Mission Concept Review (MCR)
Team 21
Habitability Explorer for Lunar Pits (HELP)

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Table of Acronyms

MCR : Mission Concept Review

HELP : Habitability Explorer for Lunar Pits

ISRU : In Situ Resource Utilization

TRIDENT : The Regolith and Ice Drill for Exploring New Terrain

NIRVSS : Near-Infrared Volatile Spectrometer System

BRAILLE : Biologic and Resource Analog Investigations in Low Light Environments

RAD : Radiation Assessment Detector

DTN : Disruption Tolerant Networking

APXS : Alpha Particle X-Ray Spectrometer

CDR : Critical Design Review

LIBS : Laser Induced Breakdown Spectroscope

LHDAC : Lander Hazard Detection & Avoidance Camera

LROC : Lunar Reconnaissance Orbiter Camera

LRA : The Laser Retroreflector Array

SIR : System Integration Review

SSR : System Requirements Review

DR : Decommissioning Review

PLAR : Post-Launch Assessment Review

TRRs : Test Readiness Reviews

1. Mission Concept Review

1.1 Mission Statement

The objective of Habitability Explorer for Lunar Pits (HELP) is to send rovers into the Compton Pit for exploration to be tested for thermal isolation. The rover is also expected to obtain clear dimensions of the cave including deformations, points of stress, and terrain information. 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 are different from the surrounding surface and after nightfall due to shielding from solar radiation and the low thermal conductivity of the lunar regolith. Therefore, the hope is to find a cave with the least amount of change in temperature from day to night. With the findings from the Compton Pit, there will be more information about lunar caves in terms of their conditions and what life can survive there. Learning about the lunar environment further develops the understanding of what needs to be done to sustain life in conditions that are different from Earth. Obtaining research data regarding the temperature and radiation levels within the lunar pit will help find differences between the surface and within the pit itself.

Finding the presence of Silicon, Carbon, and Hydrogen gives the ability to understand the environment and be able to adjust the living conditions accordingly. The presence of Oxygen and Hydroxyl on the lunar surface outside of the pit will also be taken into consideration for the selection of the most suitable environment. This implication contributes to knowledge of other planets or solar systems that contain celestial bodies that share a similar landscape to the Moon. Getting an overall understanding of these pits expands the opportunities for sustaining life on other celestial bodies. These caves will be candidates for providing a stable environment for long-term lunar habitation to support human exploration on the Moon.

1.2 Science Traceability Matrix

In order to address the overarching science goals established for this mission, several science objectives have been defined. These objectives were created within customer restraints, and they each collect specific measurements relevant to one of two science goals. Analyzing the resulting data and samples obtained from these science objectives will lead to valuable mission discoveries regarding the Compton Pit and the lunar surface surrounding the pit.

The first science goal defined for this mission considers the mission’s robotic system and the role it’ll play in defining the future research humans will conduct on the surface of the Moon. To prepare astronauts with the resources necessary to sustain human habitation, two science objectives have been defined. The first science objective requires spectral signatures of Oxygen and other metal substances to be collected. By quantifying the amount of Ilmenite, Pyroxine, Olivine, Anorthite, Magnesium-rich silicates, and Anorthitic Plagioclase, necessary in situ resources can potentially be identified, further justifying the use of the Compton Pit as an option for human habitation. The process of in situ resource utilization (ISRU) reduces human and robotic reliance on resources being transported from Earth to the Moon to sustain lunar presence (Green, 2019). The Regolith and Ice Drill for Exploring New Terrain (TRIDENT) is an effective instrument used to obtain samples of in situ resources a short distance below surface level (Williams, 2022). It is likely that either this instrument or a similar implementation will be used to collect the necessary data measurements for this science objective.

The second science 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. By identifying and collecting spectral signatures of Hydrogen, Oxygen, water, and Hydroxyl, water can potentially be sourced, and it can be determined whether or not a mini magnetosphere might exist in the area surrounding the Compton Pit (Barry, 2024). Water is an incredibly important resource for future habitation. While water molecules may not come in abundance, the process of combining Hydrogen and Hydroxyl molecules can be further studied to obtain the water necessary to survive. Regarding the mini magnetosphere, this potential area of protection from solar wind may pose the ideal environment for future habitation due to lower levels of radiation (Zhang, 2023). Given the Moon has no magnetosphere to protect itself from high levels of radiation, identifying regions on the surface that provide some or even temporary protection from these uninhabitable radiation levels is an important area to further explore. The Near-Infrared Volatile Spectrometer System (NIRVSS) is an efficient instrument that has been used to collect similar minerals in past research experiments such as NASA’s Biologic and Resource Analog Investigations in Low Light Environments (BRAILLE) (“Biologic and Resource Analog Investigations in Low Light Environments”, 2024). This instrument or a similar design will be implemented in the mission to ensure this data is properly collected.

The second science goal defined for this mission considers the ability of the robotic system to provide and locate a safe habitat system that can protect individuals, equipment, and associated infrastructure. The first science objective is to characterize the depth, height, terrain variation, ease of access, and structural integrity of the

Compton Pit. Defining and mapping these key physical features will lead to conclusions regarding human habitation of this lunar pit. The ability to assess the dimensions and deformations of a lunar pit is crucial for astronaut safety. By identifying overhangs and stress points, astronauts can pinpoint potential hazards that could endanger both personnel and equipment. Identifying these dangers allows them to implement measures to either avoid or reinforce vulnerable areas to increase safety within the lunar pit. A Rover Lider (SQRLi) System is a useful cave dimensioning device that will potentially be used in the final design of this robot.

The second science objective is to measure the temperature and radiation levels within the Compton Pit. By measuring this data, the astronauts will be able to make decisions about the sustainability and survivability of the individuals and equipment that will be staying within this potential habitat. This will also provide valuable research data about the temperature and radiation levels within this lunar pit and expand their knowledge of the differences between the surface readings and how they differ within the lunar pit. The NIRVSS device can also be applied in this situation, as it records surface temperature measurements that reach as low as 100K (Williams, 2022b). Regarding radiation levels, it’s important the cave remains below a radiation threshold of 25,000 millirems (“Radiation, How Much Is Considered Safe for Humans?” 1994). Exceeding this threshold indicates radiation levels that are critically dangerous for human habitation. The Radiation Assessment Detector (RAD) has been used on the Mars Curiosity rover to obtain similar measurements (“Mars Science Laboratory - Curiosity Rover”, 2024). A similar instrument will be incorporated into the rover design to ensure the radiation measurements are taken efficiently.

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, Pyroxine, Olivine, Anorthite, Mg-rich silicates, and Anorthitic Plagioclase.	Collect spectral signatures of Ilmenite, Pyroxine, Olivine, Anorthite, Mg-rich silicates, and Anorthitic Plagioclase present 10 cm below the surface in a 3km area.	Wavelength range:	TBD1	TBD21	The Regolith and Ice Drill for Exploring New Terrain (TRIDENT)	TBD41
				Integration time:	TBD2	TBD22		
				Sensitivity:	TBD3	TBD23		
				Spatial Resolution:	TBD4	TBD24		
	Determine the amount of solar wind materials, water, and Hydroxyl molecules present in the lunar regolith located around and inside the Compton Pit.	Identify Hydrogen (H) Oxygen (O2), water (H2O), and Hyrdoxyl (OH) molecules.	Collect spectral signatures of H, O2, H2O, and OH in the 10-30 nm range over a 3km area.	Wavelength range:	TBD5	TBD25	Near-Infrared Volatile Spectrometer System (NIRVSS)	TBD42
				Integration time:	TBD6	TBD26		
				Sensitivity:	TBD7	TBD27		
				Spatial Resolution:	TBD8	TBD28		
Life Support & Habitat: mLSH1 - *"Provide safe and enduring habitation systems to protect individuals, equipment, and associated infrastructure"* (Lunar Exploration Analysis Group (LEAG) Habitation: HAB-SAT Report, Priority Objectives)	Characterize the depth, height, terrain variation, ease of access, structural integrity, temperature, and radiation levels within lunar pits/caves to determine the viability of human habitation.	Define the dimensions and deformations of the lunar pits/caves.	Collect and map the dimensions, deformations, terrain, overhangs, and stess points in a 35m or greater range.	Wavelength range:	TBD9	TBD29	Rover Lidar (SQRLi) System	TBD43
				Integration time:	TBD10	TBD30		
				Sensitivity:	TBD11	TBD31		
				Spatial Resolution:	TBD12	TBD32		
		Identify the Galactic Cosmic Ray flux in the Compton Pit, measure variation in its diurnal, seasonal, and solar cycle, and measure temperature variation.	Detect temperature measurements between 273K and 373K and radiation levels that exceed 25,000 millirems.	Wavelength range:	TBD13	TBD33	Near-Infrared Volatile Spectrometer System (NIRVSS)	TBD44
				Integration time:	TBD14	TBD34		
				Sensitivity:	TBD15	TBD35		
				Spatial Resolution:	TBD16	TBD36		
				Wavelength range:	TBD17	TBD37	Radiation Assessment Detector (RAD)	
				Integration time:	TBD18	TBD38		
				Sensitivity:	TBD19	TBD39		
				Spatial Resolution:	TBD20	TBD40		

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 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 (William Steigerwald) 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, and the western wall shows multiple layers. 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 landing site was chosen to be in a radius of 5 km from the pit. The average slope of the area is 0.667 degrees*. 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).

Lunar Pit Trade Study						
Criteria	**Explanation**	**Grade**	**Weight**	**Mare Moscoviense Pit**	**Sinus Iridum Pit**	**Compton Pit**
steepness of surrounding terrain	Is important so that the craft can land safely	10 = high, 5 = medium 1 = low 0 = Fail	40%	9	8	7
Latitude	is the location halfway between the lunar equator or the pole	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	8	9
Larger inner diameter than external diameter	is the interior cavity of the cave wider than the entrance	10 = high, 5 = medium 1 = low 0 = Fail	30%	5	9	7
Angle of ramp	is it accesible for humans or entrance ramp for rover	10 = high, 5 = medium 1 = low 0 = Fail	20%	8	5	5
		TOTALS:	**100%**	74.00%	77.00%	68.00%
			Lacus Mortis Pit	**West Marius Hills Pit**	**Mare Insularum Pit**	**Central Mare Fecunditatis Pit**
			0	7	1	8
			8	3	3	0
			8	8	9	7
			6	10	7	6
			44.00%	75.00%	48.00%	65.00%

Figure 2: Lunar Pit Trade Study

*Data collected using tools in the LROC Lunar QuickMap

1.4 Mission Requirements

The customer has outlined several key requirements for the mission, including a mission budget. The mission’s budget is capped at $425 million, which means every part of the project - from hardware development to operations - must be carefully planned to ensure cost-effective solutions that still meet the mission's scientific and exploratory goals.

In addition to managing costs, the spacecraft must be ready to launch by March 1, 2030. This firm deadline requires precise scheduling and strong coordination across all teams to make sure each phase of development stays on track. Aside from the budget and schedule, the mission has several important scientific objectives that focus on expanding our understanding of the lunar environment. One of the main goals is to analyze the presence of valuable resources in the lunar soil, particularly around the cave. Resources like oxygen and metals, including minerals such as Ilmenite, Pyroxene, and Olivine, are critical for future in situ resource utilization. The spacecraft will also search for water, Hydroxyl molecules, and solar wind-implanted substances, all of which are key to sustaining long-term missions and producing fuel.

The mission will also evaluate the potential use of lunar pits and caves as future habitats for astronauts. These formations could provide natural protection from extreme temperatures and cosmic radiation, making them ideal for long-term habitation. To assess their suitability, the spacecraft will map their dimensions, study terrain variations, and test the structural integrity of the caves. Additionally, it will monitor environmental conditions such as temperature and radiation levels to determine if these areas are safe for human use. This data is essential for deciding whether lunar pits and caves could be viable sites for future astronaut habitats as NASA continues its exploration of the Moon.

1.5 Physical Environmental Hazards

Hazards on the moon include radiation, the condition of lunar regolith, darkness, maneuverability, and extreme temperature. These must be considered when designing the rover and preparing for human habitation.

Radiation is one of the most dangerous hazards on the Moon. It comes in three types: solar radiation, cosmic radiation and radiation from the ground. Radiation can cause equipment malfunctions and fatal illness in humans. Solar radiation comes from the Sun, and irradiates the ground. Unlike Earth, the Moon has no atmosphere to reflect the radiation and no longer shares a magnetic field with Earth. Cosmic radiation is produced in outer space and travels across the universe, spreading high-energy atomic nuclei.

Solar radiation consists of lower energy when compared to cosmic rays but has occasional deadly solar flares which may pose a risk to our mission. Radiation is a major limiting factor when it comes to long-stay missions on the moon, not including solar flares. According to NASA, spaceflight radiation should not exceed 600 millisieverts, and the annual radiation dose on the Moon is about 11% of that 600 millisieverts. The Compton Pit would provide acceptable protection while saving time that would be wasted for an extensive protection setup. The main risk would be the occasional deadly solar flares which may hit at any time.

Cosmic rays: Cosmic rays are higher energy atomic nuclei that are more dangerous than solar radiation. These rays are harder to shield against and are more prone to penetrating the pit walls. The dangerous thing about these rays is that they travel at a near-constant rate and are also isotropic from space. When taking cosmic ray risks into account, it is important to consider the primary cosmic rays affecting the area as well as the secondary cosmic radiation scattered from the pit walls. The main risk associated with cosmic rays is the radiation that can penetrate through our pit walls.

Lunar regolith hazards is a fine gray sand-like material, consisting from pebbles to boulders, its sharp edges will damage equipment due to the non-existent erosion factor of the lunar surface. In addition, being electrostatically charged, the lunar regolith can mess with the rover’s inner conductor as well as getting in between non-sealed gaps, and easily damage vital hardware components. (Dorota Budzyń et al., 2022).

As the rover travels from the landing site to the pit, it may come across areas too dark to travel through unaided. However, the rover will likely not travel at night. Once it reaches the pit, some parts of the pit will be shrouded in permanent darkness. For ease of navigation, it was decided that the rover will contain LED headlights. However, headlights require a lot of energy and add to the mass of the craft. This will be the first time that a rover is installed with headlights. This means that the time for missions in the permanently shadowed areas is limited, as the rover must not stay in continuous darkness for more than 50 hours before the battery drains (Wetzel, 2021). This must also be carefully calculated such that the rover does not exit the permanently shadowed region at night. The walls of Compton Pit will also decrease the amount of time that the rover can charge per day, as the sun must be overhead the pit.

The rover will be controlled from Earth, which requires a stable connection such as the Deep Space Network or Delay/Disruption Tolerant Networking (DTN). This may be a challenge when inside the pit. This may be assisted with a stationary relay on the Moon (Wyatt et al., 2018).

Before the rover reaches our pit, it will endure extreme temperatures varying from up to 121 degrees Centigrade during the day to -133 degrees Centigrade at night. Once it reaches the permanently shadowed region of Compton Pit, temperatures may drop as low as -246 Centigrade (Barry, n.d.). The rapid and extreme heating and cooling of parts may result in damage to the rover or its hardware. In addition, the rover will typically enter hibernation mode at night to keep itself warm and conserve energy. This will not be possible when exploring permanently shadowed regions. This will mean that the time spent exploring permanently shadowed areas will be an additional strain on the rover's battery supply.

1.6 System Evaluation Criteria

To adhere to the given constraints for the rover's mission, accurate instrumentation measurements were primarily considered for the rover's subsystem decisions, believing expensive subsystem instrumentation would provide accurate data for NASA to base decisions on for Compton pit. Since the rover is required to work and move in a rocky low-light environment with depths estimated to be up to 40m, the rover will need to be large enough to maintain balance using its center of mass. The rover will also need to be able to collect samples of materials using a drill. The primary goal of this mission is to collect data in order to determine if the lunar cave will be safe for astronaut habitation. For these goals, accurate thermal and radiation instrumentation will be required for the rover to analyze the long-term temperature changes in the cave, as well as the radiation present in the lunar cave to make decisions regarding the habitation possibility of the cave.The rover will also need to identify materials. Instrumentation accuracy and rover stability in the rocky environment should be heavily prioritized. The subsystems used in the rover include the Alpha Particle X-Ray Spectrometer (APXS) and Laser Induced Breakdown Spectroscope (LIBS). The APXS will derive the chemical composition and can detect radiation. The LIBS determines elemental composition of lunar soil and rocks around the landing site.

The team also prioritized technological readiness of rover technologies in order to adhere with the 2030 launch goal. LHDAC (Lander Hazard Detection & Avoidance Camera) would be a very beneficial sensor for our mission because it would enable terrain mapping, hazard detection, and safe site designation in real-time during landing maneuvers. Inclinometer & Touchdown sensors would be a beneficial sensor for the rover because it can measure the magnitude of the inclination angle or deformation of any structure. The sensor would give real time data so there can be immediate response to obstacles that arise. The Propulsion Module: 758 W is the power system used within Chandrayaan-3, the specifications for this module are 738 W and partially uses solar power. This will allow us to power our rover.

1.7 Concept of Operations

This mission aims to identify and collect samples of various materials to determine if the Compton Pit is a suitable habitation site on the Moon. To do this, a landing capsule and a rover will be used. The rover will be deployed from the capsule upon landing on the surface and will enter the pit by maneuvering down the 20-degree entrance ramp. It will have 4 to 6 wheels that should work in the many types of terrains that it could encounter on the lunar surface.

Sensors in the rover will allow it to determine the existence of oxygen, ilmenite, pyroxene, olivine, anorthite, magnesium-rich silicates, anorthitic plagioclase, hydrogen, water, and hydroxyl in the regolith in and near the pit. Once these molecules are located, the rover will be able to collect and store samples of the regolith with a retractable arm. The lander and rover will rely mostly on solar power with a backup battery source that will be determined at a later date.

Design and fabrication of this mission will continue until March 1st, 2027. Before this date, the Critical Design Review and the System Integration Review will be completed. Assembly, integration, and testing will occur from this date until launch on March 1st, 2030. Once the landing capsule makes contact with the surface, the rover will spend up to 48 hours collecting samples. Once sufficient samples are collected, the rover will return to the lander and will return to Earth. The data will be compiled and analyzed, and the rover and landing capsule will be decommissioned. The final report will be written in the months following the launch, and the mission is tentatively set to end on June 6th, 2030.

1.8 Alternative Mission Concepts

I. Alternative Pit Locations

Before selecting Compton Pit as the primary mission target, other potential lunar pit sites were explored that met the mission's requirements. The primary factors considered were entrance ramp accessibility, pit structure, thermal conditions, and the potential for containing caves, which could act as natural habitats for long-term lunar habitation. The three primary candidates evaluated were the Mare Moscoviense Pit, Sinus Iridum Pit, and Lacus Mortis Pit.

a. **Mare Moscoviense Pit**

   Mare Moscoviense Pit is a large, bowl-shaped pit with an entrance ramp that allows rover access. This pit has a lower angle ramp (8° drop over 100 m), calculated using the data tool from the Lunar Reconnaissance Orbiter Camera (LROC) map (NASA 2024a), making rover navigation potentially easier. However, it lacked the overhangs and layered wall structures present in Compton Pit, reducing the potential for discovering diverse thermal environments. Additionally, its lower latitude of 30° meant reduced chances of harboring ice, a key resource for sustaining long-term human habitation. Mare Moscoviense Pit was not chosen due to its less favorable thermal conditions and geological features compared to Compton Pit (NASA 2024a).

b. **Sinus Iridum Pit**

   Sinus Iridum Pit is elliptical in shape with a 20° drop over a 90 m ramp, also calculated using the LROC data tool (NASA 2024b). While it offers a steep entrance suitable for studying extreme terrain navigation, the pit itself is relatively featureless, lacking overhangs and nearby pits that could offer additional exploration opportunities. Its small size (a diameter ratio of 40m) also limits its suitability for large-scale operations, and it offers fewer potential scientific discoveries compared to Compton Pit. For these reasons, Sinus Iridum was deemed less suitable for the mission (NASA 2024b).

c. **Lacus Mortis Pit**

Lacus Mortis Pit presented a promising candidate with its large, diamond-shaped structure, offering a variety of geological formations such as debris slopes and overhangs. Its ramp has a 14° drop over 200 m, calculated using the data tool from the LROC map (NASA 2024c), making rover access feasible. However, it does not have the same level of permanent shadowing as Compton Pit, which decreases its potential for studying temperature variations critical to the mission's objectives. While its size and geological complexity made it an attractive option, the lack of distinct thermal features compared to Compton Pit ultimately led to its rejection (NASA 2024c).

II. Alternative Robot Designs

Potential rover designs, including Yutu-2 and Viper, were thoroughly evaluated prior to selecting Pragyan (Chandrayaan-3) as the preferred model reference for this mission. These designs were assessed based on their ability to navigate the rugged lunar terrain, endure extreme temperature fluctuations, and collect precise scientific measurements, all of which are essential for the successful exploration of the Compton Pit.

a. **Yutu-2**

Yutu-2, a rover from China's Chang'e-4 mission, has dimensions of 1.5 m × 1.0 m × 1.0 m and a weight of 140 kg. It has demonstrated excellent performance in extreme lunar conditions, particularly in the South Pole-Aitken Basin. The structure of Yutu-2 allows it to handle the lunar surface's harsh conditions, making it a viable option for navigating the steep inclines and rugged terrain of lunar pits. However, its heavier weight restricts the mission to deploying a single rover, which limits data collection flexibility and overall mission efficiency. Despite its success in moving through rough terrains, Yutu-2's larger mass and inability to carry additional instruments or secondary rovers make it less favorable for missions prioritizing multi-point data collection and increased maneuverability in confined areas such as Compton Pit (The Planetary Society 2024).

b. Viper

The Viper rover, designed by NASA for a future lunar mission initially set for 2025, is notably larger than Yutu-2, measuring 1.4 m × 1.4 m × 2 m. Its golf-cart-sized structure allows for the transportation of more scientific equipment, making it highly capable of conducting a comprehensive range of scientific investigations. Viper's design prioritizes stability and durability, key for exploring steep inclines and navigating rocky landscapes. However, its significant size and mass present challenges when operating in the narrower, more constrained environments found in lunar pits and caves (Wetzel 2021).

1.9 Programmatics

1.9.1 Team Organization

The team has been divided into three groups thus far: the Science Objective team, the Lunar Pit Selection team, and the Robot Architecture team. These teams should smoothly flow into the official Science, Programmatics, and Engineering teams. Each team member was tasked with completing a section of the Mission Concept Review, and as members dropped the academy, the remaining members picked up work as needed.

It was decided that the simplest and fairest way of determining a major decision was via a democratic approach. In order to reach a common consensus, polls were sent in the team's Discord channel. This way, members did not have to type out responses and could easily select their choice. At times, there were fewer responses to polls than expected, resulting in a consultative decision being made. There were always at least three members that supported every decision that was made, and this decision was only made if these were the only responses received.

The team is equipped to handle this project, but it's going to be a lot of work. It was not anticipated that so many of the member's would drop the academy, and it was difficult to work around this last-minute. However, the remaining members worked hard to finish as many remaining parts as possible, and if this attitude and commitment is upheld, there will be no trouble succeeding in the mission.

There has not been much need for conflict resolution up to this point simply because the primary focus has been completing this review. In the future, if conflict were to arise, the decided approach is to take into account all opinions and ideas and work through each one to come to a common consensus. The team mentor has been a helpful resource as she is able to remain more unbiased than the team members can.

1.9.2 Cost and Schedule 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).

In addition, cave exploration instrumentation will be incorporated into the rover's design in order to determine the dimensions and physical characteristics of the Compton Pit. Technology similar to this application is actively being used in cave exploration on the Earth through NASA's Biologic and Resource Analog Investigations In Low Light Environments (BRAILLE) program ("Biologic and Resource Analog Investigations in Low Light Environments", 2024). The instruments used in this cave mapping project include Near Infrared Volatile Spectrometer Subsystem (NIRVSS) and an adenosine triphosphate (ATP) luminometer. Repurposing these subsystems along with BRAILLE's Exploration Ground Data Systems (xGDS) software will result in the necessary cave mapping technology to explore the Compton Pit crater. Assuming these instruments will have to be reconstructed to fit the rover design for this mission, it is estimated that an additional $30,000,000 will be added to the total cost of this mission to account for manufacturing and testing.

By combining the rough estimates for personnel, travel, and direct vehicle related systems, a total rough cost estimate comes out at $129,865,000. In no way does this current cost estimate represent the definite cost required for the mission to be completed. While analogous solutions and assumptions were made as precisely as possible, it's difficult to find accurate measurements without defined instrumentation, personnel requirements, plans for community outreach, and distinct strategies for manufacturing and testing. These costs will be progressively updated and refined as further research is completed for each of these subsections related to the total cost 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 deliverables must be considered. The first of these two major points 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. 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 2028, 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.

ID#	TASK	START	END	DAYS
1	**Phase C: Final Design and Fabrication**	12/23/24	3/1/27	799
1.1	Draft and Submit Critical Design Review (CDR)	12/23/24	1/23/26	397
1.1.1	Develop detailed designs of necessary hardware and software	12/23/24	7/23/25	213
1.1.2	Further explain how subsystems effecitvely interface	12/23/24	10/23/25	305
1.1.3	Continue updating plans for operations, risks, and anticipated procedures for manufacturing	12/23/24	1/23/26	397
1.1.4	Submit Production Readiness Review (PRR) for necessary instrumentation	12/23/24	1/23/26	397
1.2	Draft and Submit System Integration Review (SIR)	1/23/26	1/30/27	373
1.2.1	Finalize design plans and plans for integrating the subsystems and instrumentation	1/23/26	11/23/26	305
1.2.2	Baseline how each subsystem will operate	11/23/26	1/30/27	69
1.2.3	Begin outlining the process of Verification & Validation (V&V)	11/23/26	1/30/27	69
1.3	Schedule Margin	1/30/27	3/1/27	31
1.4	◆ Completion of Phase C	2/1/22	3/1/27	1855
2	**Phase D: System Assembly, Integration & Test, Launch & Checkout**	3/1/27	3/1/30	1097
2.1	Complete Test Readiness Reviews (TRRs) of Instrumentation and System	3/1/27	3/1/28	367
2.1.1	Manufacture system components and then assemble and integrate them	3/1/27	1/1/28	307
2.1.2	Inspect instrumentation and system capability to obtain science measurements	1/1/28	3/1/28	61
2.2	Draft and Submit Operational Readiness Review (ORR)	10/1/27	2/1/29	490
2.2.2	Test instrumentation and instate confidence in its usage	10/1/27	3/1/28	153
2.2.3	Begin V&V of subsystem and instrumentation results	3/1/28	5/1/28	62
2.2.4	Finalize operations plans and procedures	10/1/27	2/1/29	490
2.2.5	Baseline plans for decommissioning and disposing of the robot after mission completion	5/1/28	2/1/29	277
2.3	Draft and Submit Mission Readiness Review (MRR)	2/1/29	1/1/30	335
2.3.1	Baseline and verify V&V results	2/1/29	1/1/30	335
2.3.2	Prepare launch and confirm spacecraft flight/launch capability	5/1/29	1/1/30	246
2.4	Complete Safety and Mission Success Review	1/1/28	1/1/30	732
2.4.1	Continuously update risks	1/1/28	1/1/30	732
2.4.2	Perform safety review assessing launch and mission safety	5/1/29	1/1/30	246
2.5	Launch Vehicle (LV)	1/1/30	3/1/30	60
2.5.1	Complete Launch Readiness Review (LRR)	1/1/30	2/1/30	32
2.5.2	Launch Mission	3/1/30	3/1/30	1
2.6	Schedule Margin	3/1/30	3/1/30	1
2.7	◆ Completion of Phase D	3/1/27	3/1/30	1097

Figure 3: Schedule estimate for Phases C and D of HELP.

ID#	TASK	START	END	DAYS
3	**Phase E: Operations and Sustainment**	3/1/30	5/6/30	67
3.1	Complete Post-Launch Assessment Review (PLAR)	3/1/30	3/10/30	10
3.1.1	Conduct vehicle launch performance assessment	3/1/30	4/1/30	32
3.2	Complete Critical Events Readiness Review	3/4/30	4/19/30	47
3.2.1	Activate science instruments upon landing	3/4/30	3/4/30	1
3.2.2	Collect data measurements concerning surface features	3/4/30	3/18/30	15
3.2.3	Visit Compton Pit and cave map the pit dimensions and structural features	3/19/30	4/19/30	32
3.2.4	Collect measurements concerning cave temperature and radiation	3/19/30	4/19/30	32
3.3	Complete Decomissioning Review (DR)	4/19/30	5/1/30	13
3.3.1	Begin process of decomissioning the robot systems	4/19/30	5/1/30	13
3.3.2	Outline potential upgrades for future missions	4/19/30	5/1/30	13
3.3.3	Conduct safety review	4/19/30	5/1/30	13
3.4	Compile and Document Collected Data Efficiently	3/4/30	5/1/30	59
3.5	Schedule Margin	5/1/30	5/6/30	6
3.6	◆ Completion of Phase E	3/1/30	5/6/30	67
4	**Phase F: Closeout**	5/6/30	6/6/30	32
4.1	Complete Disposal Readiness Review (DRR)	5/6/30	5/7/30	2
4.1.1	Conduct robot disposal according to outlined plans	5/6/30	5/7/30	2
4.2	Ensure Organized Documentation and Draw Conlusions Based on the Collected Data	5/6/30	5/7/30	2
4.2.1	Baseline and write up the mission final report	5/6/30	6/1/30	27
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	27
4.3	Schedule Margin	6/1/30	6/6/30	6
4.4	◆Completion of Phase F and Mission	5/6/30	6/6/30	32

Figure 4: Schedule estimate for Phases E and F of HELP.

1.10 Conclusion

With a set launch date for March 1, 2030, HELP is tasked with going to the Compton Pit to gather data as well as evaluate it as a potential stable thermal environment. The lunar rover will be sent out to get information regarding getting spectral signatures of Oxygen and water as well as in situ resources. The other goal includes characterizing the terrain, accessibility, and adaptability of the Compton Pit all to assist future lunar habitation. This MCR outlines the hazards, system evaluation criteria, mission programmatics, team organization, and costs and schedule estimates.

This mission lays the foundation for future endeavors to establish human habitation on the Moon. Given more time, the robotic architecture would be further defined, as well as its individual subsystems and instrumentation. This research would further be represented in the completion of the STM. The physical environmental hazards could further be improved upon to cover all necessary risks to consider. In the future, team roles will be assigned, leading to an improved system of communication and organization that will also help induce better strategies for work completion and decision making. The TBDs displayed in the STM will also be fulfilled as instrumentation is defined and performance expectations are updated. Approaching the System Requirements Review (SSR), these points of improvement will be taken into consideration and applied in order to update the information baselined throughout this document and begin outlining system requirements.

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Appendix

Appendix A: Table of TBD/TBRs

TBD/TBR #	Plans and Timeline for Resolution
1-20	TBDs 1-20 signify a performance required value for each instrument incorporated into HELP's design. Each of these required values will correlate to required performance parameters. Since the instrumentation has yet to be confirmed and the robot architecture is still in its beginning stages, this column of the STM is yet to be completed, and will be further filled out in the near future leading up to the SRR.
21-40	TBDs 21-40 signify a performance required performance and expectations for each instrument incorporated into HELP's design. Each of these required performances will specify what the instruments must do to obtain the required values. Since the instrumentation has yet to be confirmed and the robot architecture is still in its beginning stages, this column of the STM is yet to be completed, and will be further filled out in the near future leading up to the SRR.
41-44	TBDs 41-44 in the STM include mission requirements for the observables/parameters outlined for HELP. These requirements will specify what must happen for the data measurements to be sufficiently obtained, and for conclusions to subsequently be drawn. This column will be continuously updated and finalized approaching the SRR as instrumentation designs/plans become confirmed.

Appendix B: Mission Requirements

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	SCI.1		Demonstration

		accurate identification.			
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 (O2), water (H2O), and Hydroxyl (OH) molecules in the regolith.	To map the availability of water and essential gases 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, O2, H2O, 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	SCI.3		Demonstration

		levels of radiation and manageable temperature variations.			
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