAR (Asset), thereby damaging the LiDAR's light reception system or creating confusing data that affects LiDAR's mapping techniques.	Interference filters are being studied in order to assess how they can be implemented on the LiDAR device to focus only on light emitted by the sensor.

16	Payload - Micrometeoroid and Orbital Debris (MMOD)	1	5	<b>NEW</b>	R	Given that the Moon has a very thin atmosphere (Condition), micrometeoroid and orbital debris may impact the lunar surface in and around the Compton Pit (Departure) potentially threatening the HELP spacecraft (Asset) by striking the spacecraft directly or impeding its path from the landing site to the pit (Consequence).	Sensors are being considered that will help identify and assess MMOD damage, and redundant payload instruments are being researched to be implemented.
17	Payload - Instrument Failure	4	5	<b>NEW</b>	R	Given that the lunar environment presents extreme conditions such as severe temperatures, radiation, and lunar dust (Conditions), these conditions are difficult to replicate on the Earth (Departure) impacting the trade studies conducted for payload instruments (Asset) thereby causing failure uncertainties as to how instruments will function on the Moon (Consequence).	Testing facilities and sufficient testing strategies are being researched to raise the TRL of the payload instruments and reduce uncertainties regarding component success.
18	Budget - Schedule Delays	3	5	<b>NEW</b>	R	Given that scheduling often goes hand-in-hand with cost planning (Condition), major setbacks in scheduling due to instrument scrapping and retesting (Departure) will heavily increase the HELP mission estimated cost (Asset), thereby pushing this mission's necessary allocated value to over the cost constraint (Consequence).	Subsystem component costs are being evaluated in trade studies, and testing is being researched to be completed early so that any faults that occur won't threaten the cost and schedule of this mission.
19	Budget - Unanticipated Cost Increases	3	5	<b>NEW</b>	R	Given the complexity of our space mission (Condition), unanticipated cost increases may happen due to unexpected technical challenges, delays, or resource demands in the HELP mission (Departure), leading to exceeding the budget (Asset) and compromising the mission's ability to be completed within financial limits (Consequence).	Periodic financial evaluations are being researched and enforced to monitor and control unforeseen expenses.
20	Schedule - Testing	2	5	<b>NEW</b>	R	Given that testing will have to be completed on the spacecraft's instruments (Condition), setbacks may when a device is reevaluating to not be sufficient enough to be used in the HELP mission (Departure), leading to deadline delays (Asset) thereby affecting the mission launch date of the mission (Consequence).	Trade studies have been completed, and testing procedures and facilities are actively being researched to address any issues that arise sooner than later in the mission life-cycle process.
21	Schedule - Resource Constraints	3	4	<b>NEW</b>	R	Given that scheduling depends on the resources available for testing and development phases (Condition), resource constraints can lead to delays and restrictions on equipment readiness or facility access (Departure). This would delay key milestones	Resource allocations are being reviewed to make sure there is sufficient personnel, time, and equipment for high priority tasks. Scheduling will be adjusted as

						in the HELP mission's timeline (Asset) and push the launch date back, affecting the mission objectives (Consequence).	needed to prevent delays.
22	Outreach - Lack of Support	2	3	<b>NEW</b>	R	Given that mission success and lessons learned relies on public and shareholder support of the mission (Condition) failing to stress the importance and impact of the HELP mission for space exploration (Asset) impact data recorded by the spacecraft (Asset) in that the subsequent lessons learned won't be efficiently documented and shared across school systems and major shareholders (Consequence).	Analogous missions are being researched to better understand what can be done to stress mission importance and valued takeaways. Programs will be subsequently developed that address this learning curve across all ages.
23	Outreach - International Engagement Limitations	2	3	<b>NEW</b>	R	Given the global interest in the HELP mission (Condition), limited international outreach efforts may restrict the HELP missions's ability to create a global engagement and learning (Departure), thus affecting international partners (Asset) by reducing the HELP mission's collaborations (Consequence).	Outreach strategies focusing on international space agencies are being researched to increase global engagement.
24	Personnel - Testing	3	5	<b>NEW</b>	R	Given that personnel will be testing system components in extreme conditions (Condition), risks are present in relation to system failure and lack of safety protocols (Departure) impacting personnel safety (Asset) thereby threatening the health of any engineering or science professionals conducting testing procedures (Consequences)	Safety protocols are being researched and enforced in testing facilities to ensure personnel are properly protected in the case of mistakes or component failure during testing procedures.
25	Personnel - Staff Turnover & Skill Gaps	3	4	<b>NEW</b>	R	Given the specialized skills needed for critical tasks (Condition), high staff turnover or skill gaps may result in operational delays or knowledge loss (Departure), leading to a decrease in the quality and continuity of mission outcomes (Asset) and increasing training costs and loss of time (Consequence).	Mitigation strategies such as cross-training are being researched to ensure mission continuity

Figure 19: HELP Mission Risk Summary Table

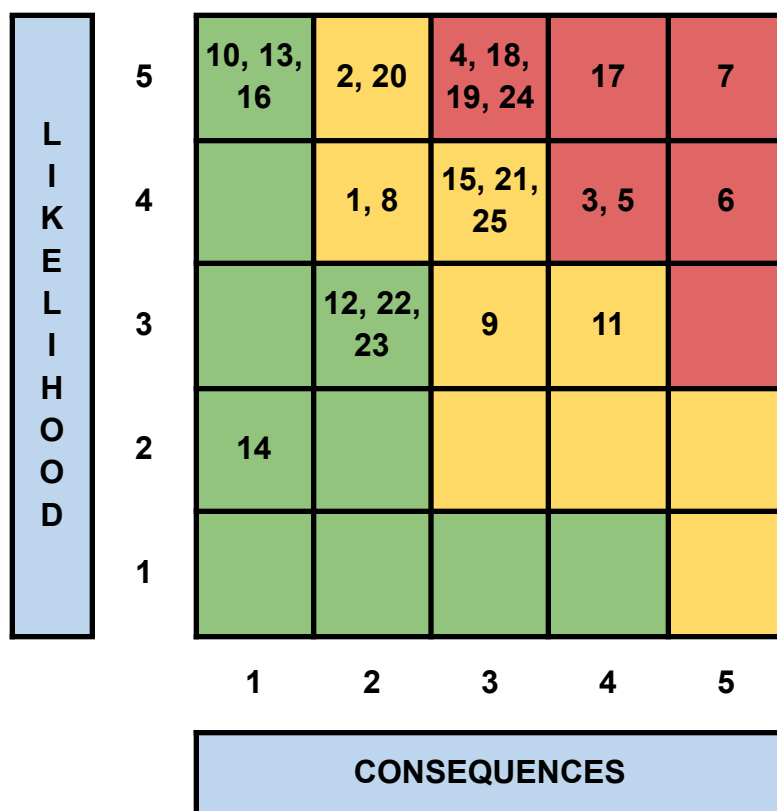


Figure 20: HELP Mission Risk Matrix

## 1.7 Programmatics

### 1.7.1 Team Organization

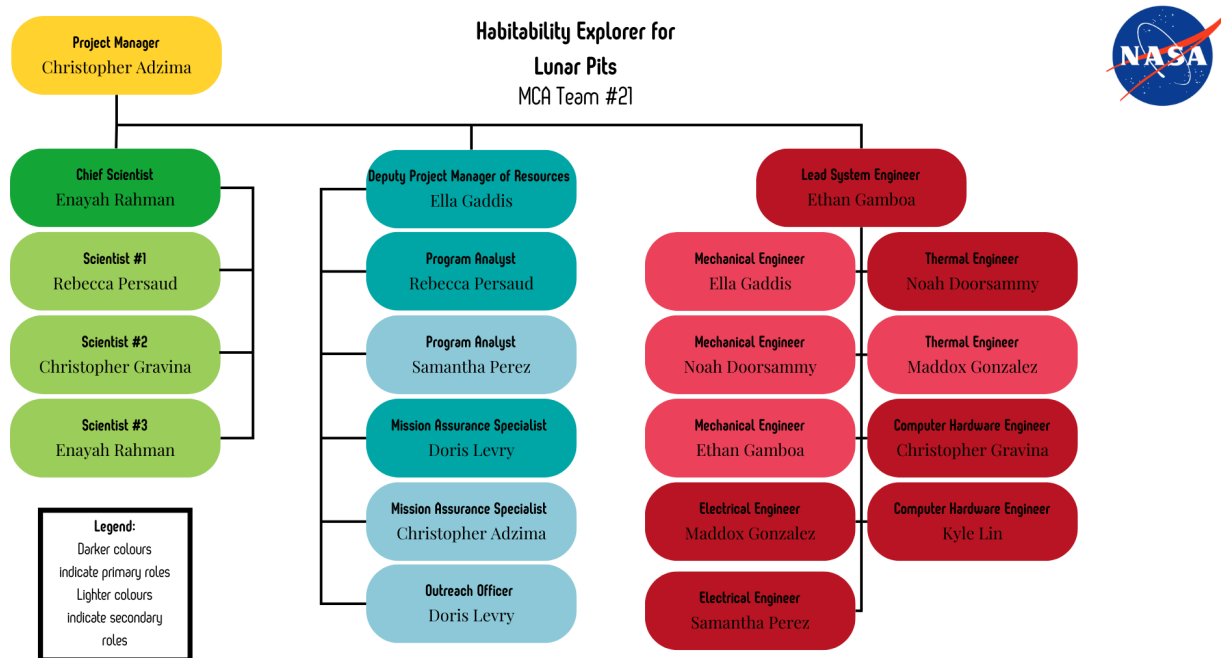


Figure 21: Team Organization Chart

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.

To obtain team opinions on significant decisions, a democratic polling method was initially employed; however, this method occasionally proved to be too time-consuming. Currently, decision-making is more centralized, with designated leads promptly weighing the advantages and disadvantages of choices.

The HELP mission decision-maker is presumed to be 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.

One major challenge has been adapting to an unexpectedly reduced team size. To complete all required review parts, the remaining members made adjustments by taking on more duties and placing a strong emphasis on cross-training.

Passive communication is another problem that has come up, where team members perform their duties 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.

### **1.7.2 Cost Estimate**

Based on the chosen robot architecture and instrumentation needed to collect the necessary science measurements for HELP, a rough cost estimate has been calculated that covers the majority of this mission concept. This cost includes approximated estimations for personnel, travel, and direct vehicle related pricing. While many assumptions were used to find this predicted budget, analogous missions were also considered especially when researching options for instrumentation.

The drafted personnel costs are based on a rough estimate of the number of personnel needed throughout each phase of the mission. Typically, a discovery-class mission contains approximately 30-50 members in the team (Yost, 2021). Assuming this mission will model similar numbers, 34 members were divided into five primary categories that will together encompass the individual teams needed for this mission: science, engineering, technicians, administration, and management.

The NASA Mission Life Cycle encompasses Phases A, B, C, D, E, and F (Deiss, 2023). The cost estimation generated here only encompasses necessary costs from Phase C to Phase F. Given this range, each phase typically requires variable numbers of personnel depending on the workpower needed for manufacturing, documentation, or science research. After assessing the deliverables required in each phase, an approximate amount of personnel was assigned to one of the five subteams. Throughout Phase C, science and engineering design is prioritized for drafting science objectives and finalizing system, subsystem, and instrumentation design. Therefore, a greater number of people were assigned jobs in these two subcategories. In Phase D, the manufacturing of the robot architecture will be completed, which will require more technicians for their input and ability to test the instrumentation's capabilities. As a result, it's predicted that more engineers and technicians will be needed for this phase. For Phases E and F, science personnel are prioritized to document the data collected by the rover and draw resulting conclusions. Administration and management remain consistent throughout each phase in order to coordinate progress between each

subteam and maintain a consistent flow of information. The total personnel cost estimate is \$24,600,000.

Based on this personnel cost estimate, travel estimates can be further drawn assuming team members will travel a certain amount of weeks each year to coordinate partnerships with contractors, organize facilities and materials for manufacturing and testing, and travel to witness the mission launch. Throughout Phase C, the required instrumentation is clearly defined and its design must also be finalized. Personnel will have to travel and discuss plans with contractors to organize the creation of these instruments. Given approximately four instruments will be necessary to complete the collection of the science measurements, it's estimated that during each fiscal year of Phase C, four weeks will be set aside for travel.

The cost estimation includes flight costs at the highest commercial flight rate to Miami, FL ("City Pair Program (CPP)", 2024), hotel costs at the highest rate ("FedRooms", 2024), car rental transport at the highest rate ("Expedia", 2024), and per diem costs at the highest rate available ("FY 2025 Per Diem Rates for Cape Canaveral, Florida", 2024). Four weeks were also approximated throughout Phase D, since manufacturing and testing on each of the instruments will have to be completed. During the last fiscal year of Phase D, costs are estimated for the 34 members of the team to travel to Cape Canaveral, FL, and attend the mission launch. For Phases E and F, only a single week was estimated for cost. There should be much less travel during this phase. The total rough estimate for cost of travel is \$265,000 for the moment.

Most of the direct vehicle cost estimates for this mission are based on analogous missions and research that have conducted similar science experiments. The Chandrayaan-3 Lander Module and Rover utilize instrumentation that collects data very similar to that needed to be collected for this mission's science measurements. The Laser Retroreflector Array (LRA) rover incorporates a Laser Induced Breakdown Spectroscope (LIBS) and an Alpha Particle X-ray Spectrometer (APXS) ("Chandrayaan-3", 2024). The LIBS collects science data based on minerals present in the lunar surface, and the APXS determines chemical composition of the lunar soil ("Chandrayaan-3", 2024). Both of these measurements are applicable to the science obtained by this mission. The total cost estimate of the Chandrayaan-3 is \$75,000,000, which forms a basis for the total cost estimate of this mission to explore the lunar Compton Pit (Bhattacharjee, 2023).

The known direct costs are the thermal/fluids subsystem, power subsystem, and CDH subsystem. Between these three subsystems accounts for 51.8 kg of the allotted 350 kg for the mission payload.

Personnel Table	Total Salary
Science Personnel	\$4,544,640
Engineering Personnel	\$5,641,920
Technicians	\$3,862,080
Administration	\$1,334,880
Management	\$766,800

Figure 22: Personnel Cost Estimates

	Manufacturing	Testing
Payload	TBD42	TBD44
Mechanical	TBD43	TBD45
Thermal/Fluids	\$2,600,000	\$800,000
Power	\$56,300,000	\$16,900,000
CDH	\$7,000,000	\$2,100,000

Figure 23: Facilities and Manufacturing Cost Estimates

### 1.7.3 Schedule Estimate

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 3 and 4.

The first major category specified in Figure 3 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 Figure 3. 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, 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).

Once the rover’s components have been activated, it will begin collecting data from the lunar surface concerning in situ resources and other important molecules, including Oxygen, Hydrogen, and Hydroxyl. 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 take approximately one lunar day to travel the short distance to the Compton Pit, where it will document the dimensions and structure presented by the pit and cave below (“Lunar Roving Vehicle”, 1972). Cave mapping is expected to take approximately a month to completely collect all of the necessary data. The largest caves can typically take around 27 days to be completely mapped (Gibb, 2021), therefore a month is given in case the cave found within the pit is larger than expected. As the robot traverses the cave, it will also stop and obtain science measurements concerning temperature and radiation. Once all of the data has been collected, it must then be organized and documented correctly for further research and analysis. The robot then completes its decommissioning process outlined by the Decommissioning Review (DR) marking the closing stages of the robot’s role in completing this 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.

1	Phase C: Final Design and Fabrication	12/23/24	3/1/27
1.1	Major Milestone 1: Draft and Submit Critical Design Review (CDR)	12/23/24	1/23/26
1.1.1	Develop detailed designs of necessary hardware and software	12/23/24	7/23/25
1.1.2	Further explain how subsystems effectively interface	12/23/24	10/23/25
1.1.3	Explain how the instrumentation is analyzed and considered for future implementation	12/23/24	10/23/25
1.1.4	Continue updating plans for operations, risks, and anticipated procedures for manufacturing	12/23/24	1/23/26

<b>1</b>	<b>Phase C: Final Design and Fabrication</b>	<b>12/23/24</b>	<b>3/1/27</b>
1.1	Major Milestone 1: Draft and Submit Critical Design Review (CDR)	12/23/24	1/23/26
1.1.5	Key Decision Point: Submit Production Readiness Review (PRR) for necessary instrumentation	12/23/24	1/23/26
1.2	Major Milestone 2: Draft and Submit System Integration Review (SIR)	1/23/26	1/30/27
1.2.1	Finalize design plans and plans for integrating the subsystems and instrumentation	1/23/26	11/23/26
1.2.2	Baseline how each subsystem will operate	11/23/26	1/30/27
1.2.3	Begin outlining the process of Verification & Validation (V&V)	11/23/26	1/30/27
1.3	Schedule Margin	1/30/27	3/1/27
1.4	◆ Completion of Phase C	2/1/22	3/1/27
<b>2</b>	<b>Phase D: System Assembly, Integration &amp; Test, Launch &amp; Checkout</b>	<b>3/1/27</b>	<b>3/1/30</b>
2.1	Major Milestone 3: Complete Test Readiness Reviews (TRRs) of Instrumentation and System	3/1/27	3/1/28
2.1.1	Manufacture system components and then assemble and integrate them	3/1/27	1/1/28
2.1.2	Inspect instrumentation and system capability to obtain science measurements	1/1/28	3/1/28
2.1.3	Key Decision Point: Assess instrumentation with prototypes to determine TRR	1/1/28	3/1/28
2.2	Major Milestone 4: Draft and Submit Operational Readiness Review (ORR)	10/1/27	2/1/29
2.2.2	Test instrumentation and instate confidence in its usage	10/1/27	3/1/28
2.2.3	Key Decision Point: Begin V&V of subsystem and instrumentation results	3/1/28	5/1/28
2.2.4	Finalize operations plans and procedures	10/1/27	2/1/29
2.2.5	Baseline plans for decommissioning and disposing of the robot after mission completion	5/1/28	2/1/29
2.3	Major Milestone 5: Draft and Submit Mission Readiness Review (MRR)	2/1/29	1/1/30
2.3.1	Baseline and verify V&V results	2/1/29	1/1/30
2.3.2	Prepare launch and confirm spacecraft flight/launch capability	5/1/29	1/1/30
2.4	Key Decision Point: Complete Safety and Mission Success Review	1/1/28	1/1/30
2.4.1	Continuously update risks	1/1/28	1/1/30
2.4.2	Perform safety review assessing launch and mission safety	5/1/29	1/1/30
2.4.3	Confirm spacecraft safety and capability readiness	5/1/29	1/1/30

<b>1</b>	<b>Phase C: Final Design and Fabrication</b>	<b>12/23/24</b>	<b>3/1/27</b>
1.1	Major Milestone 1: Draft and Submit Critical Design Review (CDR)	12/23/24	1/23/26
2.5	Major Milestone 6: Launch Vehicle (LV)	1/1/30	3/1/30
2.5.1	Key Decision Point: Complete Launch Readiness Review (LRR)	1/1/30	2/1/30
2.5.2	Major Milestone 7: Launch Mission at Cape Canaveral, FL	3/1/30	3/1/30
2.6	Schedule Margin	3/1/30	3/1/30
2.7	◆ Completion of Phase D	3/1/27	3/1/30
<b>3</b>	<b>Phase E: Operations and Sustainment</b>	<b>3/1/30</b>	<b>5/6/30</b>
3.1	Major Milestone 8: Complete Post-Launch Assessment Review (PLAR)	3/1/30	3/10/30
3.1.1	Key Decision Point: Conduct vehicle launch performance assessment	3/1/30	4/1/30
3.2	Major Milestone 9: Complete Critical Events Readiness Review	3/4/30	4/19/30
3.2.1	Activate science instruments upon landing	3/4/30	3/4/30
3.2.2	Collect data measurements concerning surface features	3/4/30	3/18/30
3.2.3	Visit Compton Pit and cave map the pit dimensions and structural features	3/19/30	4/19/30
3.2.4	Collect measurements concerning cave temperature and radiation	3/19/30	4/19/30
3.3	Major Milestone 10: Complete Decommissioning Review (DR)	4/19/30	5/1/30
3.3.1	Begin process of decommissioning the robot systems	4/19/30	5/1/30
3.3.2	Outline potential upgrades for future missions	4/19/30	5/1/30
3.3.3	Conduct safety review	4/19/30	5/1/30
3.4	Key Decision Point: Compile and Document Collected Data Efficiently	3/4/30	5/1/30
3.5	Schedule Margin	5/1/30	5/6/30
3.6	◆ Completion of Phase E	3/1/30	5/6/30
<b>4</b>	<b>Phase F: Closeout</b>	<b>5/6/30</b>	<b>6/6/30</b>
4.1	Major Milestone 11: Complete Disposal Readiness Review (DRR)	5/6/30	5/7/30
4.1.1	Conduct robot disposal according to outlined plans	5/6/30	5/7/30
4.2	Ensure Organized Documentation and Draw Conclusions Based on the Collected Data	5/6/30	5/7/30
4.2.1	Baseline and write up the mission final report	5/6/30	6/1/30
4.2.2	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
4.3	Schedule Margin	6/1/30	6/6/30

1	Phase C: Final Design and Fabrication	12/23/24	3/1/27
1.1	Major Milestone 1: Draft and Submit Critical Design Review (CDR)	12/23/24	1/23/26
4.4	◆ Completion of Phase F and Mission	5/6/30	6/6/30

Figure 24: Schedule estimate for Phases C-F of HELP

#### 1.7.4 Change Control

To request a change to the mission, the team will utilize the Change Request Form that is designed to be submitted to the Change Control Board (CCB). To date, none have been submitted as the science objectives previously defined have not been altered in any way, only developed or expanded upon. In the future, to decide if a CCB is needed, the team plans to discuss this in depth and conduct trade studies to determine the best course of action.

However, several requests for action (RFAs) were suggested from the Mission Concept Review in order to strengthen the mission. The first RFA was that instrumentation should not be selected until there were no TBDs or TBRs and that trade studies must be conducted for each selection. The Science team conducted these trade studies and thus were able to select instrumentation. The second RFA was that a mission requirements table needed to be included in order to further define the mission. The Science team created this table that highlighted the various science goals of the mission and included it in the Mission Requirements section of this document. The third RFA was that Planetary Protection Concerns needed to be addressed, which they were in the Risk Analysis section of this document. The fourth RFA is that the risk associated with choosing the Compton pit needed to be addressed. The risks, along with possible mitigations, were discussed in the Risk Analysis section of this document.

In addition to RFAs, several advisories (ADVs) were suggested as well, the first being that the risk from the Concept of Operations should be separated from the rover's operations. This risk was instead included in the Risk Analysis section of this document. Another ADV was a discussion of why the Compton pit is favorable to the mission. The discussion is now included in the Mission Location Section. A third ADV was that criteria for all subsystems should be considered, which the RIDM in the Risk Analysis section does. The final ADV was that the budget's four categories needed to be more clearly separated, thus a restructuring of the budget was completed.

A table of these RFAs and ADVs and their implementations can be found in Appendix A. It should be noted that not every suggested RFA or ADV was implemented at this time due to the nature of this deliverable. All RFAs and ADVs will be implemented before the submission of the Preliminary Design Review.

#### 1.8 Conclusion

This SRR establishes much, but not all, of the engineering pieces necessary for the HELP mission to successfully be implemented. Payload, thermal, power, and computer and data handling devices have been outlined and researched to begin quantifying mass and dimension estimates of the HELP rover. Trade studies have been

completed for many of these components, justifying their use in the mission, and allowing the mission personnel to move forward with testing in the near future. Science was expanded on to further define measurement parameters and expectations of instruments to be used to collect the necessary science measurements of this system. The JMOON tool was also applied to obtain more detailed images of the Compton Pit that can be analyzed to justify the potential use of the pit for human habitation.

There is much still to be done regarding the engineering of this mission. Given more time, technical drawings of the spacecraft and its individual subcomponents would be included to better visualize how this mission might proceed. In addition, an increased amount of trade studies would have been conducted to justify the use of certain components, especially in the mechanical, payload, and computer and data handling subsystems. Interface control and recovery and redundancy implementations must also further be expanded on going into the MDR. Their completion is crucial for ensuring the entire spacecraft mechanism functions as a whole, and will be able to adapt to certain challenges it may face given the insurmountable amount of risks present on the Moon. These risks were thoroughly outlined in risk analysis, but they should be continuously monitored going into MDR and beyond. Once each risk has been thoroughly researched, strategies for alleviating each risk will begin to be implemented leading into the Mission Definition Review (MDR). Approaching the MDR, there is much to do regarding engineering, science, and programmatics, and these points of improvement will be taken into consideration to ensure the HELP mission operates sufficiently.

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## **DECLARATION OF GENERATIVE AI**

During the preparation of this work, the ChatGPT was used in order to generate criteria to conduct the Power Storage Subassembly trade study. After using this tool, the team reviewed and edited the content as needed and takes full responsibility for the content of the deliverable.

During the preparation of this work, the team utilized Claude.ai to conduct grammar and spelling checks specifically for Section 1.7. After using this tool, the team thoroughly reviewed and edited the content to ensure accuracy and consistency, taking full responsibility for the final deliverable.

## APPENDIX A: RFA/ADV Table

ID	RFA/ADV Received	How RFA/ADV was Implemented
MCR-RFA-1	Instrumentation shall not be selected until columns 1-4 are defined with no TBDs/TBRs. Trade studies must be conducted for each instrumentation selection.	Instrumentation was selected using trade studies after all TBDs and TBRs were defined.
MCR-RFA-2	Include a requirements table	A mission requirements table was created by the Science team and is included in the Mission Requirements section of the SRR.
MCR-RFA-3	The team needs to address Planetary Protection Concerns	These concerns are addressed in the Risk Analysis section of the SRR.
MCR-RFA-4	The team should address the risk associated with their specific pit	The risk associated with the Compton pit, as well as possible mitigations to the risk, was discussed in the Risk Analysis section.
MCR-ADV-1	Discuss how the site(s) of-interest are favorable to carry-out this specific mission's science objectives.	The discussion as to why the Compton pit was chosen for this particular mission is included in the Mission Location section for the SSR.
MCR-ADV-3	The team should separate or clarify the risk from ConOps. Although addressing the importance of the risk the rover can experience is vital, the team should only address the risk and not mention details in how the rover needs to operate.	The risk addressed in ConOps was separated from the rover's operations and was only included in the Risk Analysis section of the SRR.
MCR-ADV-4	The team should consider criteria for ALL subsystems, and how criteria related to cost, volume, time, and TRL will inform decision-making.	Criteria for all subsystems has been considered in the RIDM.
MCR-ADV-5	Restructure the budget section to clearly separate the four categories: outreach, direct costs, transportation, and personnel.	The budget section has been restructured in order to separate these four categories.

## APPENDIX B: TBD/TBR Table

TBD/TBR #	Plans and Timeline for Resolution
TBD (thermal subassemblies)	The thermal subassemblies have TBD's within the mass and dimension sections which will be filled in when the team finalizes the design and the exact dimensions of the spacecraft. These sections require exact dimensions to be used to calculate the total mass and specific dimensions of each subassembly.