L'SPACE MCA

Planetary Habitat Operations & ExploratioN Investigation eXpedition

MISSION DEFINITION REVIEW

TEAM 1 - P.H.O.E.N.I.X

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Table of Acronyms

Abbreviation	Definition
ADV	Action/Decision Vector
AI	Artificial Intelligence
AZUR	AZUR Space Solar Power GmbH
CCB	Change Control Board
CCHP	Constant Conductance Heat Pipe
CDH	Command and Data Handling
CDR	Critical Design Review
CER	Cost Estimating Relationships
ConOps	Concept of Operations
COTS	Commercial Off-The-Shelf
CP-MU	Critical Protection - Monitoring Unit
DC	Direct Current
DMU	Data Management Unit
ECC	Error-Correcting Code
EMI	Electromagnetic Interference
EOL	End Of Life
ESDMD	Exploration Systems Development Mission Directorate
FMEA	Failure Modes and Effects Analysis

Abbreviation	Definition
FPS	Fluid Protection System
HBS	Human Biology System
IMU	Inertial Measurement Unit
ISRU	In-Situ Resource Utilization
JMARS	Java Mission Planning and Analysis for Remote Sensing
JPL	Jet Propulsion Laboratory
L’SPACE MCA	L’SPACE Mission Concept Academy
L’SPACE NPWEE	L’SPACE Proposal Writing and Evaluation Experience
MCCET	Mission Concept Cost Estimate Tool
MCR	Mission Concept Review
MG	Mission Goal
Mini-TLS	Miniature Tunable Laser Spectrometer
MLI	Multi-Layered Insulation
MRO	Mars Reconnaissance Orbiter
MDR	Mission Definition Review
NASA NCAS	NASA Community College Aerospace Scholars
PDR	Preliminary Design Review
PWR	Power
RAD	Radiation Assessment Detector

Abbreviation	Definition
RIMFAX	Radar Imager for Mars' Subsurface Experiment
RLS	Raman Laser Spectrometer
ROI	Region of Interest
ROSA	Roll-Out Solar Array
RTG	Radioisotope Thermoelectric Generator
SMD	Science Mission Directorate
SRB	Systems Review Board
SRR	System Requirements Review
STM	Science Traceability Matrix
SYS	System
TCS	Thermal Control System
TBD	To Be Determined
TBR	To Be Resolved
TLS	Tunable Laser Spectrometer
TRL	Technology Readiness Level
UHF	Ultra High Frequency
VCHP	Variable Conductance Heat Pipe

1.0 Mission Definition Review

1.1 Mission Statement

P.H.O.E.N.I.X (Planetary Habitat Operations & Exploration InvestigatioN eXpedition) is an unmanned rover mission to Mars. The basic mission design is derived from the goal of investigating subsurface ice reservoirs to characterize environmental hazards, and better understand them in order to support future human exploration. As with NASA's Discovery-class missions, the rover will land in the northern mid-latitudinal region of Mars where there is high potential for shallow ice beneath the surface. This location is also favorable due to high solar solar access, and traversable terrain for the rover to collect data on. The mission aligns with the NASA Science Mission Directorate (SMD) and Exploration Systems Development Mission Directorate (ESDMD) by targeting in-situ resource utilization (ISRU), minimizing risks and hazards, and driving habitability research.

Science goals are derived from NASA's HBS-1LM Moon to Mars Objective and the Origins, Worlds, and Life Decadal Strategy goal Q10.3b. The mission is guided by four key objectives. The first encompasses assessing the effects of radiation on a pressurized liquid sample using a neutron probe, informing ISRU and life support safety based on the results. Secondarily, analysis of subsurface stratigraphy and dielectric properties via radar to evaluate ice accessibility and potential for potable water. Third, determining the ratio of certain hydrogen atoms available in samples of hydrated volcanic rock with a laser spectrometer to trace water source evolution. Finally, to identify the crystal structure of asteroid-impact minerals using a Raman Laser Spectrometer to study endogenic and exogenic processes affecting water distribution.

To accomplish these objectives, P.H.O.E.N.I.X is engineered for long-duration autonomous operation in harsh Martian conditions. Its mechanical subsystem utilizes a heritage rocker-bogie suspension, titanium fittings, and an aluminum chassis for resilient mobility across more than 10km of variable terrain. The power subsystem includes ROSA-style solar panels, a 4300 Wh lithium-ion battery, and a smart distribution unit for efficient, fault-tolerant energy management. The CDH system features radiation-hardened processing and redundant communication pathways. Thermal control maintains internal temperatures from -120°C to +30°C using multilayer insulation and active heating using electric heaters. All subsystems meet planetary protection guidelines and mission constraints on mass, volume, cost and schedule.

By locating accessible water ice, monitoring radiation exposure, and expanding understanding of Martian water cycles, P.H.O.E.N.I.X delivers critical data to guide astronaut landing site selection and surface system design. The mission represents a significant step toward enabling a sustainable human presence on Mars.

1.2 Science Traceability Matrix

The Science Traceability Matrix (STM) holds the primary focus of four objectives derived from the *Human Exploration goal HBS-1LM* and the *Science Exploration goal Q10.3b*.

Human Exploration goal HBS-1LM objectives:

These objectives below will contribute directly to goal *HBS-1LM* by increasing knowledge of planetary science, planetary geology, and materials engineering innovation that is vital to understanding the Martian environment, sustaining long-duration manned missions, and protecting the health of astronauts. Mission constraints are met within the instruments' 15kg allocated mass, volume, and resolution requirements.

1. Investigate potential Martian environmental exposure impacts on a custom-engineered, pressurized, and rover-attached Fluid Protection System (FPS) that internally houses the CP-MU DMU-100 Submersible Gamma Neutron Probe and an earth water sample. The probe will use its passive ionization chamber to monitor for, document, and transmit gamma radiation level (μSv/h) fluctuations in weekly intervals for a minimum of one year. The planetary science data collected from this objective will drive Materials Engineering innovation to uncover and eliminate planetary hazards that threaten the integrity of mission-critical fluids (life support, rocket propellant, agricultural fluids containing minerals for successful plant cultivation, and drinking water) in transportation, storage and recycling on the Martian surface during future long-duration manned missions. This research is essential for preventing fluid contamination, depressurization and explosion hazards, and unstable thermal regulation across the extreme temperature variations of the Martian environment.

2. Investigate how subsurface stratigraphy, dielectric properties, and dust layer thickness influence the accessibility and long-term stability of near-surface ice. The Radar Imager for Mars' Subsurface Experiment (RIMFAX) will use a ground-penetrating radar to analyze signal delays and reflection strength, allowing identification of subsurface layer boundaries, material transitions, and dielectric properties indicative of dust and possible ice-rich zones [18]. From these observables, dielectric permittivity and radar wave velocity can be estimated to derive subsurface material properties such as layer thickness, composition variation, and porosity across a 10 km traverse [18].

Science Exploration goal Q10.3b objectives:

These objectives below will contribute directly to goal Q10.3b by exploring the geological history of the Martian subsurface and the environmental impact on the endogenic and exogenic controls on the presence of liquid water. The stakeholder's experiment constraints of 185 kg mass, under 5 grams of radioactive materials, and $450 million budget for the system and its instruments are met within these requirements. Under the prohibited materials constraint the Radioisotope Thermoelectric Generator (RTG} is prohibited and not used.

1. Determine the Deuterium to Hydrogen (D/H) ratio in hydrated volcanic rock on the Martian surface for understanding the history of water presence through insights into the sources, losses, and recycling of water. The Miniature Tunable Laser Spectrometer (TLS) will collect absorbance spectra in the 2500–25,000 nm range of H in hydrated volcanic rock samples in order to define the relative abundance of protium and deuterium, demonstrate an understanding of the long-term controls that have influenced the availability of liquid water on Mars through both endogenic, such as internal volcanic and geologic processes, and exogenic, such as surface-atmospheric interactions.

2. Determine the crystal structure of minerals formed by asteroid impacts that interact with exposed subsurface ice within 0-1m depth for understanding the long-term endogenic and exogenic controls on the presence of Martian liquid water. The Raman Laser Spectrometer will operate within ±10% mineral identification accuracy, 10 cm^{-1} spectral resolution and a 6–8 cm^{-1} peak separation capability allowing for precise and accurate identification of hydroxyl groups and raman spectra collection in Olivine in asteroid rocks surface sites. This investigation explores Martian geological history, its evolution to the present state through the past Martian dynamic force interactions, and how time has affected the subsurface.

<table>
<tr><th rowspan="2">Science Goals</th><th rowspan="2">Science Objectives</th><th colspan="2">Science Measurement Requirements</th><th rowspan="2" colspan="2">Instrument Performance Requirements</th><th rowspan="2">Predicted Instrument Performance</th><th rowspan="2">Instrument</th><th rowspan="2">Mission Requirements</th></tr>
<tr><th>Physical Parameters</th><th>Observables</th></tr>
<tr><td rowspan="8">"HBS-1LM: Understand the effects of short- and long-duration exposure to the environments of the Moon, Mars, and deep space on biological systems and health, using humans, model organisms, systems of human physiology, and plants." — Moon to Mars Objectives, NASA</td><td rowspan="4">Investigate the long duration Martian environmental impacts on a protected and pressurized earth-fluid sample for unknown hazards that may threaten the integrity of future mission-critical life support, rocket propellant, and agricultural fluids.</td><td rowspan="4">Periodically monitor the Earth fluid sample for risks, hazards, and contamination that may bypass the custom-engineered Fluid Protection System's protective layers and document via data generation.</td><td rowspan="4">Use a passive ionization chamber to monitor gamma radiation levels in μSv/h, recording data at weekly intervals over a one-year period for transmission back to Earth.</td><td>Range</td><td>1 μSv/h to 10Sv/h</td><td>1 μSv/h to 10Sv/h</td><td rowspan="4">CP-MU DMU-100 Submersible Gamma Neutron Probe</td><td rowspan="3">The instrument must survive fluid submersion for a minimum of one year while measuring for potential radiation contamination within the fluid protection system.</td></tr>
<tr><td>Operating Temperature</td><td>30°C to +57°C</td><td>30°C to +57°C</td></tr>
<tr><td>Accuracy</td><td>±5%</td><td>±10%</td></tr>
<tr><td>Time Constant</td><td>12 seconds slow</td><td>2 seconds fast, 12 seconds slow</td><td rowspan="4">The instrument must study the difference in permittivity to identify insulating dust layers and potential ice-rich zones</td></tr>
<tr><td rowspan="4">Investigate how subsurface stratigraphy, dielectric properties, and dust layer thickness affect the accessibility and long-term stability of near-surface water ice, in support of in-situ resource utilization and environmental risk reduction for future human exploration.</td><td rowspan="4">Estimate dielectric permittivity and radar wave velocity to characterize subsurface material properties, including layer thickness, composition changes, and porosity variations across a 10 km traverse.</td><td rowspan="4">Analyze radar signal delay and reflection strength to determine layer boundaries, depth to subsurface features, and dielectric (Ɛ) contrasts indicative of dust deposits and possible ice-rich zones.</td><td>Penetration Depth</td><td>≥ 10 km</td><td>≥ 10 m</td><td rowspan="4">Radar Imager for Mars' Subsurface Experiment (RIMFAX)</td></tr>
<tr><td>Frequency Range</td><td>100-1200 MHz</td><td>150-1200 MHz</td></tr>
<tr><td>Permittivity Range</td><td>$\Delta\varepsilon_r \leq 0.1$</td><td>$\Delta\varepsilon_r \leq 2$</td></tr>
<tr><td>Vertical Resolution</td><td>≥ 15 cm</td><td>15 cm - 30 cm</td><td>The instrument must detect the subsurface layering to a depth of at least 10 m to assess ice stability underneath dust and regolith</td></tr>
</table>

<table>
<tr><td rowspan="8">“Q10.3b: What are the long-term endogenic and exogenic controls on the presence of liquid water on terrestrial planets?”— Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032</td><td rowspan="4">Determine the Deuterium to Hydrogen (D/H) ratio in hydrated volcanic rock on Mars' surface.</td><td rowspan="4">Define the relative abundance of protium and deuterium within samples of hydrogen from hydrated volcanic rock.</td><td rowspan="4">Collect absorbance spectra in the 2500–25,000 nm range of H in selected hydrated volcanic rock samples at multiple surface sites.</td><td>Wavenumber Range</td><td>3593.3-3594.3 cm^-1</td><td>3593.3-3594.3 cm^-1</td><td rowspan="4">Miniature Tunable Laser Spectrometer (Mini-TLS)</td><td rowspan="3">System must navigate to and collect samples of hydrated volcanic rock.</td></tr>
<tr><td>Spectral Resolution</td><td>0.0001 cm^-1</td><td>0.0001 cm^-1</td></tr>
<tr><td>Sensitivity</td><td><80 ppb</td><td>10 ppb</td></tr>
<tr><td>Integration Time</td><td>1 s</td><td>2.4 s</td><td rowspan="3">System must have the ability to heat volcanic rock to 935 K to study structural water released as gas.</td></tr>
<tr><td rowspan="4">Determine the crystal structure of minerals formed by asteroid impacts interacting with exposed subsurface ice.</td><td rowspan="4">Identify chemical structure, crystal structure, and bond structure of Olivine from asteroids.</td><td rowspan="4">Collect raman spectra in the 11,111–33,333 nm range of Olivine in selected asteroid rocks at multiple surface sites.</td><td>Mineral Identification Accuracy</td><td>±10%</td><td>≥ 90%</td><td rowspan="4">Raman Laser Spectrometer (RLS)</td></tr>
<tr><td>Detection Sensitivity</td><td>≤ ~100 ppm</td><td>6–8 cm^{-1} peak separation</td></tr>
<tr><td>Power Consumption</td><td>20 - 30W</td><td>Between 20 - 30 watts</td><td rowspan="2">System must operate in the Martian Temperature range of 293.15° K to 120.15° K</td></tr>
<tr><td>Spectral Resolution</td><td>10 cm^{-1}</td><td>10 cm^{-1}</td></tr>
</table>

Figure 1.2.1: Science Traceability Matrix

1.3 Mission Requirements

Customer constraints are a key driver of mission architecture, which determines the high-level requirements concerning mass, volume, and budget. Team P.H.O.E.N.I.X seeks to meet the system constraints presented by NASA, serving as the funding agency for the Mission Concept Academy's Discovery-class mission.

The spacecraft shall not exceed a mass of 200 kg. In a stored configuration, the spacecraft shall not exceed the dimensions of 2.5 m x 2.5 m x 2.5 m. This volume will house all the electronics, instruments, and payload suite. The spacecraft shall maintain the stored configuration for the entirety of the launch, transit, and entry into the Martian atmosphere. In an expanded form, there is no volume or mass constraint placed on the spacecraft. The spacecraft shall demonstrate resistance to temperatures consistent with atmospheric entry and descent. The spacecraft shall incorporate a landing attenuation system capable of withstanding surface impact.

After deployment on the landing site selected, the spacecraft shall traverse the terrain effectively to travel a minimum of 10 km. The spacecraft shall demonstrate an ability to traverse various Martian terrains, including sandy regions, icy regions, and small, medium, and large-sized rocks. The spacecraft shall demonstrate the ability to endure fluctuations in Martian atmospheric conditions, including dust storms, diurnal temperature variations, and reduced atmospheric pressure.

The spacecraft shall carry a scientific payload containing all instrumentation to complete science objectives. The volume of the scientific payload shall not exceed a cube of dimensions 0.5 m x 0.5 m x 0.5 m, nor a mass of 15 kg. This is to ensure the mission satisfies the human exploration goal and gets samples from the Martian surface that can be transmitted back to Earth for research. Furthermore, this research will contribute a great deal to the future of sustainability on Mars and future manned missions.

P.H.O.E.N.I.X is a discovery mission and not a flagship mission; hence, the budget allocated to this mission is 450 million USD and shall be used effectively for the manufacturing of the spacecraft, its components, employee-related expenses (ERE), and testing of the spacecraft. The Spacecraft system shall not have a Radioisotope Thermoelectric Generator (RTG) or any similar power generation system. Furthermore, any radioactive material is allowed for use on other spacecraft subsystems, but cannot exceed a cumulative mass of 5g of radioactive material on all subsystems. The spacecraft must be ready for integration with the other systems by October 1st, 2029, and must be ready for launch on December 1st, 2029. The launch site shall be in Cape Canaveral in Florida.

Req #	Requirement	Rationale	Parent Req.	Child Req.	Verification Method	Req. met?
MG 0.1	System shall survive the martian environment for a minimum of one year.	The system must be able to survive the martian environment to fulfill its purpose and send data back to earth ground station and potentially return martian samples	Customer	SYS.01 SYS.02 SYS.05 SYS.06 MECH.01 PAYL.02	Demonstration	Met
MG 0.2	Shall investigate the presence of ice glaciers on Mars for future missions and sustainability	Foundational science driver for the mission: Human habitation requires large volumes of drinkable water, water for propellant and agricultural use for long term sustainability missions on Mars	Customer	SYS.03 SYS.07 SYS.08	Demonstration	Met
SYS.01	The system shall have sufficient power to carry out the objectives for the duration of it's mission	System needs power to operate, communicate back to earth and carry out its objectives	MG 0.1	PWR.01	Test	Met
SYS.02	System shall maintain operating temperatures and survive the harsh thermal environment ranging from on the martian surface	The system and its scientific instrumentation must be kept in operating temperature ranges in order to function properly	MG 0.1	TCS.01	Test	Met
SYS.03	System shall traverse the martian surface smoothly and reach the required science points of interest	Points of interest are marked across potential high priority Radar targeting zones on Mars that are defined by the thickness of the atmosphere to allow for easy landing and research point.	MG 0.2	MECH.02 MECH.03 MECH.04	Test	Met
SYS.04	System shall not exceed a total mass of 200kg	Constraints provided by NASA for the mission	Customer		Inspection	Met
SYS.05	System shall have a backup that is always	In the case of failure, if the main system fails, the backup can takeover and still carry out the	MG 0.1	PWR.04 PWR.05	Analysis	Met

	ready to take over	mission				
SYS.06	System must withstand the solar winds for the duration of its mission	All components on the rover must be strong enough to withstand the strong solar winds on mars	MG 0.1	PWR.02 PWR.03	Test	Met
SYS.07	System shall send and receive data collected with the science instrumentation back to the earth ground station	Data sent back to the earth ground station about Mars will be essential to future scientific research for sustainability on mars	MG 0.2	CDH.03 CDH.04	Analysis	Met
SYS.08	System shall comply with all applicable planetary protocol regulations	NPR 8020.12D *Planetary Protection Provisions for Robotic Extraterrestrial Missions*	MG 0.2		Analysis	Met
SYS.09	Radioactive material used for any subsystem excluding the power subsystem shall not exceed a total mass of 5g	Constraints provided by NASA for the mission	Customer		Inspection	Met
SYS.10	System shall not make use of a Radioisotope Thermoelectric Generator (RTG) or any derivative thereof for power generation	Constraints provided by NASA for the mission	Customer		Inspection	Met
SYS.11	System shall not exceed the dimensions of 2.5 m x 2.5 m x 2.5 m while in its stored configuration	Constraints provided by NASA for the mission	Customer		Inspection	Met
SYS.12	System shall not exceed a cost of $450M	Constraints provided by NASA for the mission	Customer		Inspection	Met
CDH.01	The Command and Data Handling (CDH) system shall have a minimum uplink rate of 1 Mbps and a	The system must be able to send scientific and telemetric data to and from Earth.	SYS.07	CDH.02	Analysis	Met

	minimum downlink rate of 16 Kbps.					
CDH.02	The CDH system shall have a minimum processing rate of 1 GHz.	The system must be able to process the scientific and telemetric data it receives from both Earth and instrumentation/sensors.	CDH.01		Test	Met
CDH.03	The CDH system shall have a minimum memory of 8 GB of RAM.	Provides working memory for executing flight software, processing sensor data, running algorithms, and sending commands.	SYS.07		Inspection	Met
CDH.04	The CDH system shall have a minimum storage of 10 TB.	Due to incoming datastreams and intermittent opportunities for uplink, large onboard data storage helps limit data loss and data can be stored for the duration of the mission.	SYS.07		Inspection	Met
MECH.01	The chassis shall tolerate a static load up to 1500 N.	The system must not risk fracture or fatigue that would result in complete structural failure and inability to carry out the mission.	MG.01		Analysis	Met
MECH.02	Mechanical subsystems shall tolerate vibrations up to 2000 Hz.	The system must be able to tolerate vibrations from travel.	SYS.03		Analysis	Met
MECH.03	Suspension subassembly shall tolerate shock loads up to 6000 N.	The system must be able to tolerate shock loads from travel.	SYS.03		Analysis	Met
MECH.04	Suspension subassembly shall withstand a 45 degree tilt in any direction.	The system must be able to tolerate tilts from travel.	SYS.03		Demonstration	Met
PWR.01	The system shall generate at least 200 Wh per sol under average Martian insolation and withstand peak power draws of 120 W for a minimum of 30 minutes up to 3 times per Sol.	Supports nominal rover operation, mobility, communication and science payloads	SYS.01		Analysis	Met
PWR.02	Solar panels shall deploy autonomously and tolerate	Ensures survivability under common Martian conditions	SYS.06		Test	Met

	up to 20 m/s wind.					
PWR.03	The system shall maintain operation of critical components between -30°C to +50°C.	Ensures battery and electronics functionality	SYS.06		Test	Met
PWR.04	The system shall minimize integration risk using EMI shielding to absorb shockwaves and modular connectors to divert signals from critical components.	Reduces failure during integration and operations	SYS.05		Test	Met
PWR.05	Provide redundant power paths for critical systems via RCE's and power and analogue modules	Enhances fault tolerance by dividing power distribution and handling between two computers, helping to reduce uptime	SYS.05		Test	Met
TCS.01	The Thermal Control System (TCS) shall help maintain the system at the allowable temperature range of 303K to 313K.	This ensures the TCS keeps components within safe temperature limits to prevent failure from Mars' extreme thermal conditions.	SYS.02	PAYL.04	Test	Met
PAYL.01	RIMFAX shall detect radar signal changes in subsurface layers down to 10 meters depth.	Fulfills Human Exploration science objective #2 by identifying ice-rich zones defined by a permittivity difference of less than or equal to 0.1.	MG.02		Test	Met
PAYL.02	CP-MU Submersible Gamma Neutron Probe shall measure and record radiation dosage measurements ranging from 1 μSv/h to 10 Sv/h.	Fulfills Human Exploration science objective #1 by recording Martian environmental radiation impact data in the transported Fluid Protection System over a minimum one year duration period.	MG 0.1		Test	Met
PAYL.03	Miniature Tunable Laser Spectrometer shall collect and receive data from hydrated volcanic rock	Fulfills Science Exploration science objective #2 by determining the Deuterium to Hydrogen (D/H) ratio.	SYS 0.7		Test	Met

	within a 1-second integration time.					
PAYL.04	Raman Laser Spectrometer shall collect Olivine Raman spectra in the 11,111–33,333 nm range.	Fulfills Science Exploration science objective #2 by identifying the chemical structure, crystal structure, and bond structure of Olivine from asteroids.	TCS.01		Test	Met

Figure 1.3.1: Requirements Table

1.4 Concept of Operations

P.H.O.E.N.I.X shall be a semi-autonomous exploration rover, designed to contribute to the goals of the NASA Science Mission Directorate (SMD) and Exploration Systems Development Mission Directorate (ESDMD). The Concept of Operations (ConOps) encompasses the operational steps involved in landing, all activities on the Martian surface, and decommissioning. The purpose of the experiment is to investigate subsurface ice reservoirs, characterize environmental hazards, and better understand them in order to support future human exploration.

The rover shall begin surface deployment procedure upon T-1 sol, Martian day, of landing at the designated chosen landing site. It shall begin activation of the system operational instruments. The power systems shall first be stabilized. Upon power stabilization, the scientific instruments shall be deployed and brought online, and initial communication and telemetry tests shall be conducted. Thermal control systems shall be activated to maintain the appropriate daylight temperature, which includes using heaters to ensure the electronics operate within their designated temperature range. The rover shall then calibrate the scientific instruments and await initial command from ground operations located at Kennedy Space Center.

As seen on the ConOps graphic, the mission is divided into 5 major operational phases: Rover Touchdown (T+1 days), Traversal to Target Site (T+2-44 days), Science Mode (T+45 days), Repeat Sites #2-#3 (T+46-135 days), and End of Life (T+135-365 days). Rover Touchdown (T+1 days) consists of verification of Instrument Calibration, System Start-up, Data Link, and Signal Verification, as well as the initial command execution from MRO. Traversal to Target Site (T+2-44 days) contains a Day and Night Mode to better allocate available power during the autonomous travel period. Day mode has the rover traveling as TBD km/h with a Heartbeat telemetry transmitted at TBD hz, while Night mode aids in power conservation by having the rover traveling TBD km/h with a reduced Heartbeat telemetry transmitted at TBD hz, with the addition of the electric heaters powered on and solar panels retracted back into the rover. In all modes, power will be focused on thermal control systems and maintaining appropriate temperatures throughout the system. The transition from day mode to night mode shall repeat throughout the Martian sol cycle during the autonomous travel period to the designated science site. Science Mode (T+45 days) utilizes a Gamma Ray Neutron probe to detect radiation, while RIMFAX sends radio-frequency electromagnetic waves. The surface Mini TLS heats up rocks and collects gas to measure the D/H ratio. The RLS emits a laser beam and gets a spectroscopic reading. All data is stored and transmitted to MRO. Repeat Sites #2-#3 (T+46-135 days) have the rover traveling to complete additional mission locations. End of Life (T+135-365 days) has final data transmission, and the system finally shuts down.

After verification of all systems, the rover shall begin autonomous travel to the designated science site at TBD rate of travel by the design of the rover and the environment, which shall occur at TBD sol after surface deployment procedure and instrumental calibration.

Upon arrival at the science site, a switch will occur from either day or night mode to science mode. Once switched to science mode the system will deploy its science instrumentation for use similarly to that of Mars 2020 Perseverance [28]. Once science instrumentation is deployed the system shall begin calibration of science instruments and ready systems for data collection. Instrument calibration occurs during Rover Touchdown (T+1 days), where scientific instruments undergo initial system checks to confirm functionality.

Once science instruments have been successfully deployed and calibrated data and sample collection of ice on the Martian surface will begin. P.H.O.E.N.I.X shall relay all collected data during its time in science mode to the Mars Reconnaissance Orbiter, which shall relay stored data to Earth for scientific research on the future of sustainability on Mars.

Upon completion of the data collection objectives at the designated travel site, the rover shall travel to the next site and repeat travel mode and science mode procedures until completion of the mission objective.

Towards the end of the mission, the rover shall transmit all scientific stored data to the MRO and conduct standard shutdown procedures and proceed into a dormant state. This will be implemented by a command executed by the OBC once all of the scientific objectives have been achieved, the scientific data required has been acquired and the rover is not able to further continue to traverse or it full-fills the mission timeline decided by the team.

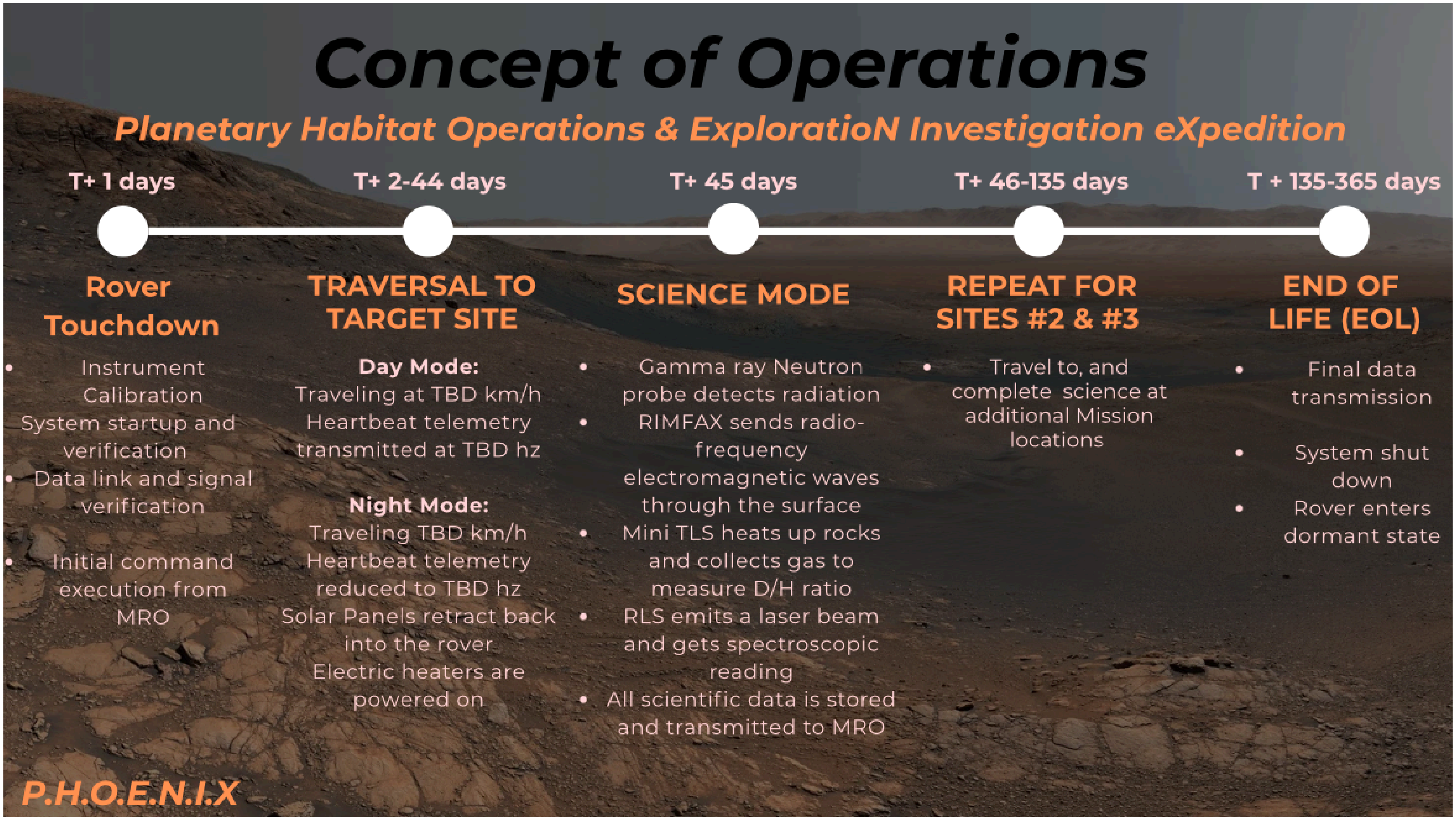

Figure 1.4.1: Concept of Operations

1.5 Team Management Overview

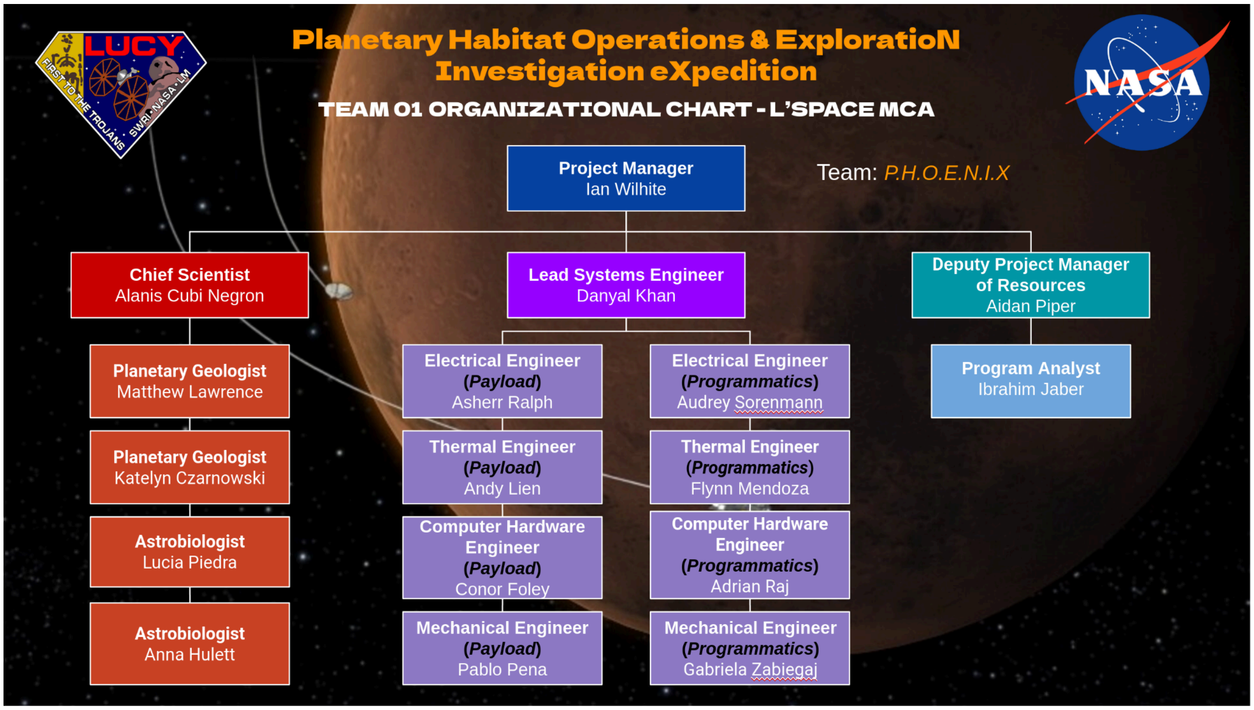

Figure 1.5.1: Organizational Chart

Current workload distribution follows a similar structure to past deliverables where the deliverable is split into broad sections which are then assigned to subteams by the project manager. Subteam leads then assign individual tasks and sections to individuals or small groups on their subteam. By tracking progress with a shared spreadsheet, the team reinforces mutual accountability while setting a clear pace for the completion of the deliverable.

Team organization has shifted slightly since the SRR to accommodate personnel turnover within the programmatic subteam. An updated organizational chart, seen in Figure 1.5.1, reflects the departure of dedicated mission assurance specialists. In response to changes in personnel, all team members are now expected to document and mitigate risks as they perform their expressly assigned tasks while the DPMR coordinates high-level tracking and communication regarding risks.

The decision-making methodology of the team remains largely unchanged from its original iteration, focusing on input from the entire team before the leadership makes a decision. This process proved effective following the addition of a separate science experiment payload and the subsequently associated descope. As the decision was not time-sensitive, the team was able to discuss the options regarding how to incorporate the addon and the benefits and drawbacks of each approach. By taking in feedback from all members, this approach led to success in a real-world environment. After considering the feedback, team leads and the project manager selected an external mounting option. While this approach is preferred when time allows, the team can still exercise the option to consult the relevant subteam members, team lead, and project manager when time is of the essence.

Moving forward, there are a few areas where the team can improve. Firstly, by implementing an unobtrusive system of informal progress check-ins, whether it be at the beginning of each subteam's weekly meeting or through some asynchronous upload of a research summary, trade study, or section drafts, the team reduces procrastination without overburdening members. Secondly, reinforcing active usage of the task tracker will ensure everyone can get a status update on the team's progress at just a glance.

In recent weeks, the team has faced some challenges ranging from personnel turnover to the sudden announcement of a third-party payload being integrated into the spacecraft. The team also recently had to adjust to the withdrawal of the two dedicated mission assurance specialists. Not only did this loss in personnel impact the programmatics subteam, but also the team as a whole given the role's dedicated focus on identifying, documenting, and mitigating risks. As noted above, the team distributed the responsibility of mission assurance across the entire team with the DPMR overseeing. Aside from personnel issues, the team had to adjust and rescope following the addition of a third-party science payload. Key impacts were identified across all three subteams and a cohesive plan to move forward within the new design constraints and considerations was devised.

1.6 Project Management Approach

For a NASA Discover-Class mission team sized between thirty and fifty personnel, the project's leadership and organizational structure is critical for team efficiency and mission effectiveness. At the top of the organizational chart, the Project Manager (PM) assumes responsibility for overall mission execution. They also possess authority over technical, programmatic, and personnel decisions. The Deputy Project Manager of Resources (DPMR) serves as the PM's primary support, overseeing daily operations and acting as the PM when necessary. Resources and project controls, including budgeting, major scheduling milestones, and compliance, fall under the DPMR. The DPMR directly oversees the programmatic team, however works in close coordination with both technical subteams.

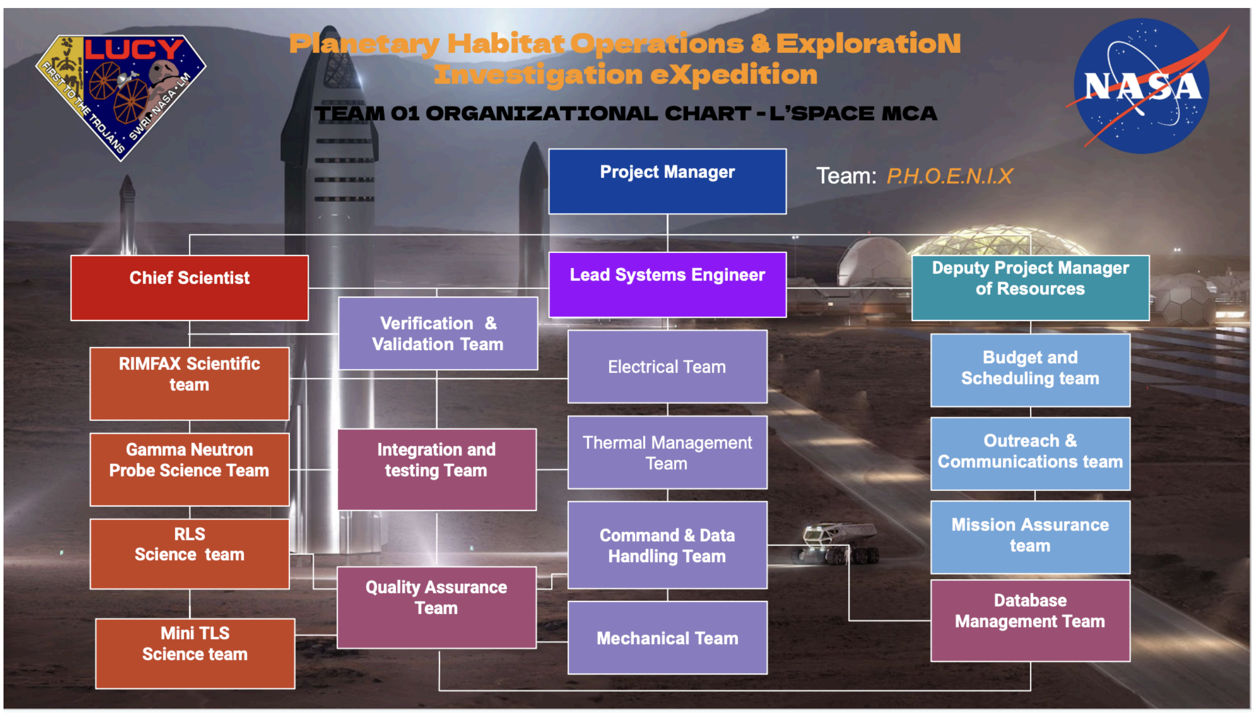

Figure 1.6.1: Teamwide Organizational Chart

The team has decided to move forward with ten engineers per subteam. These engineers will serve to draft technical documentation, oversee contractors during manufacturing, ensure proper integration and testing. Additionally, each subteam shall consist of five technicians, a quality assurance specialist. The team has also decided to move forward with a Verification and Validation (V&V) team that will consist of ten personnel responsible for verifying requirements across each Engineering subteam and scientific instrumentation. The V&V team will ensure the system shall meet specifications and shall serve mission needs. Each scientific instrument shall also have its own subteam, after a detailed review with the Chief scientist, the team decided there will be five scientists per instrument each having its own technician and a quality assurance specialist. Figure 1.6.1 represents the team-wide organizational structure that includes every personnel responsible for the success of this mission.

All subsystem leads including those for mechanical, thermal, CDH, electrical and payload systems will report directly to the Lead Systems Engineer. This chain of command ensures successful integration and coordination across all engineering disciplines, reducing the risk of technical misalignment. The programmatic team encompasses finance, scheduling, and documentation roles, and reports to the DPMR. Specialized teams including Quality Assurance (QA), Verification & Validation (V&V), Integration & Test, and Risk Management report to each subteam lead.

The programmatic team's responsibilities include scheduling and budgeting, to ensure the mission maintains its budget and schedule. One financial analyst shall manage real time budget tracking, allocation, and report generation. Scheduling is managed by a dedicated Scheduler or scheduling team, which maintains the integrated gantt chart created by programmatics and coordinates all project milestones and deadlines. Documentation and configuration management are also vital, handled by at least one specialist who is responsible for maintaining design change logs, requirements traceability, and version control across all project documentation which ensures clarity and accountability.

Beyond the core and academy teams, technical and specialized subteams are essential. The main engineering disciplines such as systems, mechanical, thermal, electrical/avionics, power systems, and structures/mechanisms are each represented as teams supporting the Systems Engineering Lead. Dedicated teams within each discipline are responsible for handling Integration & Test, V&V, Quality Assurance, and Risk Management. In addition, a Database Management Team is in place to handle the large quantities of mission telemetry, design files, and test data which will consist of 3 personnel.

Outreach and engagement are critical both for public awareness and education. Those responsibilities are organized under an Outreach & Communications team, which may include roles such as Communications Specialist, STEM Education Lead, Outreach and Engagement Coordinator, and Social Media Specialist. This team manages the mission's public profile, including website updates, press releases, social campaigns, and educational resources for the STEM community and broader public. This approach was inspired by the Lucy mission to the trojan asteroids where the mission concept academy (MCA) and NASA proposal Writing and Evaluation Experience (NPWEE) both act as outreach for the Lucy Mission, each having their own outreach & communications team that post frequently on social media platforms such as Instagram and platforms such as Linkedin, making the public aware of the Lucy mission

[33].

Within this framework, budgetary authority is carefully distributed. Subsystem and team leads receive dedicated budgets from the DPMR, with autonomy restricted to mission-related expenses such as design, build, testing, and training. Non-mission team expenses such as morale events, team meals, or family days may be authorized up to a pre-defined cap, typically ranging from five hundred to fifteen hundred dollars per team annually for the core academy team. Minor, routine purchases can proceed within this cap, while any single expense over a defined threshold (such as $250) requires secondary approval from the PM or DPMR. This structure maintains fiscal responsibility while supporting flexibility at the team level. Technical, process, and purchasing decisions are permitted within budgetary boundaries, but any changes impacting system performance, cross-team integration, or major requirements require higher-level approval from the PM or DPM.

Every subteam is explicitly represented as a distinct branch in the organizational chart. This mirrors the structure of successful missions such as the Mars Pathfinder and supports close coordination across technical and programmatic teams.

Finally, this management strategy draws directly on NASA Discovery-class precedent. Strong discipline leads, clear separation between technical and support teams, integration of QA and V&V, explicit configuration management, and defined budgetary oversight have been repeatedly validated as best practice by missions such as Mars Pathfinder and InSight. Adopting and adapting these structures ensures your mission is set up for technical, financial, and public success.

1.7 Manufacturing and Procurement Plans

Mechanical Subsystem:

For the mechanical subsystem, including the spoke hub, wheels, rocker-bogie mechanism, and chassis, Xometry's CNC machining lead time calculator was utilized as a baseline. Xometry was selected as a method of lead time estimate because of its proven capabilities in precision CNC machining and ability to handle aerospace-grade metals such as Aluminum and Titanium. For the wheel spokes, which are made from Aluminum 6061, Xometry estimated a lead time of 11 business days. To account for logistics, possible rework, and quality assurance, a 25% margin of error was created, yielding an estimated total lead time of 11 to 14 business days. The rocker bogie subsystem was split into 2 parts to improve maneuverability: the front rocker and the back rocker, which are made of Titanium Grade 2. Both components will be processed via CNC machining. According to Xometry's lead times, the front and rocker have estimated lead times of 11 business days each. Utilizing the 25% margin of error, this results in an estimated total lead time of 11 to 14 business days. The differential in the rocker-bogie mechanism was split into three parts - two mounts, two pivoting links, and one bar that attaches to the chassis. Each component is made of Titanium Grade 2 and will be manufactured through CNC machining. Xometry estimated lead times of 11 days, 7 days, and 11 days for the three differential parts respectively. Adding the 25% margin of error, the estimated total lead times for the differential components are 9 to 14 business days. The final component of the mechanical subsystem is the chassis. Made from Aluminum 6061, the chassis is split into two parts for simple assembly and integration. Xometry estimated lead times of 11 business days each to manufacture the chassis via CNC machining, and with the error margin, each component of the chassis will have an estimated lead time of 14 business days.

All mechanical components were chosen to be manufactured in-house via CNC machining for a number of reasons. The mechanical subsystem's ability to integrate other subsystems is of utmost importance, and design revisions will likely be necessary during integration of other subsystems. In-house manufacturing eliminates the time needed to contact contractors with the changes that will inevitably occur, allowing for smoother integration. In addition, all mechanical components, most notably the chassis and rocker-bogie legs, will undergo structural testing, meaning that multiple iterations will be necessary as tests shall be conducted to component failure.

Manufacturing in-house allows for more rapid prototyping and iteration, which will be very necessary for the mechanical subsystem. Relying on external contractors to manufacture mechanical components would increase the lead times by introducing delays in iteration. Communication between NASA engineers and the contractor would be inherently slower and more formal than in-house collaboration. Any issues discovered during testing or assembly would be discovered after waiting for the parts to arrive from the supplier, and only then could changes be submitted to the contractor which would add even more time. The use of alternate suppliers will slow the iteration severely, resulting in a great loss of valuable time that could be spent testing or assembling, and in-house manufacturing shall therefore be used.

Power Subsystem:

The components of the power subsystem are almost all commercially available. Power generation methods in space generally rely on radioactive materials, like RTGs, which are not utilized in this mission, and solar power. For each of the components, the team selected multiple different suppliers with space-rated and mission-tested components that will enable mission success without heightening risks dramatically.

For power generation, AZUR SPACE Solar Power GmbH will be the primary supplier for the quad-junction solar cells. This COTS component was selected for its high efficiency, established spaceflight heritage, and alignment with the mission's power density requirements. Because AZUR SPACE does not assemble panels in this product line, bare cells and bypass diodes will be procured directly from the manufacturer. Final array integration will be outsourced to a qualified U.S.-based contractor, such as MMA Design or DSS, based on their prior experience in flight-grade solar array assembly and in compliance with NASA NPD 1370.1 procurement policy. Drawing from industry reports and timelines from analogous missions, the team estimates a 6–8 month lead time, allowing for a 25% margin with an estimated time for delivery of 10 months for the solar cells and an additional 4–6 months for panel assembly and testing, yielding a total procurement and fabrication timeline of approximately 12–16 months with margin [42]. To maintain schedule margin, procurement will commence by March 2028. SolAero (Rocket Lab) serves as a backup supplier, offering triple-junction flight-qualified cells with integrated U.S.-based manufacturing, potentially reducing export risks at the cost of slightly lower efficiency. If invoked, the power system will be re-optimized accordingly.

To supply isolated power to the external rover payload, we have selected the VPT SVRFL2800S-series isolated DC-DC converter; a Class K, space-qualified, radiation-tolerant COTS power module with strong flight heritage. VPT, Inc., a trusted supplier of aerospace-grade power solutions, does not list this product on public distributor platforms; therefore, procurement will occur directly through the manufacturer or its authorized aerospace distributors [63]. The estimated lead time is 12–16 weeks, supported by procurement timelines for similar hybrid microcircuits in NASA small satellite programs and EEE-INST-002 guidelines [34]. To allow room in the schedule, an additional 25% of time shall be assumed for the lead time, allowing 14-20 weeks for procurement. As a contingency, the team has also identified space-grade alternatives from Texas Instruments, which may require electrical interface modifications and additional screening, potentially impacting the project schedule. The procurement strategy for this converter mirrors that of the solar array: direct engagement with vetted suppliers to ensure quality, schedule control, and mission compatibility.

In addition to the power generated by the quad-junction solar panels, backup power storage and backup power will be handled by an EaglePicher Technologies SAP-10211 lithium ion battery. This is a space-qualified battery with a beginning capacity of 4,380Wh at 20°C. This battery is capable of surviving temperatures from -10°C to 40°C, well within operating range of the mission and has been utilized in previous space missions as a battery in satellites. With this in mind, there is confidence in the successful application of this component to the electrical system. The estimated lead time for this battery is 24-32 weeks, as it is a specialized component that is not commercially ready for “off the shelf” purchase. In order to remain on schedule, an additional 10% estimated margin of error for the lead time is assumed, allowing 2-3 weeks in the schedule for errors. This additional time will allow for any manufacturing defects to be repaired, or additional testing as needed.

The estimate for the cost of this component ranges from $35,000-$40,000, based on estimates from the NCIM Concept Cost calculator provided by NASA, along with testing methods and level of craftsmanship required to create a custom battery for this mission. This procurement time is supported by similar suppliers, but could be lessened if tests prove to be nondestructive. If this component does not arrive as expected, other suppliers, such as ChargeX and Mobile Power Solutions, could produce a similar component within the expected time and budget [8].

Command and Data Handling Subsystem:

For the Command and Data Handling subsystem, various components must be identified and sourced with satisfactory cost estimates and lead times. As NASA is required not to compete with the commercial sector, many of these specialized parts are rare but commercially available and therefore must be procured from these suppliers.

The onboard computer (OBC) selected is the RAD5545 by BAE Systems with a lead time of 12 months [4, 48]. A margin of one month will be built in to account for any issues with manufacturing. BAE Systems is the sole contractor for the RAD5545 computer and has an extensive history of supplying NASA with OBCs in the past including on perseverance and the MRO. The RAD5545 is radiation tolerant up to a 100 Krad ionizing dose and can withstand a range of -55 to 125 degrees Celsius. The processing power offers 5.6 giga-operations per second/3.7 giga-floating-point operations per second [4, 29]. The backup option is its predecessor, the RAD750 which still meets the mission requirements although not preferred due to its slower performance and memory capacity. The RAD5545 has a processing power 10 times greater than the 750. The RAD750 would also have a lead time of 12 months from BAE Systems with a margin of 1 month.

The UHF Transceiver selected is the L3Harris C/TT-510 Electra-lite Transceiver (ELT) [20, 21]. Lead times for the transceiver are not publicly available but based on similar technology the lead time is estimated to be 18 months based on similarly complex technology. To account for the use of an estimate, a longer, four month margin will be applied to this lead time. The procurement costs are not directly available, however based on similar technology, other transceivers cost between $200-400k. The L3Harris ELT has been used on Curiosity, Perseverance, and MRO relays, and from those missions a reasonable estimate is $250k. L3Harris has supplied the UHF radio for the past three Mars rovers and has been a reliable radio in each. The radio can supply data rates up to 2 Mbit/s and operates within the Mars UHF bandwidth. Additionally, its lightweight and small design is specifically catered to Mars missions. The backup supplier is JPL with its ELT. JPL has historically developed the technology that allowed Electra-lite to be possible [21]. This is a backup because JPL has not had to manufacture a similar radio since 2009, but JPL has continued to consistently supply NASA with outstanding technology. The estimated lead time for JPL is 24 months due to the lack of recent development of an Electra-lite radio with a margin of 6 months to account for this need for new development. The necessity for a light weight UHF radio limits the choices making JPL the backup supplier despite rules against competing with the industry.

The Data Storage selected is the Mercury RH3440 Solid-State Data Recorder [53]. The SSD has 440gb of flash memory and can support write speeds of 1160 MB/s and read speeds of 1040 MB/s. Additionally, it is low power, 14w max, and light weight, <620g. The SSD is designed for space and is currently in use on the ISS and a L3Harris space project. It can survive in the temperature ranges of Mars with its range of -55°C to 105°C, and it is radiation hardened to a dose of 100 krad. The lead time is 12 months based on similar radiation hardened storage devices with a margin of 2 months. The backup is the RH3480 from Mercury [32]. This SSD is very similar to the 3340 with more storage and faster speeds. However, this is accompanied by higher weight and power draw. This is still in the acceptable range, just not as fit to the mission as the 3340. It has a similar lead time. Another possible backup if Mercury is unavailable is Exascend, but this may pose problems due to the company being based in Taiwan [24].

The RS-422 Transceiver selected is the Texas Instruments SN65C1168EMPWSEP supplied by Mouser with a published lead time of 2 weeks and a margin of 2 extra weeks [30]. Using a COTS supplier for transceivers is advantageous due to the large amount of stock they contain, which means the margin can be small. Because multiple transceivers will be needed, and will be purchased potentially more than once, the short lead time will not deter progress. The backup supplier is also

Mouser which has Texas Instruments THVD9491DTSEP with an 18 week lead time and a built in margin of 4 weeks if they have to purchase more stock to cover the 20 total needed [31]. The benefits of COTS are less abundant here with a longer lead time and only 15 currently in stock.

The Data Interface cable is the WireMasters supplied Gore DXN2605, 30 AWG Twisted Pair [65]. Wiremasters publish a lead time of 5 weeks for orders. Because it is currently in stock the margin is 2 weeks. The backup product shall be the DXN2604, also supplied by WireMasters with similar lead time [66]. Both cables have an impedance of 100 ohms and high temperature ranges of −55 °C to +200 °C. The DXN2605 is chosen over the 2604 because of its lighter weight and smaller size. This cable is for data transfer, not power, so a high-profile cable is unneeded.

The UHF antenna shall be the UC-3004-531R (Quadrifilar Helix), as sourced by Antennas.us [46]. The antenna is primarily used in military satellites, but is tuned for the correct bandwidth and has omnidirectional gain allowing it to be used on Mars Rovers. Antennas US publishes a lead time of 10-12 weeks. To build in margin an extra 4 weeks will be added to allow for any slowdowns in production. The backup supplier and product shall be the Anywaves QFH. This antenna may be the better option, but costs and lead times are unavailable due to the custom nature of the antenna. Anywaves has made antennas for cubesats and small rovers in the past and each antenna is custom made to meet the specifications of the system.

Thermal Subsystem:

The companies for the thermal subsystem, such as Dwyeromega, Sierra Space, Advanced Cooling Technologies, NI Solutions, Dunlap, Dunmore Aerospace, Sheldahl, and Skygeek, were selected due to their past and ongoing affiliations with NASA through contracts, etc [22]. Dwyeromega specializes in electrical heater units, which are part of the TCS [12]. The backup supplier for the heaters would be McMaster-Carr with their ultra-thin heaters. Sierra Space aids in the production of thermal louver radiators for heat dissipation and retention [28]. McMaster-Carr would also be the backup for thermal louvers [28]. Advanced Cooling Technologies specializes in variance heat pipes like Variable and Constance Conductance Heat Pipes. Backups for the Variable Conductance Heat Pipe(VCHP) would be Celsia Inc. for their thermal solutions and Pure World Energy Inc. for their Constance Conductance Heat Pipe (CCHP) design solution. NI Solutions specializes in thermal sensors such as the thermistor, which will be a part of the rover system to monitor any thermal irregularities. The backup supplier for the thermistors would be TE Connectivity and their NASA-qualified thermistors as well. Dunlap shall serve as the main supplier of nylon threads for sewing the MLI together. The backup would be Jaco Aerospace with their specialized nylon threads. Both Dunmore Aerospace and Sheldahl specialize in MLI blanket films as well as adhesive tapes; both of these companies will be backup suppliers for one another in case the other does not have the necessities. SkyGeek worked with aerospace companies and helped in the production and distribution of adhesives for the MLI, such as EPON 815C, which is used to bond fasteners to the overall structure. The backup supplier for this particular adhesive is Ellsworth, which also has EPON 815C for aerospace applications. The team has gone ahead and chosen these companies due to their past and current affiliations by providing high TRL of material and more for NASA, for instance, the Apollo 11 Mobile Quarantine from Dwyeromega, utilization of LABVIEW FPGA for the James Webb Space Telescope from NI Solutions, etc [3].

Lead times for these products vary by the complexity of the design, testing, approval, and shipment. Dwyeromega provided their lead time of 6 weeks if not in stock, but a 2-week margin should be given in case of any unforeseen occurrence so therefore around 8 weeks [12]. For the backup supplier, lead time for McMaster-Carr would be 98% of the time they would do a same-day or next-day delivery [28]. For the Sierra Space Thermal Louver Radiators, lead times should be around 12 weeks for manufacturing approval and delivery, according to similar manufacturers like Kelair Dampers, with a 2-week margin for any unforeseen circumstances [23]. Advanced Cooling Technologies lead times for the CCHP, especially for the VCHP, vary, as the VCHP must be designed in accordance with the mission requirements and therefore shall be placed at around 14 weeks due to the complexity of the design as well as manufacturers that make similar heating solutions plus testing with a 2-week margin to account for any uncertainty. The backup suppliers, such as Celsia and Pure World Energy, would also be around 14 weeks with a 2-week margin. NI Solutions' thermistor lead time would be around 26 weeks, according to manufacturers such as AvNet, which makes similar products [1]; a 2-week margin would also be implemented to account for uncertainties as well. The team's backup thermistor would also come from McMaster-Carr, which has the same lead time as the electrical heater one, with the same day or next day in-stock delivery. Dunmore Aerospace MLI film lead times would be between 1-3 months as these numbers come from the SatCatalog [52]; however, taking the upper bound being 3 months, a 1-month margin would be put in place to account for any errors for Dunmore, as well as noting the backup supplier Sheldalh. Dunlap's nylon thread lead time would be around 6-7 weeks according to Superior Threads; however, a 2-week margin shall be put in place as well [58]. This lead time plus margin also applies to the backup supplier, Jaco Aerospace, as well. Skygeek lead times would be 4 weeks as they provided their lead time on the catalog, and shall be given a 2-week margin as well for any uncertainty [55]. The same lead time applies to the backup supplier, Miller-Stephenson, as well as the margin. These procurement times should adhere to the scheduling of the development of the P.H.O.E.N.I.X rover.

Payload Subsystem:

The most appropriate contractor for delivering the CP-MU DMU-100 Submersible Gamma Neutron Probe is Technical Associates, the manufacturer and developer of the original DMU-100 system, which is designed for high-resolution gamma and neutron monitoring in harsh environments such as nuclear waste storage and deep geological repositories. The DMU-100 utilizes a passive ionization chamber for long-term gamma radiation monitoring and has been tested for reliability in highly pressurized and submerged conditions which are characteristics essential to its deployment within a custom-engineered, pressurized Fluid Protection System attached to a Martian rover. In this case, the protection system will internally house both the DMU-100 and an Earth water sample to simulate and monitor radiation impacts on mission-critical fluids. The probe will transmit gamma dose rate data (in µSv/h) on a weekly cadence over a full Martian year to evaluate material shielding performance and radiological degradation risk, directly supporting Materials Engineering advancements for fluid transport, recycling, and protection on Mars. While the DMU-100 was not originally built for planetary applications, its compact cylindrical form (94 cm length, 4.5 cm diameter), sealed pressurized body, and low-power passive sensing make it a strong candidate for Martian adaptation, provided the FPS handles external environmental exposure. Technical Associates has not published lead times for space applications, but based on comparable ruggedized radiation probes and historical shipment cycles for geological monitoring systems, a conservative fabrication and modification lead time of 10–14 months is estimated. With a 25% margin, the final lead time projection is 12.5–17.5 months, assuming integration of Martian-specific housing and thermal protection. [61]

The best primary contractor for Radar Imager for Mars’ Subsurface Experiment (RIMFAX) is the Norwegian Defence Research Establishment (FFI), that originally developed and delivered the flight model for NASA’s Perseverance rover. With direct experience designing ground penetrating radar systems tailored for extreme planetary environments, making them the most reliable and flight proven option for any mission requiring subsurface imaging or ice detection. RIMFAX demonstrated its capability to detect dielectric contrasts and resolve subsurface layers down to 10 meters with depth resolution from 10 - 40 cm depending on material permittivity. If FFI is unavailable, a strong alternative is Mala GeoScience, a commercial leader in modular radar systems.While they lack direct spaceflight heritage, their field tested hardware has potential for adaptation, provided design for justification and address thermal/radiation constraints. Research shows the instrument was developed between 2014 - 2019, with the flight model delivered in early 2019, suggesting a conservative lead time estimate of 12 - 18 months for a mission-adapted system. Including a 25% margin for integration and testing, the final expected lead time is 15 - 22.5 months, based on historical milestones and integration pacing from NASA and FFI [49].

Thales Alenia Space is the best primary contractor for the Raman Laser Spectrometer for missions focusing on life detection on Mars due to their direct experience, mission-specific design, and successful development of the ExoMars RLS, the only Raman system made for biosignature detection on Mars. Should Thales Alenia Space be unavailable, Teledyne Princeton Instruments (TPI) is the recommended backup for the Raman Laser Spectrometer. Their specialization in deep cooled detectors and customizable spectrometers have been used in NASA missions such as Europa Clipper and Lunar Trailblazer. Furthermore, they also provide radiation tolerant, thermally stable, and compact Raman systems, making them a good alternative to Thales Alenia Space. Detailed manufacturing and delivery timelines for the Raman Laser Spectrometer are not publicly disclosed. However, publicly documented delivery or upgrade milestones can be used as indirect indicators. Using publicly available sources, the flight model of the Raman instrument control unit (RLS) was delivered to Thales Alenia Space Italia in Turin from IRAP on June 25, 2024 and it is estimated that it will be integrated into the full system in 2025, giving a 6-10 month lead time estimate but with a 25% margin of error, the total lead time estimate increases approximately to 8-15 months.

The primary supplier selected for the mini-TLS instrument is the Southwest Research Institute (SwRI), as this organization is known for its successful contribution to missions with spectrometers and gas analyzing instrumentation, such as the MAss Spectrometer for Planetary EXploration (MASPEX) and the Magnetic Anomaly Plasma Spectrometer (MAPS) [59]. As stated by the Southwest Research Institute’s Department of Space Operations, their specialties include particle radiation detection and spectroscopy, which is imperative to achieve the scientific goals and objectives within this mission. SwRI is a flight-proven contractor that is able to deliver time leads with accuracy and quality which will ensure the mini-TLS instrument performs reliably to meet mission requirements [60].

As a backup supplier, Ball Aerospace is chosen for its strong flight heritage and proven experience in developing spectrometry instruments. Ball's instrumentation includes systems designed for a full spectrum of electromagnetic observations, such as in missions like the Ozone Mapping and Profiler Suite (OMPS) and the Green Propellant Infusion Mission (GPIM), as both served to test environmental sensors, which are vital to the payload of P.H.O.E.N.I.X. [13, 16]. Ball Aerospace is also considered because this company values the importance of compact and lightweight instrumentation, critical within the payload subsystem to meet requirements and criteria, as the mini-TLS was decided [5]. Overall, it optimizes the mass and volume constraints, which increases the level of precision.

The decision to use a COTS was based on the considerations of time, cost, risk, and reliability. Choosing a part that is already designed, tested, and manufactured allows for efficient use of time and budget, which increases predictability in performance outcomes, along with lowering technical risks. SwRI and Ball Aerospace are able to contribute to the performance that the mini-TLS must meet to be successful within the P.H.O.E.N.I.X. mission with their extensive experience and reliable performance.

1.8 Risks and Safety

1.8.1 Risk Analysis

Every space mission carries unique risks due to the complexity of spacecraft design and operations. The team is committed to identifying and mitigating these risks wherever possible using NASA-defined risk identification and mitigation strategies such as Risk-Informed Decision Making (RIDM) and Continuous Risk Management (CRM). RIDM enables structured, transparent decisions by explicitly weighing risks and uncertainties against mission goals and constraints, while CRM ensures that risks are continually identified, analyzed and managed throughout the project lifecycle.

By team consensus, the most effective methods for identifying risks included thorough Failure Modes and Effects Analysis (FMEA), in-depth Fault Tree Analysis (FTA), and regular expert reviews. To evaluate and prioritize risks, a risk matrix was developed that assesses each risk according to the likelihood of occurrence and the severity of its consequences. The matrix enabled the team to efficiently rank and allocate resources toward the most pressing risks.

The construction of this matrix followed NASA recommendations, customized with data from analogous missions such as the Mars Science Laboratory (Curiosity), the Mars Exploration Rovers (Spirit and Opportunity), and the Mars 2020 Perseverance rover, providing valuable insights from comparable operational environments.

Risk ranking in our project was the result of collaborative technical and non technical discussions among subteams and subteam leads. For each risk, likelihood and consequence ratings were justified using available data,technical analysis, and lessons learned from analogous missions.

The risk analysis approach for this mission is further strengthened by directly integrating RIDM and CRM within the team’s workflow. RIDM ensures that every major decision is weighed, maintaining alignment with overall mission drivers, while CRM ensures these risks are continuously managed and updated as the project moves forward in different phases.

Central to this process is the team’s ongoing development and use of a risk matrix. The risk matrix organizes all identified risks based on their likelihood and the severity of potential consequences. This tool not only drives prioritization for mitigation but is also actively referenced in decision making and design trade-offs. The team developed the matrix using the risks identified in the advanced risk log that is updated every other deliverable.

The information from the risk matrix is integral to mission design and operations, prompting targeted mitigations such as redundancies and contingency planning for high-priority risks. This matrix also frames weekly risk review meetings, where risk status is tracked, new risks are identified.When certain risks are categorized as "Accepted," the justification for this acceptance is thoroughly documented to ensure transparency, providing assurance to both internal teams and external stakeholders. In summary, the risk management strategy combines NASA's RIDM and CRM approaches with proven identification and ranking tools such as FMEA and the risk matrix. At the moment, the team has not accepted any risks and have mainly moved forward with researching and mitigating risks as it pertains to the design of the rover as it is still in the design and development phase.

Subsystem-specific risks and mitigations include the following: due to the presence of sharp, embedded rocks on Mars, there is a risk of wheel skin puncture or grouser breakage, compromising wheel integrity and rover mobility. This risk is mitigated by using thicker wheel treads, adaptive driving algorithms, and regular wheel imaging to monitor and avoid hazardous terrain, as informed by experience from the Mars Exploration Rovers. The rover is also at risk of suspension fatigue, where high mass and frequent traverses could cause loss of shock absorption, increasing risk of failure to traverse rough terrain. Mitigation strategies include the use of robust suspension materials, periodic load analysis, and redundancy in suspension design, drawing on design lessons from the Curiosity rover [44].

Thermal Control Subsystem (TCS) failure, particularly in Mars's harsh temperatures, could damage electronics. The team has decided to use multilayer insulation (MLI), redundant electric heaters, and real-time thermal monitoring, ensuring backup heaters are available if any were to fail which are approaches validated in previous missions such as Mars Pathfinder and InSight.

Instrumentation risks include dust infiltration addressed by seals, protective covers, and cleaning routines and possible mechanical misalignment or shock damage during landing, mitigated by shock-absorbing mounts and post landing calibration protocols similar to those employed on Mars 2020 Perseverance [44].

Power subsystem failure in the Martian environment could lead to electrical overloading of other subsystems, and ultimately to mission failure. To decrease the likelihood of this occurring, the team has integrated radiation-resistant materials into the design of our subsystem. Using deployable solar panels that are able to angle away from the sun, MLI panels that utilize bandgaps to absorb solar radiation, and engineering with redundancies allows the system to withstand the Martian environment for longer. Lessened radiation on the solar panels, batteries, and distribution units lessens the chances that the systems will degrade to critical levels.

Risk ranking is performed collaboratively across subteams, with each likelihood and consequence rating documented with clear rationale backed by technical analysis, previous mission experience, and open dialogue between leads. These rankings are not stagnant; they are periodically revisited and updated as the mission evolves or new information is readily available.

In addition to technical risks, the team rigorously manages programmatic risks such as schedule delays, budget uncertainties, and resource constraints that could impact mission success. Drawing on lessons from NASA's Mars Pathfinder mission, a Discovery class mission that faced compressed timelines and strict budget limits, the mitigation plan the team decided on for programmatic risks are strategies like rapid prototyping, parallel subsystem development, and regular milestone reviews, enabling early problem detection and efficient resource reallocation [19]. Scheduling risks are proactively addressed with detailed planning, schedule reserves, and continuous progress monitoring, while budgeting risks are managed via ongoing cost tracking, contingency funding, and early identification of potential funding issues. Other programmatic factors, including supplier reliability and partner coordination, are incorporated into the risk matrix and reviewed regularly, ensuring these non-technical risks receive the same thorough attention and mitigation planning as technical challenges.

Planetary protection is ensured within the P.H.O.E.N.I.X mission as it is imperative to conserve the environment of the planet Mars from any form of external bacteria and microbes. Contamination may interfere with the Martian ecosystem and potentially mislead data collection for future scientific missions, rendering the data inaccurate to the original Martian domain. Furthermore, upholding ethical responsibility on Mars supports the sustainability of future exploration and ensures the protection of any potential life forms that may be present.

To explore responsibly and effectively, sterilization of spacecraft, instrumentation, and crew is carried out to minimize the risk of biological contamination to planetary environments and potential native organisms. Through the mission, contamination control is also guaranteed through various testing that may be conducted promptly, which upholds standards to meet expectations of scientific integrity.

Abiding by the Outer Space Treaty, this mission will respect the guidelines designed to protect celestial bodies for the preservation of their environments and the success of future exploration efforts [49].

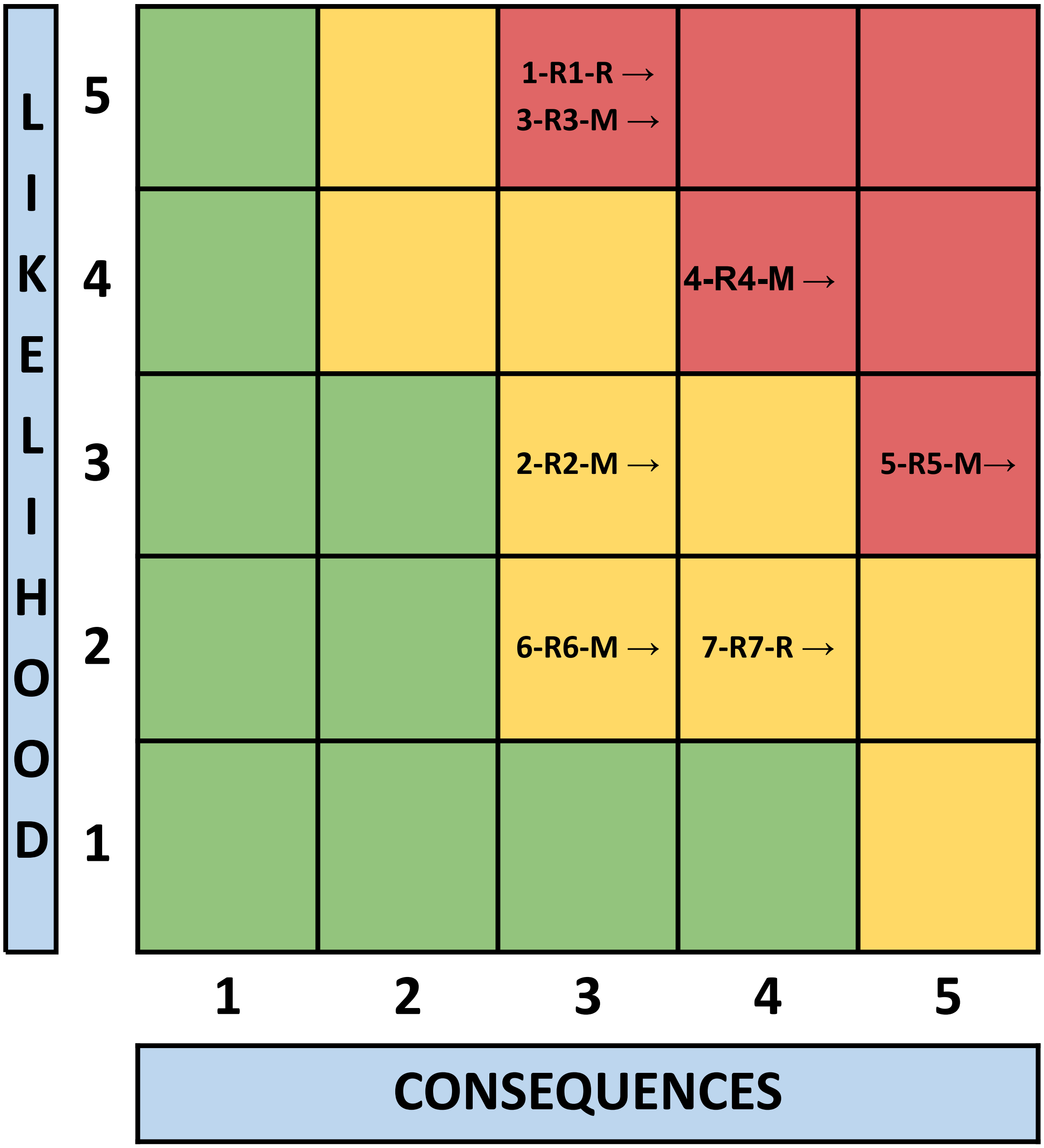

Fig 1.8.2.1 Risk Matrix

Rank	Risk ID #	WBS Element	Risk Owner	Category	Timeframe	Risk Title	Risk Statement	L	C	Rating	Approach	Trend	Mitigation Plans
1	R1	Thermal Payload	Flynn Mendoza	Cost/Scope	Medium Term	Electric heaters failure	Given that extremely low temperatures frequently occur on Mars, there is a possibility that the electric heaters on the rover may malfunction or cease to operate , resulting in an inability to maintain required temperatures for critical subsystems or instruments , thus risking the failure or degradation of performance of these key components of the rover.	5	3	High	Research (R)	→ Neutral	Make use of redundant heaters and separate circuitry
2	R2	Electrical System	Audrey Sorenmann	Cost/Scope	Medium Term	Reduced power generation from solar panels due to Martian dust	Given that Martian dust can accumulate over time on exposed surfaces , there is a possibility of gradual build-up on the solar panels of the rover , reducing the amount of solar energy received by the power generation system, and consequently limiting the availability of electrical power for performing mission-critical activities.	3	3	Moderate	Mitigate (M)	→ Neutral	Make use of dust removal systems.
3	R3	Payload System	Lucia Piedra	Cost/Scope	Short Term	Mini TLS overheating risk	Given that internal heat dissipation and external thermal conditions on Mars can cause localized temperature increases , there is a possibility that the Mini Tunable Laser Spectrometer (Mini TLS) may overheat during extended use or in sun-exposed environments , potentially impairing the instrument's measurement accuracy or causing component damage , thereby compromising atmospheric data collection and scientific mission objectives	5	3	High	Mitigate (M)	→ Neutral	Only run instrument at temperature between -10 C up to 20 C
4	R4	Payload System	Anna Hulett	Cost/Scope	Short Term	RLS laser induced sample ignition	Given that the 785-nm laser used in the Raman Laser Spectrometer can deliver enough thermal damage or ignite certain materials, this leads to degradation of samples and scientific evidence, or hazardous reactions with flammable or explosive reactions. The risk could heighten when analyzing the Martian	4	4	High	Mitigate (M)	→ Neutral	If applicable, use a lower power laser setting and avoid direct exposure of

							surface that could potentially have reactive chemicals.						dark/unknown energetic materials
5	R5	Payload System	Matthew Lawrence	Cost/Scope	Short Term	CP-MU DMU-100 freeze risk	Given that ambient Martian temperatures can drop well below operational limits during the night or in shadowed regions , there is a possibility that the CP-MU DMU-100 instrument may become exposed to prolonged cold without adequate thermal protection or heating , leading to freezing of internal components or malfunction , thus resulting in loss of valuable data acquisition or critical measurement capabilities.	3	5	High	Mitigate (M)	→ Neutral	Thermal material layers should be built into instrument housing
6	R6	Mechanical System	Gabi Zabiegaj	Cost/Scope	Medium Term	Wheel skin puncture or grouser breakage	due to the presence of sharp, embedded rocks on Mars, there is a risk of wheel skin puncture or grouser breakage, compromising wheel integrity and rover mobility	2	3	Moderate	Mitigate (M)	→ Neutral	Make use of thicker wheel treads, adaptive driving algorithms, regular wheel imaging
7	R7	CDH system	Conor Foley	Cost/Scope	Short Term	Data memory corruption	Given that radiation levels on Mars can be relatively high and the rover is subject to repeated power cycling and mechanical vibrations , there is a possibility of memory corruption in the onboard data storage systems , compromising the integrity of mission data and software functionality , which may lead to communication errors, data loss, or malfunction of autonomous systems.	2	4	Moderate	Research (R)	→ Neutral	Use ECC memory, regular memory scrubbing, software validation

Fig 1.8.2.2 Advanced Risk Matrix

1.8.2 Failure Mode and Effect Analysis (FMEA)

Should a loss of drive or steering capabilities occur, the mission would likely be compromised depending on the severity. In the worst case scenario significant mobility loss on the rover can lead to possibly getting stuck in one location. Most likely only one failure would occur, still compromising mobility, possibly limiting locations the rover could navigate to, and impact the speed with which the rover can navigate to new places. In such a case backups and manual steering would be implemented. Manual steering, if necessary, would require more man power and resources to perform this manual maneuvering, and introduces human error.

In regards to MLI degradation, the effects this would have on the mission should be minimal since the end of life conditions for the MLI will be taken into account in the calculations. As it degrades more power and resources will be required to maintain the rover in its operational temperature, but that has been built into the design. In the worst scenario, debris could rip the MLI during a sandstorm, although unlikely, this will likely decrease the lifespan of the rover as the MLI would degrade to a less functional state than accounted for in the end of life calculations.

In the case of thermal sensor failure, this would compromise the science by compromising the ability to monitor the temperature of each instrument. Increasing the risk of failure for each of these instruments. Because of built in redundancies, failure of one should not compromise the thermal control system, since because of the redundant heat sensors the interior of the rover will be kept in the general operational range. On an instrument by instrument basis the risk is still minimal since there will be two sensors monitoring each instrument. Were multiple failures to occur at once though, likely from a power failure, to a degree where the redundancy does not help, the mission would likely be compromised as a whole. While the TCS could continue operating, without knowing exactly what temperatures P.H.O.E.N.I.X is operating at, the use of guesswork would exponentially increase the risk of overheating or getting too cold.

Regarding the CP-MU DMU-100 freeze risk, were this to occur despite the mitigation strategies, part of the science of the mission would be compromised and would be unable to be finished. P.H.O.E.N.I.X would have to return the data it collected before failure from that instrument.

Now considering loss of battery capacity, the effects on the mission would be catastrophic were multiple failures to occur. Power would be lost, rendering P.H.O.E.N.I.X inoperable. The rover would be kept operational as long as possible to collect and transmit as much data as possible, shutting down non critical systems to accomplish this. In the case of one battery failing to recharge or losing capacity power would begin using a second backup battery, at worst risking a reduced efficiency.

When considering the risk of electrical shortages in power distribution, it is important to consider in which subsystem the loss of power were to occur. Were it to stop providing power to the TCS during a cold night, there runs a risk of damage to the circuitry before system recovery can occur. Were the loss of power to happen to the science instruments, data would possibly be lost but recovery would be able restore the system later and recovery operability.

If the power generation from the solar panels were to be reduced from dust accumulation or something similar, that would result in the rover having to switch to a low power mode, reducing the efficiency of all systems, while dust removal measures are employed. At worst this would result in total power loss and the loss of the mission.

Were a process failure in the CDH subsystem to happen, communication abilities with the rover would be lost, rendering it inoperable. For this reason a redundant OBC is implemented, so if failure in one happens the rover can switch to the backup system. Total mission loss would only occur if both failed.

ID	Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions	Approach
2		Suspension fatigue	Loss of shock absorption, increased risk of mechanical failure	3	High mass and frequent traverses	2	Robust suspension materials, periodic load analysis, redundancy	7	42	Reducing speed and avoiding rough terrain can help slow further fatigue.	Research
3		Loss of drive or steering calculator	Reduced mobility, inability to steer or drive one or more wheels	7	Hardware or cable failure, wear over time.	3	Redundant actuators, regular actuator health checks.	4	84	Switching to backup or manual control is the most logical step.	Mitigate
4		Loss of shock absorption capability	Increased transmission of shocks to chassis and instruments	3	Material fatigue, extreme temperature cycling.	3	Use of advanced materials (e.g., shape memory alloys), regular health monitoring.	5	45	Rough terrain should be avoided if this failure persists	Mitigate
5	Thermal Subsystem	Heat Pipe failure	Loss of thermal regulation, risk of overheating or freezing	8	Faulty manufacturing, extreme pressure changes	1	Redundant heat pipes, redundant thermal control systems in the form of heaters	3	24	Rely on electric heaters, plan for alternate cooling systems	Mitigate
6		Multi-layer insulation (MLI) degrades over time.	Increased heat loss, reduced thermal protection.	7	Micrometeoroid impacts, material aging, radiation	3	Use of high-durability MLI, periodic thermal performance checks.	3	63	Operate rover primarily during warm periods away from areas of high radiation	Research
8		Thermal sensor Failure	Loss of thermal monitoring, risk a system failure is not reported	7	Material aging, overheating, electric failure	1	Redundant sensors, seperate circuitry	6	42	Rely on redundant sensors, develop a software recovery plan	Mitigate
9	Payload Subsystem	RIMFAX signal attenuation	reduce the depth it penetrates and degrade the	2	Materials like clays or ice-dust mixture	3	Running at its low end frequency of 150-1200 MHz	1	6	Reduce depth objective to 2 m - 4m for clear data and	Research

			signal-to-noise ratio		which absorb and scatter radar energy		band as low frequencies penetrate better			schedule multiple low frequency soundings	
10		RLS calibration drift	calibration change throughout image collection	3	temperature swings disrupt calibration due to temperature sensitivity	3	calibration verification before and after each science run	1	9	heating samples to 935 K and cooling them down to 120 K to reserve fully calibrated quantitative measurements for high temperature, and qualitative data for lower temperature	Mitigate
13	Power Subsystem	Loss of battery capacity or failure to recharge	Reduced operational time, possible mission loss.	9	Repeated charge/discharg e cycles, extreme temperatures.	5	Battery health monitoring, thermal management, redundant batteries.	5	225	Utilize second battery. If second battery is also inoperable, begin powering down noncritical systems to reduce power load	Mitigate
14		Electrical short in power distribution	Loss of power to subsystems, reduced redundancy.	8	Dust, material degradation, component failure.	4	Robust insulation, regular voltage monitoring.	6	192	Shut down system and reboot, if the issue persists then continue to monitor. Perform analysis on systems to ensure they remain within operational capacity.	Mitigate
15		Reduced power generation from solar panels	Insufficient power for operations	7	Dust accumulation, mechanical damage.	7	Dust removal systems.	3	147	Reduce subsystem power usage to redirect remaining power to critical systems. If transmission is impossible, store data for potential future collection	Mitigate

16		Drift in transistors not allowing them to turn on/off	Loss of signals for power distribution	5	Radiation ionizing deposits within technological components	7	Shielding systems, radiation-hardened materials in manufacturing	3	105	Perform maneuvers to shield components from further damage, reduce operation of damaged systems, continue to monitor	Mitigate
17		Processor failure	Loss of command/control, mission halt	10	Hardware defect, radiation, overheating	4	Use radiation-hardened processors, implement thermal control, redundant processors	8	320	Physical Redundancy by having two OBCs	Mitigate
18		Memory corruption	Loss of stored data, erratic behavior	2	Radiation, aging	8	Use ECC memory, regular memory scrubbing, software validation	3	48	Offboard system cleansing processes, rad-hard memory units	Research
19	CDH Subsystem	Data uplink/downlink loss	Loss of communication with ground, inability to send/receive commands	2	Antenna failure, RF interference, ground station issue	8	Antenna redundancy, RF shielding, multiple ground stations	4	64	Autonomous sourcefinding recovery behavior	Research
20		Command errors	Incorrect commands executed, potential for unsafe actions	8	Software bug, memory corruption	4	Command validation, memory error detection, queue integrity checks	2	64	Increase detection using verification codes	Research

Figure 1.8.2.2: FMEA Table

1.8.3 Personnel Hazards

Notable hazards during the rover's manufacturing process include injury from cutting, grinding, or drilling. Since components like the chassis and rocker-bogie mechanism are made from titanium and aluminum, machining is required. This poses risks such as lacerations, amputations, and injury from flying debris. To reduce this risk, all personnel will undergo safety training per NASA and OSHA standards, use appropriate PPE including safety glasses, long pants, steel-toed shoes, respirators, gloves, and face shields. and operate machinery with proper guarding in designated areas.

Going along with the hazard of machining metals, a related personnel safety hazard is sharp edges on metal surfaces. Machined parts typically have sharp edges, ridges, and burrs that can cause cuts or abrasions. This will be mitigated by making deburring tools readily available and using them immediately after any cutting, grinding, or drilling, as well as sectioning off working areas from walkways.

Another risk to personnel safety during the manufacturing process is crushing or pinching. There are many heavy components of the rover that need to be manually lifted and integrated, for example the solar panels and battery systems. If not handled properly, the weight of these components could crush or pinch personnel and cause serious injuries. To mitigate this risk, personnel in contact with heavy components will complete proper heavy machinery training, utilize cranes whenever it is necessary to lift a heavy component, wear proper PPE when working with heavy components, and employ clear team communication and coordination to avoid any potential crushing or pinching.

In parallel with the risk of crushing and pinching is the risk of falling objects. Since heavy components are present in this design, they could fall and injure personnel if not secured properly. To mitigate this risk, proper precautions will be taken while moving heavy objects, including but not limited to securing items with straps and supports, utilizing safety nets and protection when possible or applicable, and taking steps making sure components are always secure and before and during integration.

An additional risk associated with the heavy components of the rover is manual handling injuries. If proper technique is not used to lift heavy components, joint strain or muscle injuries could occur. To mitigate this risk, personnel will complete training for and utilize cranes and hoists when applicable in addition to implementing manual lifting techniques.

Manufacturing risks and hazards are present in all phases of the design process. Another example applicable to the P.H.O.E.N.I.X rover is the risk of electrical shock. The rover’s power system including the battery and electronics include many high voltage components, and improper handling during integration or testing could lead to electrical shock. To mitigate this risk, personnel in contact with these hazards will complete the required training to interact with these components. Workers shall utilize proper PPE including rubber soled shoes, insulating gloves, and insulated tools, as well as ensure proper grounding and de-energize systems during assembly to follow safe electricity protocols such as LOTO.

Another electrical hazard that is present is the risk of arc flash. If the rover’s power systems are incorrectly wired or short circuited, then it could release large amounts of light and heat in the form of arc flash. To mitigate this risk, arc flash analysis will be conducted on the rover’s power systems, personnel will wear PPE for arc flash scenarios when working on electrical systems including flame resistant clothing, safety goggles, and face shields, additionally fire extinguishers will be readily available, and safety protocols like LOTO shall be followed by performing routine checks of the system. These mitigation techniques will accurately cover the potential hazard of a fire during manufacture.

One more type of hazard to be addressed is chemical hazards. When working with paints, adhesives, solvents, and batteries (composed of chemicals that could potentially lead to leaks), it’s important to take the correct precautions to minimize risk to personnel. To mitigate this risk, there will be proper ventilation in work areas, fume hoods will be used when dealing with toxic chemicals, PPE will be worn including respirators and chemical resistant gloves, additionally chemical emergency stations will be available throughout the lab slash manufacturing area including eye showers, chemical showers.

1.9 Schedule

1.9.1 Schedule Overview

Table 1.9.1.1 provides a high level overview of mission phases focusing on the duration and major milestones. Milestones in red text require going before a standing review board (SRB) per protocol outlined in NPR 7120.5 [41].

Phase	Duration	Milestones
C	Oct 1, 2025 - April 1, 2028	KDP C, CDRs, PRR, SIR
D	April 1, 2028 - Dec 1, 2029	KDP D, SAR, ORR, FRR, KDP E, Launch, PLAR
E	Dec 1, 2029 - Sept 1, 2031	Arrival, EDL, Surface activities, CERR, DR, Mission End
F	Sept 1, 2031* - Dec 1, 2031	KDP F, DRR, Final Archiving & Report

Figure 1.9.1.1: Phase Milestones Table

1.9.2 Schedule Basis of Estimate

This Basis of Estimate outlines the foundational rules, assumptions, and relevant scheduling factors that influence the P.H.O.E.N.I.X mission. This estimate was developed as a result of detailed analysis and collaborative schedule development. Following a typical NASA lifecycle project management framework, this Basis of Estimate encompasses mission phases C through F, and is structured to ensure successful execution of all required system developments. Additionally, this schedule allows for testing and subsystem integration development. This BoE establishes the basic and strategic rationale that serves as the backbone of the planning content, and the expectations provided to our team regarding the timing and progress expected.

P.H.O.E.N.I.X's mission schedule is organized into standard NASA phases: Phase C (Final Design and Fabrication), Phase D (System Assembly, Integration and Test, and Launch), Phase E (Operations and Sustainment), and Phase F (Closeout) [42]. The duration of each phase is based on historical analogs including the Mars Pathfinder, Mars Exploration Rover (MER), and InSight missions [20]. These timelines, however, were not directly copied for P.H.O.E.N.I.X's needs, as adjustments were made to account for the unique science and payload requirements. The scope, and risks associated with our mission were also taken into account while creating this schedule. While InSight faced notable schedule delays and launch window shifts, P.H.O.E.N.I.X cannot afford the same leniency due to a more constrained mission profile, limited contingency funds, and increasing scrutiny over Class C and D mission performance. Thus, the P.H.O.E.N.I.X team adopted a conservative approach to schedule allocation, including appropriate schedule margin of 3 months ahead of a 27 months mission, and streamlined system integration after 14 months.

The ground rules for this schedule assume uninterrupted funding profiles and adequate workforce availability throughout all phases of this mission. Furthermore, the project assumes timely delivery of all long-lead components, including the high-priority thermal and CDH hardware, which are pivotal to maintaining downstream integration timelines. These assumptions are made in concert with procurement timelines for commercial vendors such as AZUR Space, Boeing, Blue Origin, and projected government procurement cycles. The mission architecture is not reliant on novel launch vehicle technology, aiding the mission in avoiding potential schedule disruption.

Key underlying assumptions of this estimate also include baseline performance from suppliers, historical integration duration trends, and NASA-mandated milestone reviews. Phase C is estimated to last approximately 30 months and includes final subsystem-level design freeze, initial manufacturing, and Engineering Test Units (ETUs). Phase D will span approximately 18 months, encompassing integration, system-level testing, environmental qualification, pre-ship reviews, and launch readiness verification. This includes a minimum 45-day Launch Campaign period at the launch site. In Phase E, the team assumes a 12-month primary operations period post-launch, supported by an extended operations plan that does not impact the original budget or resource allocations. Phase F, the shortest, covers the demobilization of operations infrastructure and archiving of mission data, scheduled over four months.

P.H.O.E.N.I.X includes approximately 8–12 weeks of critical path margin embedded throughout the integration and test flow. This margin is intended to buffer high-risk activities such as integrated environmental testing, propulsion system leak checks, and end-to-end functional testing of the science payload. The incorporation of slack in non-critical paths such as testbed development or training timelines—further supports the project's ability to absorb minor technical delays without affecting the overall launch window.

Schedule drivers for P.H.O.E.N.I.X are predominantly technical. The integration of the spacecraft's payload suite, which includes multiple high-instrumentation packages with varying heritage, imposes significant alignment and verification requirements. To mitigate the risk of schedule bottlenecks, early integration and testing of Engineering Development Units (EDUs) are planned. Another major driver is the thermal and power subsystem verification campaign. Because of its tailored architecture and compact design, this subsystem requires extensive functional and thermal vacuum testing under full system loads. Launch window constraints, tied to orbital mechanics and planetary alignment, further reinforce the inflexibility of the final launch readiness date.

Finally, the schedule is constructed with NASA project management requirements in mind, including formal Key Decision Points (KDPs), Preliminary Design Review (PDR), Critical Design Review (CDR), System Integration Review (SIR), and Launch Readiness Review (LRR). The team intends to enter Phase C with firm subsystem interface control, preliminary unit-level testing, and completed trade studies. Entry into Phase D is contingent upon successful CDR and the demonstration of full system design maturity.

The P.H.O.E.N.I.X project team has continuously refined this schedule through trade studies, expert interviews, and iterative risk analysis. As the team matures its mission design and transitions toward implementation, this BoE will continue to evolve, incorporating new insight from hardware vendors, updated test flow sequencing, and evolving institutional priorities. A shared commitment to mission assurance, early integration, and proactive risk tracking underlies this planning effort and is foundational to ensuring P.H.O.E.N.I.X meets its science objectives on time and within budget.

1.9.3 Mission Schedule

Phase C of the mission, spanning 30 months starting at the beginning of FY 26, is responsible for the finalization of the design and fabrication [42]. The phase can largely be split into two subphases–pre and post CDR–based on the CDR acting as a gate for acquisitions.

Prior to presenting the CDR, the first subphase will focus on satisfying requirements for KDP C, onboarding additional personnel to assist with future tasks, and finalizing designs at the subsystem and system level [42]. Additionally, risks to the mission are continually monitored and plans regarding verification and validation are drafted. CDRs at a subsystem-level are performed leading up to the system wide CDR presented to the SRB [45]. A timeline of these events can be seen in Figure 1.9.3.1, the gantt chart snippet for the subphase which details the task, its duration, and who it is assigned to. A month of schedule margin allows for ample time to compensate for delays with potential subphase risks regarding onboarding or finalizing designs.

Following the CDR, the mission shifts into the second subphase, C2, which encompasses acquisitions, fabrication, and testing at a subsystem level [42]. Figure 1.9.3.2 shows the schedule for the subphase. Following acquisitions and the finalization of technical documentation, the remaining tasks are largely dominated by the remaining tasks needed to satisfy the SIR, such as subsystem fabrication and testing or plans for integration alongside verification and validation [45]. Due to the enhanced level of risk associated with fabrication, a larger schedule margin of two months prior to SIR presentation is in place to cover any mishaps that may occur.

The timeline for the larger phase is in line with previous missions such as Pathfinder which cleared KDP C in July of 1993, passed CDR in September 1994, and began system assembly in June of 1995 [2]. Similarly, InSight passed its CDR in mid-May 2014 before entering integration and testing at the end of May 2015 [20, 21]. Although differing in mission architecture and scope, both Pathfinder and InSight provide valuable baselines for establishing a timeline for phase C as a whole. Adjustments applied based on instrumentation lead time alongside differences in scope allow these historical analogs to be relevant to the mission. Schedule estimations can be seen in Appendix Figures A.7-A.10 for each instrument. Based on these missions, there exists precedent for the timing of the subphases.

Transitioning into phase D, which begins with its respective KDP, the mission now focuses on full system assembly, integration and testing, and launch [42]. Phase D for this mission is split into four subphases which align with their own respective deliverables.

Subphase 1 entails the integration of subsystems alongside the third party science payload added in a previous descope. Verification and validation of subsystems alongside testing under environmental conditions representative of the mission occur prior to the start of system-level assembly. System level assembly spans across subphases D1 and D2 due to complexity and lead times, meaning that it will not be completed by the deadline for the SAR. Four months is allotted for subsystem integration to ensure that enough time remains in the phase to conduct qualification testing to satisfy SAR criteria [45]. Risks remain tracked throughout the process leading up to the composition of the SAR documentation at the end of calendar year 2028. Should any issues occur, a schedule margin in line with protocol of a month, or a little over 13 percent of the total phase duration, exists to cover high risk obstacles posed by factors such as the third part science payload. Delays with a third-party instrument endangered the continuation of the InSight mission, and if a similar case would occur with P.H.O.E.N.I.X, it is likely the mission would be canceled [10] Further descriptions and durations can be seen in Figure 1.9.3.3, the gantt chart for the section.

Subphase 2 concerns system-wide testing alongside the verification and validation process once the system is fully assembled two months after the start of the phase [42]. In addition to resolving any outstanding issues with verification and validation, crucial tasks required for the ORR regarding the operations handbook are baselined [33]. Testing is scheduled to conclude at the end of March 2029, as seen in Figure 1.9.3.4, the subphase gantt chart. This duration allows for the rest of the phase to entirely be focused on troubleshooting alongside providing ample time for the ORR documentation to be ready prior to traveling to present in front of the SRB [42]. In the event of unresolved problems, a larger margin of a month leading into the beginning of travel for the ORR is in place. While larger than the typical 15% upper bound for margin, the possibility of delay or mishap in assembly or testing justifies this departure from the norm [45].

Subphase 3 covers the final three months the team has before delivering the rover for integration with the launch vehicle and EDL on October 1, 2029 [26, 42]. Activities are largely centered on preparation to satisfy FRR requirements prior to hand off alongside outreach efforts prior to launch [45]. Outreach as a general task spans across subphases D3 and D4 as the mission proceeds towards launch. When transferred over, the rover should have proven interface functionality alongside established supporting elements [33]. A margin of one month, which can be seen in FIgure 1.9.3.5, ensures everything is proven functional and up to standards before transfer and ample time to correct any last minute issues.

Subphase 4 is the period of time following platform transfer for launch vehicle integration and ultimately culminates in launch [42]. Team efforts switch to composing the FRR alongside supporting broader integration efforts regarding the launch vehicle

[45]. Upon successful completion of the FRR and passage of KDP E, the vehicle is cleared for mission launch [42]. The entirety of the team will travel to the launch site in Florida to attend the launch, as reflected in 1.9.3.6, the subphase's gantt chart. Of note is the lack of margin for the subphase. This is due to the travel time and outreach overlapping with the launch date [26].

Phase D margins and time estimations are derived from previous missions of Spirit and Opportunity alongside Pathfinder [37, 35]. Adjusting for lead time alongside accounting for integration challenges with the third party science payload justifies the larger proportional margin allotment for each subphase.

Phase E accounts for cruise alongside EDL, seen in detail in Figure 1.9.3.7, and surface operations up to end of mission, displayed in Figure 1.9.3.8. Assuming a Homann transfer is used, an average travel time is around 9 months [46]. During cruise, tasks focus on ensuring all necessary steps are taken to satisfy the CERR [45]. Engineers and scientists will monitor the rover upon landing as it initializes instrumentation and surface operations before navigating to target sites. The science instrumentation used on the rover is slated to at a minimum deliver trustworthy data from the surface of Mars for at least a year based on analysis from the team's scientists and engineers. Per Figure CONOPS, all critical mission data will be acquired by T+135 days, and schedule margin exists from that date to the mission close at T+365. During this margin, the team can apply for mission extensions if warranted. Plans regarding decommission & archiving are finalized going into the end of mission and decommissioning review [33].

Phase F consists of mission closeout alongside archiving data and documenting lessons learned [42]. Any remaining assets will be disposed of provided that programmatics verifies resources exist to enable the process. The phase concludes with the baselining of the final report and the conclusion of the archiving process [46]. A comparably small margin of two weeks ensures the team has enough time to properly finish all tasks while wrapping up all work by the end of calendar year 2031, as reflected in 1.9.3.9.

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
1	C1: Design Finalization		0%	9/28/25	11/30/26	429	32
1.1	Satisfy KDP C Review	Leadership	Not complete	9/28/25	10/3/25	6	
1.2	Onboard newly-hired engineers, scientists, & technicians	All	Not complete	10/1/25	11/1/25	32	
1.3	Close outstanding trade studies	Engineering	Not complete	10/1/25	11/1/25	32	
1.4	Complete detailed designs at subsystem and system level	Engineering	Not complete	10/1/25	7/1/26	274	
1.5	Track & Update mission risks	Mission Assurance	Not complete	10/1/25	10/18/26	383	
1.6	Generate preliminary detailed technical documnetation	Engineering & Science	Not complete	7/1/26	10/18/26	110	
1.7	Draft plans for Verification & Validation	Engineering*	Not complete	7/1/26	10/18/26	110	
1.8	Perform subsystem-level CDRs	Engineering & Science	Not complete	8/18/26	10/18/26	62	
1.9	Compose CDR documentation	Leadership	Not complete	10/18/26	10/25/26	8	
1.10	Schedule Margin			10/25/26	11/25/26	32	
1.11	◆ Critical Design Review & Production Readiness Review		Not complete	11/25/26	11/30/26	6	

Figure 1.9.3.1: Gantt Chart Phase C1

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
2	C2: Acquisitions, Fabrication, & Subsystem Testing		0%	12/1/26	3/31/28	487	61
2.1	Begin acquisiitions	Engineering & Programmatics	Not complete	12/1/26	12/8/26	8	
2.2	Finalize updated documentation	Science & Engineering	Not complete	12/1/26	1/1/27	32	
2.3	Fabricate subsystems	Science, Engineering, & Technicians	Not complete	1/1/27	12/31/27	365	
2.4	Perform testing of components and subsystems	Science, Engineering, & Mission Assurance	Not complete	4/1/27	12/31/27	275	
2.6	Develop full system-level assembly & integration plans	Engineering	Not complete	10/1/27	1/12/28	104	
2.5	Baseline Validation & Verification plans	Engineering & V&V Team	Not complete	12/17/27	1/17/28	32	
2.7	Update mission risks	Mission Assurance	Not complete	12/17/27	1/17/28	32	
2.8	Draft documentation for SIR	Leadership	Not complete	1/12/28	1/26/28	15	
2.9	Schedule Margin			1/26/28	3/26/28	61	
2.10	◆ System Integrtion Review		Not complete	3/26/28	3/31/28	6	

Figure 1.9.3.2: Gantt Chart Phase C2

								2028								
ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN	A	M	J	J	A	S	O	N	D
3	D1: System & Subsystem Integration & Validation		0%	4/1/28	12/1/28	245	32									
3.1	Satisfy KDP D Review	Leadership	Not complete	4/1/28	4/6/28	6										
3.2	Integrate subsystems	Engineering, Technicians	Not complete	4/3/28	8/3/28	123										
3.3	Integrate external science payload from contractor	Science & Engineering	Not complete	8/3/28	9/23/28	52										
3.4	Verify & validate subsystems	V&V Team	Not complete	8/3/28	11/23/28	113										
3.5	Perform subsystem acceptance verification&	Science & Engineering	Not complete	8/3/28	11/23/28	113										
3.6	Conduct system & environmental qualifications	Science & Engineering	Not complete	8/3/28	11/23/28	113										
3.7	Update risk assessment	Programmatics	Not complete	10/23/28	11/23/28	32										
3.8	Begin full system-level assembly	Science, Engineering, & Technicians	Not complete	10/23/28	12/31/28	70										
3.9	Formulate SAR document	Leadership	Not complete	11/23/28	11/30/28	8										
3.10	Schedule Margin			11/30/28	12/31/28	32										
3.11	◆ System Acceptance Review		Not complete	12/31/28	12/31/28	1										◆

Figure 1.9.3.3: Gantt Chart Phase D1

								Phase					
								20					
ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN	J	F	M	A	M	J
4	D2: System-Wide Testing & Validation & Verification		0%	1/1/29	6/30/29	181	32						
4.1	Finish full-fledged system assembly	Science, Engineering, Technicians	Not complete	1/1/29	3/1/29	60							
4.2	Perform verification & validation tests for full system	Engineering, V&V Team	Not complete	3/1/29	4/1/29	32							
4.3	Assess verification & validation results	Science, Engineering, V&V Team	Not complete	4/1/29	4/15/29	15							
4.4	Resolve outstanding verification & validation issues	Science, Engineering, V&V Team	Not complete	4/1/29	5/18/29	48							
4.5	Archive verification & validation documentation	V&V Team	Not complete	5/18/29	5/25/29	8							
4.6	Baseline operations handbook	All	Not complete	5/11/29	5/25/29	15							
4.7	Fomulate ORR document	Leadership	Not complete	5/11/29	5/25/29	15							
4.8	Schedule Margin			5/25/29	6/25/29	32							
4.9	◆ Operational Readiness Review		Not complete	6/25/29	6/30/29	6							◆

Figure 1.9.3.4: Gantt Chart Phase D2

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN	Phase D 2029 J	A	S	O
5	D3: Launch Vehicle Integration & Support		0%	7/1/29	10/1/29	93	31				
5.2	Address any outstanding risks through mitigation or	Programmatics	Not complete	7/1/29	8/1/29	32					
5.1	Certify flight operations can proceed with current risk	Engineering, Programmatics	Not complete	7/1/29	9/1/29	63					
5.3	Ensure system & supporting elements are propely	All	Not complete	7/1/29	9/1/29	63					
5.4	Prove interface functionlity	Engineering	Not complete	7/1/29	9/1/29	63					
5.5	Generate public interest in mission	Outreach, Leadership	Not complete	7/1/29	10/1/29	93					
5.5	Schedule Margin			9/1/29	10/1/29	31					
5.6	◆ Rover Handoff		Not complete	10/1/29	10/1/29	1					◆

Figure 1.9.3.5: Gantt Chart Phase D3

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN	Phase D 2029 O	N	D
6	D4: Flight Readiness & Launch		0%	10/2/29	12/1/29	61	1			
6.1	Draft documentation for FRR	Leadership	Not complete	10/2/29	10/15/29	14				
6.2	Continue outreach efforts previously outlined	Outreach	Not complete	10/2/29	12/1/29	61				
6.3	Support launch vehicle integration efforts	Engineering	Not complete	10/2/29	11/30/29	60				
6.4	Finalize FRR document	Leadership	Not complete	10/16/29	10/16/29	1				
6.5	Satisfy KDP E requirements	Leadership	Not complete	10/17	10/19/29	3				
6.6	Travel to Kennedy Space Center for Launch	All	Not complete	11/26/29	12/1/29	6				
6.7	Schedule Margin			11/30/29	11/30/29	1				
6.8	◆ Launch		Not complete	12/1/29	12/1/29	1				◆

Figure 1.9.3.6: Gantt Chart Phase D4

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
7	E1: Cruise & Entry, Descent, & Landing		0%	12/1/29	9/1/30	275	229
7.1	Assess launch vehicle performance	Engineering	Not complete	12/2/29	1/2/30	32	
7.2	Update risks tracking	Programmatics	Not complete	12/2/29	1/2/30	32	
7.3	Finalize critical activity operations plan	Science & Engineering	Not complete	12/2/29	1/2/30	32	
7.4	Monitor platform during cruise	Engineering	Not complete	12/2/29	9/1/30	274	
7.5	Implement fault protection strategy	Engineering	Not complete	12/2/29	1/2/30	32	
7.6	Draft decomissioning plans	All	Not complete	12/2/29	1/2/30	32	
7.6	Draft & submit Critical Event Readiness Review	Leadership	Not complete	1/2/30	1/16/30	15	
7.7	Schedule Margin			1/16/30	9/1/30	229	
7.8	◆ Entry, Descent, & Landing		Not complete	9/1/30	9/1/30	1	

Figure 1.9.3.7: Gantt Chart Phase E1

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
8	E2: Surface Activity & End of Mission		0%	9/1/30	9/1/31	366	231
8.1	Monitor deployment of science instrumentation	Science	Not complete	9/1/30	9/2/30	2	
8.2	Assess initial rover functionality & responsivity on	Engineering	Not complete	9/1/30	9/2/30	2	
8.3	Analyze transmitted telemetry from travel to target	Engineering	Not complete	9/2/30	10/15/30	44	
8.4	Recieve & analyze data from instruments at site 1	Science	Not complete	10/16/30	10/16/30	1	
8.5	Repeat processes 8.3 & 8.4 for sites 2 and 3	Science & Engineering	Not complete	10/17/30	1/14/31	90	
8.6	Apply for mission extension if warranted	Leadership	Not complete	1/14/31	7/1/31	169	
8.6	Define & document reasons for decomission	Engineering & Programmatics	Not complete	7/1/31	9/1/31	63	
8.7	Implement resources for disposal, decomission, &	Programmatics	Not complete	7/1/31	9/1/31	63	
8.8	Draft & submit Decomissioning Review document	Leadership	Not complete	7/1/31	9/1/31	63	
8.9	Prepare plans for archival of mission data	All	Not complete	8/1/31	9/1/31	32	
8.2	Schedule Margin			1/14/31	9/1/31	231	
8.3	◆ End of Mission		Not complete	9/1/31	9/1/31	1	

Figure 1.9.3.8: Gantt Chart Phase E2

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN	Phase F 2031 S	O	N	D
9	**F1: Closeout**		0%	9/2/31	12/31/31	121	14				
9.1	Satisfy KDP F requirements	Leadership	Not complete	9/2/31	9/2/31	1					
9.2	Gather relevant engineering & science data from	Science & Engineering	Not complete	9/2/31	10/2/31	31					
9.3	Ensure schedule, budget, & personnel resources are	Programmatics	Not complete	9/2/31	9/16/31	15					
9.4	Close outstanding TBDs & TBRs regarding mission	All	Not complete	9/2/31	9/16/31	15					
9.5	Draft & submit DRR	Leadership	Not complete	9/16/31	9/30/31	15					
9.6	Dispose of remaining mission support processes &	All	Not complete	10/1/31	11/30/31	61					
9.7	Baseline final mission report	All	Not complete	10/1/31	12/18/31	79					
9.8	Document & capture lessons learned	All	Not complete	10/1/31	12/18/31	79					
9.9	Archive mission data	All	Not complete	10/1/31	12/18/31	79					
9.10	Schedule Margin			12/18/31	12/31/31	14					
9.11	◆ Completion of final archiving tasks		Not complete	12/31/31	12/31/31	1					◆

Figure 1.9.3.9: Gantt Chart Phase F1

1.10 Mission Cost

1.10.1 Cost Overview

The total estimated cost for P.H.O.E.N.I.X is approximately $424 million which is below the mission allowed maximum of $450 million. The mission cost is summarized in the P.H.O.E.N.I.X Budget Breakdown and Pie Chart below. This cost encompasses the full scope of the mission and includes personnel, travel, outreach, facilities, and other direct costs. These categories are developed using a combination of parametric modeling and known rates derived from the NASA cost estimating handbook and other sourced public data as sourced for each respective section.

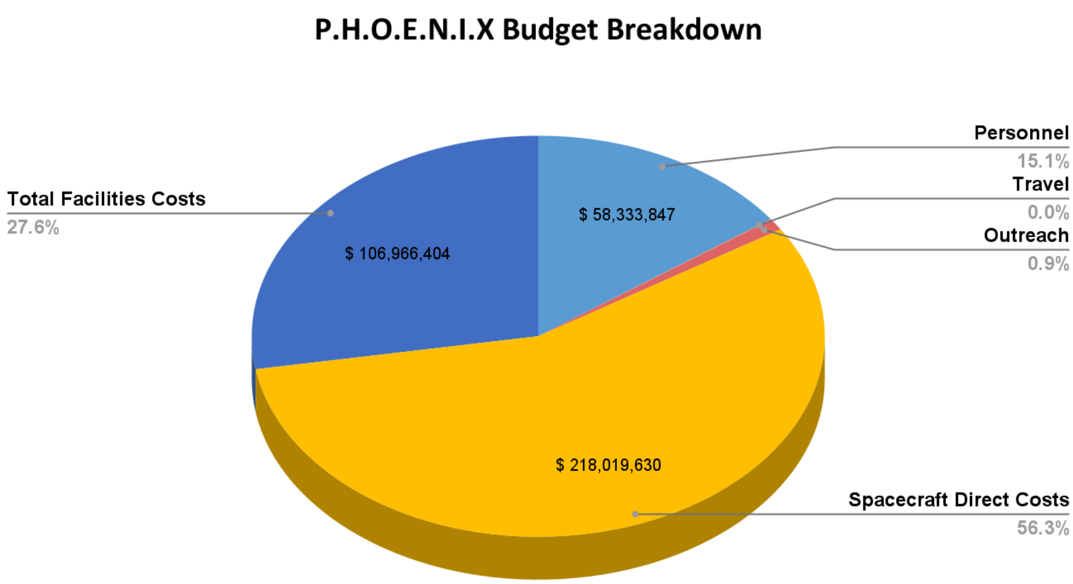

Figure 1.10.1.1: P.H.O.E.N.I.X Budget Breakdown Chart

P.H.O.E.N.I.X Budget Breakdown	
Personnel	$ 58,333,847
Travel	$ 162,853
Outreach	$ 3,759,687
Spacecraft Direct Costs	$ 218,019,630
Total Facilities Costs	$ 106,966,404
Total Mission Cost	$ 405,573,838
Total Mission Cost Limit	$450,000,000
Total Mission Cost Delta	-$44,426,162

Figure 1.10.1.1: PHOENIX Budget Breakdown Table

The budget is organized into four primary categories: Personnel, Travel, Outreach, and Direct Costs. Personnel include all personnel costs except for outreach personnel which are included in the Outreach category.

1.10.2 Cost Basis of Estimate

The Cost Basis of Estimate (BoE) for P.H.O.E.N.I.X defines the ground rules, assumptions, and cost drivers used to develop the preliminary cost estimate for phases C through F of the mission's life cycle. The purpose of the BoE is to clearly define how cost estimates were developed from the rules, assumptions, and drivers.

Ground Rules

A $450M cost limit is established specifically for the Rover System, encompassing all expected mission costs including personnel, travel, outreach, hardware, testing, direct costs, as well as cost margins of safety. The BoE only targets Phase C through F. Costs will be estimated primarily using parametric models. It is assumed that these tools provide an accurate reflection of the anticipated cost. These estimates are then aggregated into a budget template that is derived and adjusted from the Lucy Mission Budget.

Assumptions

A constant 2.7% yearly compounding inflation rate is assumed to estimate the budget across the entire mission's lifecycle [67], this annual inflation rate applied over the mission's lifecycle is based on NASA's New Start Inflation Index (NNSI). It is assumed that personnel turnover will be minimal. In cases where turnover does occur, replacement costs are expected to be negligible and are covered by the total cost margin. Outreach costs relate to the team's effort in increasing public awareness of P.H.O.E.N.I.X and the impact that it will have on the scientific community and the end science goals.To support outreach goals, four full time outreach personnel will be employed for the full duration of the mission. A graphic designer, a social media specialist, an event coordinator, and an education & curriculum specialist. These personnel will be responsible for creating content, organizing public events, and developing educational materials.

Personnel travel costs will be estimated through the City Pair Program for airfare. FedRoom for lodging, and per diem reimbursement for meals and rentals. Tests are conducted at relevant NASA centers across the country, and launch takes place at Cape Canaveral, Florida. Key personnel will be flown in to oversee and conduct in-person testing of relevant components and subsystems with rental cars, lodging, and meals priced out using the aforementioned resources [63]. It is assumed that key subteam leads will travel to NASA testing centers twice per year during Phase C and D. It is also assumed that an outreach event will occur quarterly, with travel for 2 outreach team members.

Drivers

The primary cost drivers for P.H.O.E.N.I.X include items such as scope changes or descopes, which can shift the required designs and greatly impact system costs. External government policies such as changes in import tariffs may introduce some budget uncertainty, especially for foreign-sourced hardware. Lastly, any unforeseen engineering testing failures may lead to cost inflation due to vendor lead times and/or potential redesigns. The full budget will include breakdowns of costs for each phase of the mission as well as a per-item cost breakdown. To account for any delays, uncertainties, scope changes, and unexpected problems, a 30% total cost margin will be applied to the budget totals. This margin aligns with the standard 70% confidence level in lifecycle cost estimates at the PDR stage [39].

1.10.3 Personnel Cost

The personnel cost for P.H.O.E.N.I.X is derived from a combination of analogous space missions and expected personnel workload tailored for each mission phase. Personnel are allocated by mission phase based on expected demands, with peak staffing occurring during Phases C and D where the largest amount of critical design, integration, testing, and collaboration is required to ensure P.H.O.E.N.I.X is ready for launch.

The core mission team remains consistent throughout the mission lifecycle. The baseline P.H.O.E.N.I.X team consists of 3 teams; science, engineering, and programmatics (refer to Figure 1.5.1 Organizational Chart). Each subteam is led by a designated team leader, with oversight from the PM.

- Science: 4 Personnel & 1 Management
- Engineering: 8 Personnel & 1 Management
- Progammatics: 1 Personnel & 1 Management
- 1 Project Manager

This results in a baseline mission staff of 16 personnel.

On top of the baseline team, there will be an additional 104 support staff hired over the course of the mission to distribute the workload. The support staff includes 40 engineers, 24 technicians and the Quality & Validation team that consist of 8 quality assurance personnel and 10 V&V personnel, 20 scientists, 5 administration staff, and 4 outreach personnel. During peak design and fabrication activities in Phases C and D there will be an expected peak staffing of 111 personnel working on P.H.O.E.N.I.X.

Salaries for each role are assumed fixed except for inflation rates with a 28% benefits rate applied [47]. In Figure 1.10.3.1 , technicians and the Quality & Validation(Q&V) team are grouped together as they receive the same base pay. Salaries are all derived from the Bureau of Labor Statistics and rounded up to the nearest thousand for buffer. It is assumed that all personnel are employed full time and that any turnover will be minimal or covered within the Total Cost Margin.

Personnel Phase Allotment Table						
	Phase C	**Phase C**	**Phase C-D**	**Phase D**	**Phase E**	**Phase F**
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5	FY 6
Science Personnel:	15	15	10	5	24	24
Engineering Personnel:	48	48	30	20	10	10
Technicians and Q&V:	35	35	35	20	0	0
Administration Personnel:	5	5	5	5	5	5

Outreach Personnel:	4	4	4	4	4	4
Management Personnel:	4	4	4	4	4	4
Total Personnel	111	111	88	58	47	47

Figure 1.10.3.1: Personnel Phase Allotment Table

Science:

The scientist staff count choice reflects a similar NASA mission, NASA's LROC mission which employed 22 science staff over its mission lifecycle [18]. In FY1 and 2, 15 science personnel are needed to collaborate with the team to set goals and validate that the appropriate instruments and devices are being integrated correctly and in accordance with the mission's science goals. Scientists are staffed at a peak of 24 in Phases E and F where the majority of data processing and scientific analysis are required.

Engineering:

As discussed in 1.6 Project Management Approach, there will be a need of 10 engineers per engineering subteam, with 4 engineering subteams resulting in 40 engineers being hired on top of the baseline team. For a peak total of 48 engineers. Engineers are allocated per phase based on workload. Phases C and D are where peak engineering work and fabrication is occurring, engineers are most needed then.

Technicians & Q&V:

Technicians are necessary for rover fabrication. Technicians contribute to mechanical, electrical, and general roles. A total of 35 technicians and Q&V personnel are needed during the critical phases of rover development and assembly. Technician support is phased out following launch, with no staff assigned during Phases E and F.

Administrative, Outreach, and Management:

Administrative personnel are responsible for mission organization, project supervision, and ensuring P.H.O.E.N.I.X is delivered in time, in conjunction with management. Management is composed of personnel from the baseline team for a total of 4 managers. Outreach personnel are further detailed in section 1.10.5 Outreach Costs.

In total, the projected personnel cost for P.H.O.E.N.I.X is estimated at $58.3 million. These personnel costs reflect expected mission demands and accounts for direct and indirect labor expenses.

P.H.O.E.N.I.X Preliminary Budget							
Mission Phase	Phase C	Phase C	Phase C-D	Phase D	Phase E	Phase F	
Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Cumulative Total
PERSONNEL							
Science Personnel	$ 1,200,000	$ 1,232,400	$ 843,200	$ 432,400	$ 2,127,360	$ 2,179,200	$ 8,014,560
Engineering Personnel	$ 3,840,000	$ 3,943,680	$ 2,529,600	$ 1,729,600	$ 886,400	$ 908,000	$ 13,837,280
Technicians	$ 2,100,000	$ 2,156,700	$ 2,213,400	$ 1,297,200	$ -	$ -	$ 7,767,300
Administration Personnel	$ 300,000	$ 308,100	$ 316,200	$ 324,300	$ 332,400	$ 340,500	$ 1,921,500
Project Management	$ 480,000	$ 492,960	$ 505,920	$ 518,880	$ 531,840	$ 544,800	$ 3,074,400
Total Salaries	$ 7,920,000	$ 8,133,840	$ 6,408,320	$ 4,302,380	$ 3,878,000	$ 3,972,500	**$ 34,615,040**
Total ERE	$ 2,210,472	$ 2,270,155	$ 1,788,562	$ 1,200,794	$ 1,082,350	$ 1,108,725	**$ 9,661,058**
Personnel Margin	$ 2,532,618	$ 2,600,999	$ 2,049,221	$ 1,375,794	$ 1,240,087	$ 1,270,306	**$ 11,069,024**
TOTAL PERSONNEL	$ 12,663,090	$ 13,356,128	$ 10,799,392	$ 7,436,164	$ 6,870,084	$ 7,208,988	$ 58,333,847

Figure 1.10.3.2: PHOENIX Preliminary Personnel Budget

1.10.4 Travel Cost

Personnel travel costs will be estimated through the City Pair Program for airfare. FedRoom for lodging, and per diem reimbursement for meals and rentals. Tests are conducted at relevant NASA centers across the country, and launch takes place at Cape Canaveral, Florida. Key personnel will be flown in to oversee and conduct in-person testing of relevant components and subsystems with rental cars, lodging, and meals priced out using the aforementioned resources [8]. It is assumed that key subteam leads will travel to NASA testing centers twice per year during Phase C and D. It is also assumed that an outreach event will occur quarterly, with travel for 2 outreach team members.

FY	Purpose	# Trips	People/Trip	Total Person-Trips
FY1	Design Finalization	2	4	8
FY2	CDR, Fabrication & Testing Oversight	5	4	20
FY3	SIR, Oversight	5	4	20
FY4	Oversight, ORR, Rover Handoff	5	4	20
FY5	Launch!	1	16	16
FY6	Post Launch Oversight	2	4	8

Figure 1.10.4.1: Fiscal Year Travel Costs

Travel also occurs for presenting deliverables in front of SRBs when necessary per guidelines. Leadership will be flown in to deliver the presentation in person with trips lasting five days. Two travel days pad the presentation scheduled for day three of five, ensuring crucial presentations are not missed due to external factors beyond the team's control.

1.10.5 Outreach Cost

For social media, there is a highly unlikely chance of having financial expenses, due to the widespread use, availability, and accessibility of content creating applications. However, if the team is to hire graphic designers, social media specialists, education & curriculum specialists, and event planners, they will cost $65,000, $78,000, $65,000, and $60,000 annually, respectively [8]. However, most of the team members have advanced knowledge of content creation and editing, meaning there is a high chance that professional outreach experts are not needed for promoting the mission.

For Lego NXT, each robot set will cost around $300-400, depending on the source and location of which it is bought from. The team will do a workshop in front of 30 students to educate them on the NASA mission with the costs ranging from $9,000-12,000 for all of the robots for each student. To rent an auditorium for the students, costs range from $150-300 per session in a single day. Overall, the process for hosting an informational session to 30 students with Lego NXT robots will take 1-2 weeks, depending on the response of the auditorium staff and the teachers.

For the RIMFAX geological presentation, the auditorium rental cost will be $150-300 for 2 hours. 15 high school and college students will attend a presentation and 15 workplace professionals will attend a conference to learn more about space-related careers in science and engineering. The team will also rent a live radar imager, which the cost ranges from $46,000 to $126,000, depending on the company and capabilities. However, since this will be a rental and not a purchase, the cost will most likely be scaled down to half the price ($23,000-$63,000).

For the Space Festival, it will take place at a NASA center. For tickets, each one will cost around $30-40 per person, while children 12 years and under can enter for free. The tickets will allow the patrons to access as many events and attractions as possible that the space festival can provide. For the wages of the employees working the space festival, they will earn on average $25-50 an hour, depending on the position they are working. This includes catering staff, janitorial staff, event outreach workers and hosts, industry professional speakers, professors or subject matter experts, and various other staff roles.

1.10.6 Direct Costs

Mechanical Subsystem Cost:

For the mechanical subsystem, cost estimates were derived using Xometry's automated manufacturing cost calculator. This tool provides a cost breakdown based on CAD geometry, material selection, and manufacturing process. Each of the tire treads have an estimated manufacturing cost of $232.03. Since there will be 6 wheels on the rover, this totals to an estimated $1392.18 for the tires. For the wheel spokes, each part had an estimated cost of $448.35. Given that there will be 6 wheel spokes for each wheel on the rover, this yields a total estimated cost of $2690.10. The rocker-bogie subsystem was split into 2 parts to allow for independent suspension. The front half of the rocker has an estimated price of $8,282.87 per piece. The back half of the rocker has an estimated manufacturing cost of $161,118.46. Since there are 2 of each parts of the rockers for either side of the rover drive, this yields a total estimated manufacturing cost of $322,236.92. The differential was split into 3 parts to allow for rotation in two planes. The two mounts have estimated manufacturing costs of $189.12 each, and the two rotating pegs have estimated manufacturing costs of $564.11 each. The bar connecting the pegs to the chassis has an estimated manufacturing cost of $592.26. The chassis, which has an estimated manufacturing cost of $1,435. This totals to a net manufacturing cost of $346,418.66. This figure will be rounded upwards to the nearest hundred thousand, yielding $400,000 for total cost margin considerations.

Power Subsystem Cost:

Utilizing the Mission Concept Cost Estimation Tool (MCCET) to aid in calculation of system components, the team was able to derive estimates of the cost for power subsystem components that had no readily available “shelf price”. The planned battery, an EaglePicher SAr-10211 with a 4,380Wh rating, had an estimated cost of $37,869.36. Accounting for shipping, tax, testing costs, and integration costs, we estimated $40,000 for this component. As the mission cannot afford the weight of a second battery in the launch, this is the only estimate associated with the rechargeable battery.

The roll-out solar array is a custom component that allows the solar panels to utilize less mass and produce a larger margin of usable power. The deployment system for these panels, like those used on the International Space Station, will be provided by Redwire, while the panels will be manufactured by AZUR Space. The solar panels shall also utilize EDS to shield from dust and radiation risks. This is a custom technology, and will cost more to manufacture than a typical solar cell. The chosen panels weigh 17kg per 1.3 square meters (unrolled), and cost an estimated $120,337.62 per unit. Rounding to include testing, shipping, and tax puts the estimated cost of this component at $150,000.

Providing isolated power to the external experiment requires the use of an isolated power distribution system. For the P.H.O.E.N.I.X mission, the WR62 4-Way Combining System Assembly produced by the Scientific Microwave Corporation. This bus shall provide adequate distribution and isolation for a resulting higher-efficiency architecture. For redundancy, the rover will carry two PDUs, for an estimated cost of $7,500 each, totalling $15,000 after integration, testing, shipping, and material handling costs.

For isolated thermal management of power components and batteries, the rover shall utilize variable heat pipes produced by Advanced Cooling Technologies, as well as the addition of a thermal buffer vapor chamber, which combined would cost an estimated $683,128.34, rounded to $700,000, due to the mass, complex architecture, and involved testing procedures.

In total, the estimated cost of the electrical power subsystem for this mission is $905,000.

Command and Data Handling (CDH) Subsystem Cost:

The Mission Concept Cost Estimate Tool (MCCET) provides the outline for cost estimates for various subsystems. For the costs related to CDH there are both electronics subsystem costs and software subsystems costs which must be incorporated. Both electronics and software cost estimates depend on the mass estimate of the electrical subsystem.

The RAD5545 OBC weighs 1.8 kg, and two shall be used on the rover. The SSDs weigh 620g and two will be used on the rover. The UHF transceiver weighs 2.0 kg. The data interface cable weighs ~3g/m, and at 150m of usage will weigh 0.45 kg. The UHF antenna weighs 0.6 kg. This puts the total CDH mass total at 8.25 kg. Using these mass estimates for the NICM, the output of the Cost Estimating Relationships (CERs), shall be found for the electronics and software subsystems. The electronics subsystem costs are 7,222.62, and the software development costs are 1,012.20, and therefore the estimated cost with inflation for electronic subsystems are $13,654,254.28, and software development costs are $1,912,754.34. Rounding to the nearest hundred thousand yields $13,700,000 for electronics, and $2,000,000 for software.

The Command and Data Handling (CDH) subsystem procurement costs are estimated to cost a total of $513,232. The RAD5545 onboard computer, sourced from BAE Systems, is priced at $250,000 per unit, with two units, totaling $500,000. Two Mercury RH3440 SSDs will be used for data storage at $18,000 each, totaling $36,000 [32]. The selected UHF transceiver, the L3Harris Electra-lite, is estimated at $250,000 based on past procurement of similar flight hardware. The RS-422 transceiver from Texas Instruments is estimated at $150 with 20 needed total. The primary data interface cable, the WireMasters DXN2605 30 AWG twisted pair, will cost approximately $1,500 for 150 meters. The UC-3004-531R quadrifilar helix UHF antenna is priced at $600 [46]. The sum of all procurement costs is $791,10, and rounding to the nearest hundred thousand yields $800,000.

The total CDH costs are estimated at $16.5 million dollars.

Thermal Subsystem Cost:

The team utilized the NASA Instrument Cost Model (NICM) to calculate and estimate the cost of the thermal subsystem components. For Dwyeromega KHLVA-102/5 Electrical Heaters, the cost is provided on the Dwyeromega catalog page, with it being $115.87 per unit, and we would have around 30 electrical heaters. Thus, making the subtotal cost being $3,476.10; however, we must account for tax and delivery fees, thus it should be rounded to $4,000.00. The Sierra Space Thermal Louver radiator would cost around $1,283,750.26, which includes costs for thermal analysis, materials support, load definition, and instrument system thermal hardware, etc. These costs are derived via the utilization of the CER equations from NICM. However, this analysis shall be rounded up to $1,300,000.00 to account for any total cost margin [Figure A.1]. For NI Solution's thermistor, the cost for this specific thermal sensor is calculated to be around $351,940.55, like any other components of the subsystem, with consideration of thermal analysis, etc. This estimation also comes from the thermal portion of the CER of the NICM. This number shall be rounded to the nearest hundred thousand, which rounds to $400,000.00; therefore, it shall be put as the direct cost [Figure A.2]. For Advanced Cooling Technologies' Variable Conductance Heat Pipes (VCHP), the cost would be $571,808.15 with all considerations, using the same equation from CER. This amount shall be rounded to $600,000.00 for total cost margin considerations as well [Figure A.3]. The team was not able to find the mass of any sort for the Constance Conductance Heat Pipe (CCHP); therefore, it can be concluded that the CCHP acting similarly would be around the same margin of cost as the VCHP, with total cost margin into consideration, it should also be $600,000.00. For the multilayer insulation (MLI), general information regarding the thickness of a particular layer is provided; however, the mass per unit square was not provided without the consultation of companies like Dunmore Aerospace and Sheldahl for quotes. This hindered the team's ability to calculate the cost for specific layers, for instance, double-sided mylar, goldized kapton. Without this, it also hindered operations on calculations for how much EPON 815C Epoxy Resin needs to be used, the amount of Kapton Tape, plus the amount of threads needed to stitch the MLI; thus, a total cost margin must be set in place for MLI-related components of this subsystem.

Instrumentation Subsystem Cost:

To calculate and determine costs within the instrumentation subsystem of P.H.O.E.N.I.X., each instrument was evaluated with the use of the Mission Concept Cost Estimate Tool (MCCET), which estimates the costs of wrap and testing facilities. Wrap costs include management, systems engineering, product assurance, integration, and test costs, which should be considerable because they ensure the instruments are properly supported and verified for flight readiness. Test facility costs include thermal vacuum, electromagnetic interference, vibration testing, and ambient testing, which all help confirm the quality and ability of the instruments to operate under the conditions the mission is bound to encounter. Costs are imperative to be valued properly to make informed decisions that allocate the given budget efficiently within the instrumentation subsystem.

Utilizing the Mission Concept Cost Estimation Tool (MCCET), an inflation rate of 188.97% was calculated to properly determine accurate inflation-adjusted costs for each of the four main instruments. This constant inflation rate impacts overall costs as it adjusts to the current economic conditions to prevent an inefficient use of the given budget for instrumentation that plays a major role in data collecting. With the use of the CER formula:

The CP-MU DMU-100 Submersible Gamma Neutron Probe (including its external box and probe) is approximately $1,104 based on its total values of 1.3 kg for mass and max power of 0.25 watts. The CER value calculates the final manufacturing cost per unit that includes manufacturing and wraps, approximating to a total of $2,700,000, and the final testing facility cost per unit that approximates to $800,000.

The RIMFAX instrument is made up of an externally mounted antenna at the back of the rover and an electronic unit inside the rover body. With a total mass of 3 kg and a max power of 10 watts, the CER formula calculated the cost to be $5843. This value created the total cost estimate for final manufacturing cost per unit to be approximately $14,600,000 and final testing facility cost per unit to $4,400,000.

The Miniature Tunable Laser Spectrometer (Mini-TLS) is approximately $2877 based on its total values of 1kg for mass and max power of 8 watts. The CER value calculates the final manufacturing cost per unit that includes manufacturing and wraps, approximating to a total of $7,200,000 and the final testing facility cost per unit that approximates to $2,200,000.The Raman Laser Spectrometer (RLS) is approximately $8153 based on its total values of 2.4 kg for mass and max power of 30 watts. The CER value calculates the final manufacturing cost per unit that includes manufacturing and wraps, approximating to a total of $7,200,000 and the final testing facility cost per unit that approximates to $2,200,000.

1.11 Scope Management

1.11.1 Change Control Management

After a careful review on how to approach any significant changes to the design of the rover, the mission or the payload the team has decided to follow a standard protocol for any changes that occur throughout the life of the mission. This protocol will include a set of stages for each change from its introduction to its implementation into the system. A change log has been created to track these changes. Additionally, there is a process for addressing stakeholder feedback in the form of a request for action (RFA) or advisory (ADV) that will be important for understanding the depth of the change that is needed.

A change is anything that alters a previously baselined plan for the mission. These changes may come in many forms including: design change, requirement change, objective change, programmatic changes, and stakeholder change (RFAs, ADVs, Scope). Design changes are those that change the physical configuration or functional behaviour of any system or subsystem. Requirement changes are modifications of mission requirements, low or high level. Objective changes are changes to the scientific objectives of the mission. If a change is needed to the timeline of the mission a schedule change will be implemented. Stakeholder changes include RFAs, ADVs, and scope changes from the customer, NASA. The process for scope change control is outlined in 1.11.2.

Changes can be brought up by any personnel whether it be technical or non technical. To request a change, the change log must be updated with all relevant information. Subsequently, the requestor will meet with the team lead to explain the change. The leads discuss whether the change is necessary. To be approved to submit a change request the change must be supported by the overseeing lead (engineering change by LSE, etc.) and at least two other leads.

If approved, a follow-up meeting with the leads and any personnel with affected subsystems will be conducted to discuss how the change impacts each subsystem and which personnel is responsible for its implementation. This information will be brought to the Change Control Board (CCB) by the identified relevant personnel through a change request. Once the change is approved, this personnel will implement it into the system.

Any RFA or ADV driven by stakeholder feedback will have its own process to change. RFAs are changes which must be made in past deliverables, but do not require change requests. They will follow the standard change process minus the necessity of a CCB. ADVs do not require that the team make any changes; however, they will be understood and tracked for the improvement of future deliverables. These ADVs will help the team improve the overall clarity of the mission. Scope changes will also be tracked on the change log but have a different process of management.

There are three layers of communication to ensure changes are completed. Every change will be tracked on the change log with all relevant information. At general team meetings, the change log will be displayed to ensure the whole team understands and has input into the changes. To track the completion of changes, any subteam lead with personnel working on a change will check in during subteam meetings.

Verification of tentatively completed changes will involve the same group of leads plus relevant personnel. They will discuss the changes that occurred, consider the risks, and ensure the full completion of the change. If it is not complete, it will continue to be worked on until it passes this board. Once completed, the change log will be updated to show the completed nature of the change. This includes the sign off of all four team leads.

The change log is a spreadsheet meant to track each change, the reason for a change, what will change, impacted subsystems, assigned individuals, and the changes current state.

Change Log										
ID	**Change**	**Type**	**Reasoning**	**Description of Change (If stakeholder state if RFA, ADV, Scope)**	**Assigned Individual**	**State**	**Chief Scientist Signoff**	**Lead System Engineer Signoff**	**DPMR Signoff**	**Project Manager Signoff**
0.1	Stakeholder Added Science Instrumentation	Stakeholder	The stakeholder has requested to add new scientific instrumentation to the vehicle with the option of external or internal mounting.	(Scope) A new scientific instrument will be externally mounted on the rover. Thermal - Increase in MLI and thermal coating to reduce power usage of active heaters. CDH - Antenna mounting must be moved 1m to protect the instrument from interference. Mobility systems and instruments cannot be used simultaneously to reduce risk of too much power draw.	Whole Team	Completed	Approved	Approved	Approved	Approved
0.2	Alteration of Science Objective 1 of HBS-1LM	Objective	Quantity of material to be collected for study was unquantified. The data transmission interval was too long.	One single sample will be collected and the new data transmission interval will be weekly.	Alanis and Matthew	Completed	Approved	Approved	Approved	Approved
0.3	MCR-RFA-2	Stakeholder	A thorough description of each region of interest and how they fulfill the team's science objectives must be provided.	The MCR will be changed to explain how the features of the Martian geography help fulfill the science objectives with the abundance of impact craters and lobate debris aprons which make asteroid rocks and hydrated volcanic rock abundant to study.	Conor	In Progress	Pending	Pending	Pending	Pending
0.4	MCR-ADV-1	Stakeholder	Provide more detail on the science data being collected for the Human Exploration Goal	(No change needed to MCR) In future deliverables ensure that there is a connection between data collected and the human exploration goal plus objectives.	Science Team	In Progress	Pending	Pending	Pending	Pending
0.5							Pending	Pending	Pending	Pending

Figure 1.11.1: Change Log

1.11.2 Scope Control Management

In the event that a scope change is needed, the team shall begin a process that ensures the change is implemented smoothly across the science, engineering, and programmatic teams. In both cases of descoping and upscoping, the first step should be defining mission impacts. The descope or upscope may cause science capabilities to be redefined, so the STM should be updated to reflect any necessary changes. Additionally, the requirements table and risk matrix should be updated if the descope or upscope poses new requirements or risks to the mission. All of these changes should be documented through the change control log, and all team members should be notified. Once the broader mission impacts have been identified, documented, and communicated, the descope or upscope shall go through its respective tiered process involving the management of potential engineering subsystem design changes, budget or schedule changes, and other scope change implications.

Downscoping Strategy:

The first tier of the descoping measures will be Tier 0: Redesign and Change Management. This will refer to instances where manufacturing times exceed the estimated baseline plus the 25% contingency margin (e.g., 11 business days extended to 14 days), or if manufacturing costs significantly surpass projections. In the case that machining lead times or costs exceed estimates, non-critical rocker-bogie elements or wheel tread geometry will be simplified to reduce machining complexity. This includes removing features such as edge blends on the rocker-bogie structure to simplify the machining process since they are not structurally necessary. This can reduce both material usage and production time without impacting the performance capabilities of the subsystems. Furthermore, the traverse route planning can be adjusted to reduce the wear and power consumption of the rover without compromising the primary science objectives by altering the traverse distance from 10 km to 8 km, focussing on sites with the highest subsurface ice potential.

The next tier of the descoping measures will be Tier 1: Design Simplification and Secondary Science Adjustments. This tier will involve minor alterations to the design of the mechanical subsystems such as the wheel diameter. The wheel diameter will be reduced slightly by at most, 5% if required to reduce the mass and machining costs. Additionally, the Raman Laser Spectrometer (RLS) sample count or spectral resolution for non-priority sites can be reduced by 15%, preserving critical D/H and ice data. Adjustments to the TLS measurement frequency from weekly to bi-weekly intervals can conserve energy and data bandwidth.

The Final tier of the descoping measures will be Tier 2: Instrument Reduction. This tier will involve the removal of the lowest-priority payload functions that have no impact on the scientific objectives or their value to the scientific community. This includes removing non-essential RLS scans and limiting CP-MU Gamma Neutron Probe measurements to high-priority sites instead of full route coverage. Even with these changes, the P.H.E.O.N.I.X mission's core objectives of mapping accessible ice reservoirs, monitoring radiation hazards, and analyzing water source evolution, would remain fully achievable.

Upscoping Strategy:

The upscoping strategy will start with Tier 0: Redesign and Change Management. After engineering subteams are made aware of the upscope, the scope change will be accommodated for in subsystems. The scope change may involve added risks that must be managed or accepted, volume or mass reallocations, added instrumentation, or more. During this tier, engineering subteams will decide if their subsystem must be redesigned, or if the scope change can be accommodated with the subsystems as is. For the mechanical subsystem, this may look like this expanding the chassis volume, and for the thermal subsystem, this may involve recalculating the heat flow chart and incorporating extra electrical heaters. Engineering subteams have designed their subsystems with volume, weight, and power margins, so the upscope shall be integrated within those margins. All changes will be immediately documented in the change log.

The following tier of upscoping is Tier 1: Manufacturing and Procurement Readjustments. Each subteam has allotted error margins in lead time estimation, and this time shall be used to accommodate the upscope. If the manufacturing and procurement lead times exceed the projected times in addition to error margins, alternate machining or vendors will be considered. Alternate machining may involve simplifying component geometries or accepting decreased precision for quicker manufacturing times, and alternate vendors will involve searching for contractors with shorter lead times.

The final tier will be Tier 2: Reallocation of Resources. The programmatic subteam has left cost margins, and in the event of an upscope, additional budget shall be redistributed. To accommodate for increased material, manufacturing, or component costs, budget from facility, spacecraft, or total project margins should be transferred to more specific budgets such as the engineering subteam budgets. To accommodate for the possibility of needing additional engineers or technicians in order to stay on schedule, the personnel margin should be transferred to the engineering personnel or technician budgets. In the event of resource allocation, stakeholders will be notified, but the margins should cover any additional costs or schedule changes brought by the scope change.

1.12 Outreach Plan

An outreach plan will be initiated to raise awareness of mission *P.H.O.E.N.I.X* and inspire future generations to reach for the stars through STEM, non-STEM, and trade pathways into space exploration. Outreach will be initiated through multiple components such as:

1. **Social Media content creation** will be conducted on all popular social media platforms prior to the start of the mission and concluding once the mission has ended. This is performed with the goal of raising public awareness of the mission through social media posts, livestreams, Q&A with the NASA staff involved in the mission, and 3-D simulation videos discussing the rover's ongoing scientific experiments, and collected data. An emphasis will be placed on conveying non-technical information to provide an easy-to-understand and accessible education regardless of technical/related background that showcases how space contributes to life on earth and planetary science. Ways for students to participate, learn, and get involved with NASA will also be highlighted such as L'SPACE MCA, L'SPACE NPWEE, NASA NCAS, challenges, internships, and activities for all ages. The below in-person events and future virtual events will be promoted on the social media platforms to encourage immersive engagement and in-person attendance.

2. **Lego NXT Robotics "Build-Your-Own-Rover" Challenge** for ages 8 - 17 years old at community center to encourage interest in space engineering. Participants will work in teams over the course of three days to build their rover, overcome Martian-inspired "terrain", utilize lego sensors (thermometers, infrared, Colour, Ultrasonic, Gyro, etc) to collect simulated Science data and return to "base". To remove financial barriers, the event will be free to the public with Lego NXT robotic sets provided with one per a team of 5 participants. This outreach component will bring together participants of all backgrounds, inspire a future workforce in engineering, raise awareness of rover navigation and science challenges embraced in mission: P.H.O.E.N.I.X, and provide educational opportunities for all. Participants will be awarded t-shirts, stickers, informational booklets, and posters to celebrate engagement with the challenge.

3. **RIMFAX geological presentation** of 2 hours in duration for students in high school through college and workforce professionals to raise awareness of space-related careers in Planetary Science, Biology, Geology, Geophysics, Engineering and more that may be unknown as an avenue to participants interested in space. A live radar imager demonstration along with a 3-D simulation will showcase how objects of interest are found through ground-penetrating waves, the engineering design of the instrument, physics of

the waves, and the low-environmental subsurface impact versus other intrusive methods (digging, scrapping, drilling, etc). From seeing inside Pyramids to locating ice beneath the surface of the Martian atmosphere, RIMFAX will inspire future curiosity that is out of this world. A 30 minute Q&A session will be held after to answer questions regarding the related career fields, how to get involved, where to learn more, and how to transition from another scientific field that may have overlap.

4. **Space Festival!** A fun, interactive all-day event oriented towards family fun for all ages. NASA scientists, engineers, interns, collaborative speakers and more will engage with the general public for Outreach regarding mission: P.H.O.E.N.I.X., which will include robotics engineering demonstrations of innovative technology used in the rover, Planetary Geology presentation talks on picking landing location and developing scientific objectives, challenges faced in the mission, and using Real scientific data from the mission to educate how it will make meaningful contributions to both life on earth and future manned missions to Mars. Immersive and educational visual VR and short film entertainment will be available to watch and be immersed into the cosmos. Small children will be included in the fun with hands-on activities such as arts and crafts, face painting, and space games. Space-themed food vendors will be available for tasty eats during the day. As the day turns to night, a space-themed drone show will take place as a send-off and thank you to the attending participants and encourage returning for the next Space Festival!

1.13 Conclusion

Since the completion of the System Requirements Review (SRR), the P.H.O.E.N.I.X team has completed identification of instrumentation for each subsystem. Hardware components from the SRR trade studies have had suppliers and products identified. The cost of production and lead procurement times for these instruments and parts have been identified. Additionally, the mission Concept of Operations (ConOps) has been finalized. The mission schedule and costs have also been determined. The mission project management style and staffing needs have been determined according to prior mission needs. The total mission timeline has been developed, and all important milestones have been determined. The team is confident that the budget and timeline allotted are feasible, and achievable in regard to the intended science.

The P.H.O.E.N.I.X mission shall resolve any current TBD/TBRs by the Preliminary Design Review (PDR). The team will continue to evaluate the system risks and continue to refine any uncertain estimations on costs, lead times, or personnel needs. The P.H.O.E.N.I.X mission continues to meet NASA's science and exploration goals for Mars and gather useful science for planetary habitation.

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Declaration of Generative AI

During the preparation of this document, the team used OpenAI's ChatGPT as a search aid to find resources for various hardware. The tool was also used to ensure consistent information throughout the deliverable.

During literature reviews, the team utilized Google's AI in Search to identify cited resources. The team identified key facts and figures and verified their technical correctness.

During the preparation of this document, the team utilized online translation tools including Google Translate to aid in writing and editing, specifically for bilingual or English-secondary-language team members.

After using various tools, the team reviewed and edited all content to ensure consistency, original contribution, and technical accuracy. Team 01 takes full responsibility for the content of this deliverable.

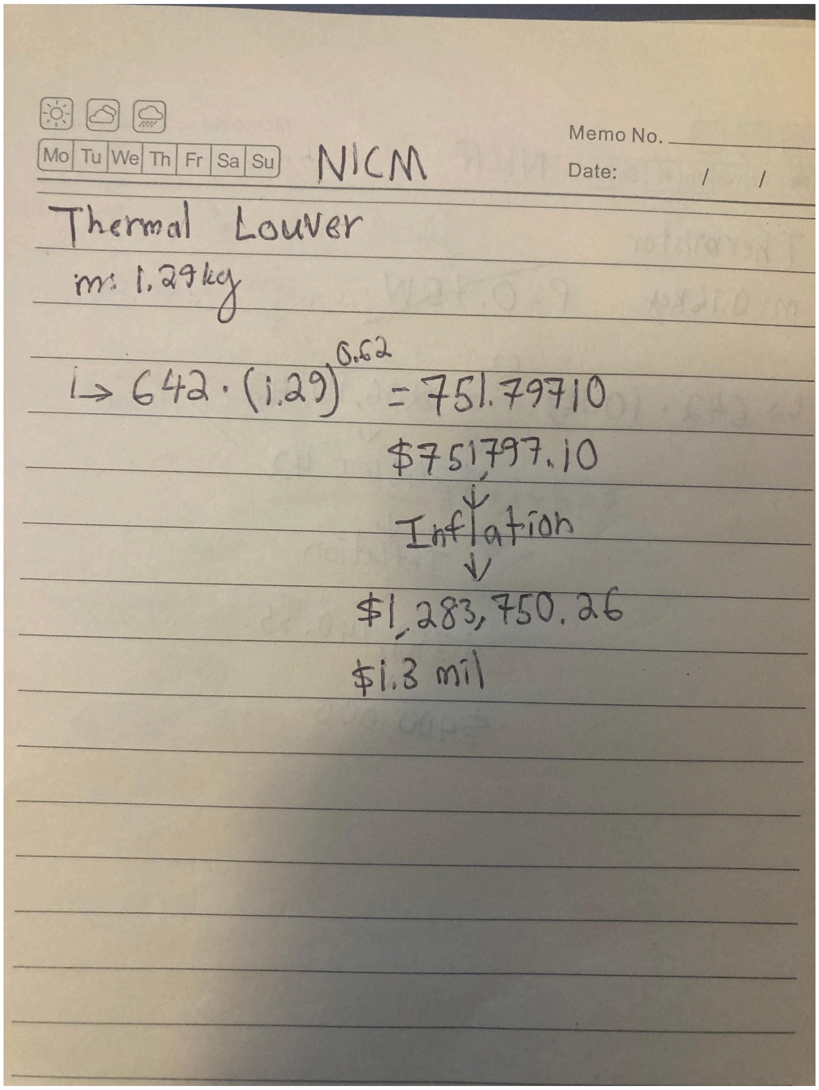
Appendix

TBD / TBR #	Plans and Timeline for Resolution
1	Rover speed of travel
2	Rate of heartbeat transmission from rover
3	Sol that the rover shall begin autonomous travel

Figure A.1: (TBD/TBR Table)

Changes	Description
MCR-RFA-1, Section 1.2	The measurement observables must directly relate to the physical parameters with which the STM was addressed and a CRF was filled due to changes in both our human exploration goal objectives to meet this RFA.
MCR-RFA-2, Section 1.3	A thorough description of each region of interest and how they fulfill the team's science objectives must be provided, and was also addressed by defining the region of interest.
CRF - Science objective 1# of HBS-1LM (waiting on approval)	Science objective 1# of HBS-1LM: The team is requesting a minor alteration to the science objective and add clarification within the STM from “various samples” (exact quantity was originally unspecified) to one single sample. Science objective 1# of HBS-1LM - STM observable: Change data transmission interval from “monthly” to “weekly”.
CRF - Science objective 2# of HBS-1LM (waiting on approval)	The second objective of HBS-1LM’s main purpose still remains the same, but the measurement approach to provide quantitative data had to change.

Figure A.2 (Mission Change Log)


Mo Tu We Th Fr Sa Su NICM Memo No. Date: / /

Thermal Louver

m: 1.29kg

$\hookrightarrow 642 \cdot (1.29)^{0.62} = 751.79710$

\$751,797.10

↓

Inflation

↓

\$1,283,750.26

\$1.3 mil

Figure A.3 (Thermal Louver Cost Calculations)

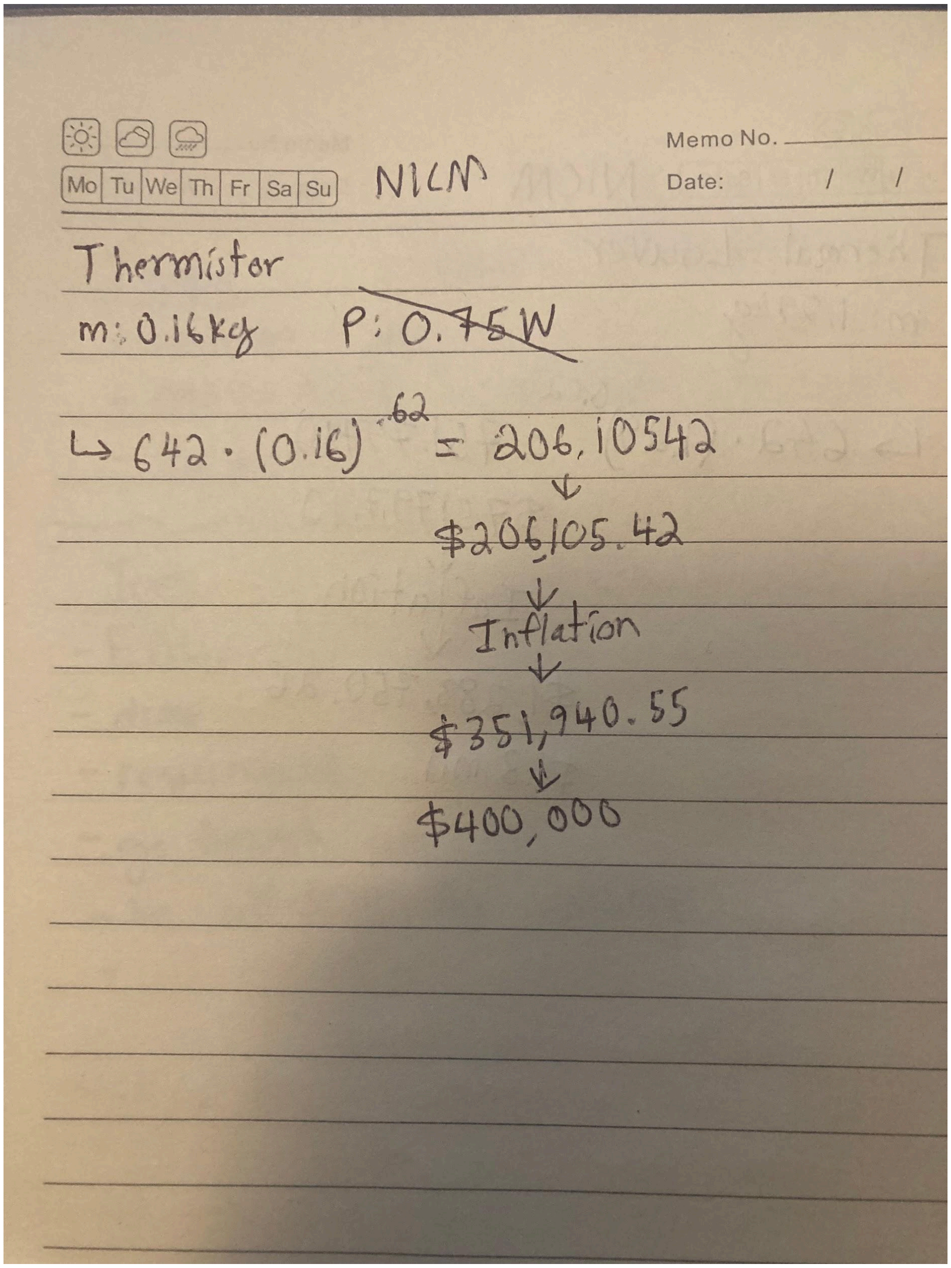


Figure A.4 (Thermistor Cost Calculations)

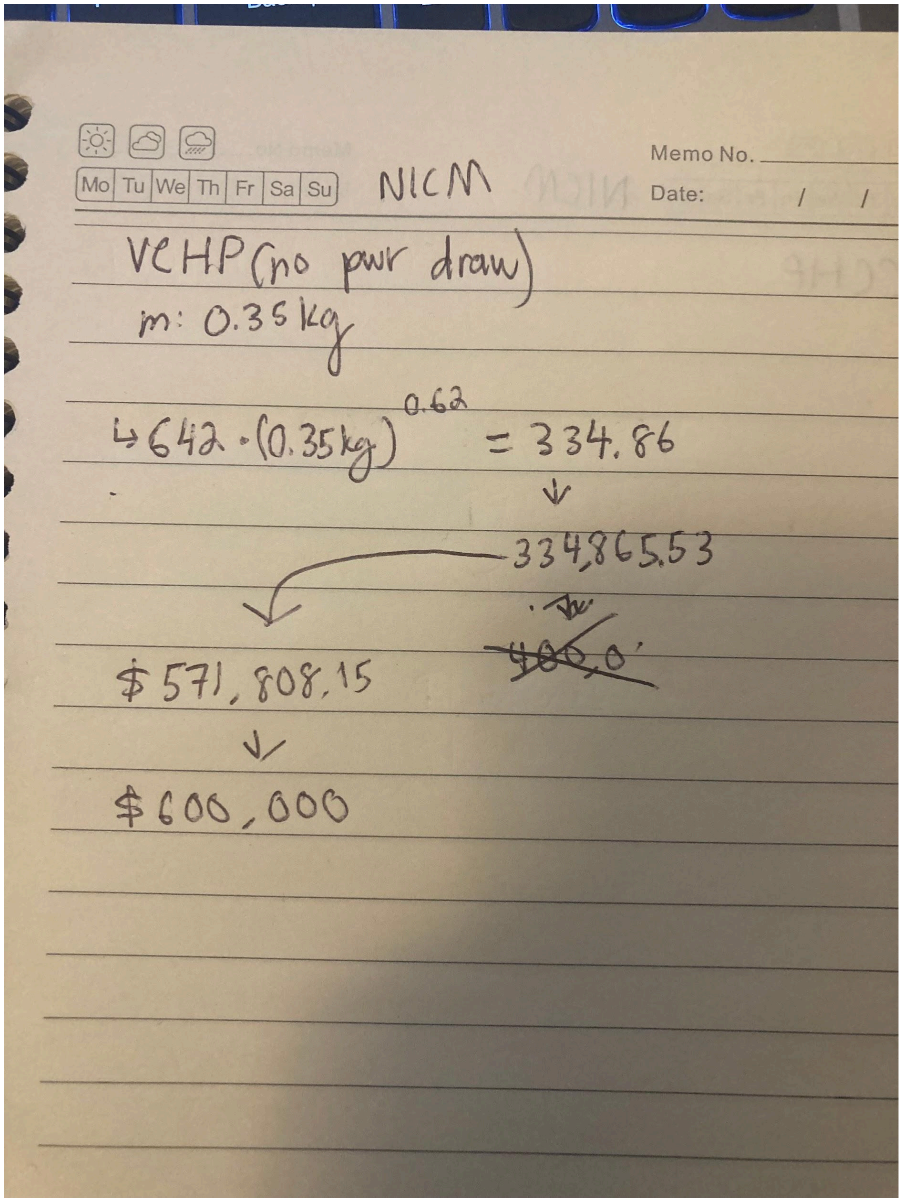


Figure A.5 (VCHP Cost Calculations)

Enter the inflation rate (Default for 2023 is 154.44%)	188.97%	Inflation rate calculator
Enter the number you recieved from the CER formula	21,487.00	The CER provides a cost that is orginally in 2004 dollars and in thousands of dollars. It needs to be multiplied by a percentage to account for inflation, and then 1000 to be turned into millions. This tool does the math for you.
Estimated cost with inflation (Without Wraps)	$40,603,983.90	

$ 100 in 2004 will be worth $18
Using an inflation rate of 2.60 % from 2026 to 2
This is an average inflation rate of 2.59% and cumulati

Mechanical Subsystem

Wrap Costs	Cost Estimate	Info
Management Costs	$1,860,000.00	?
Systems Engineering Costs	$1,420,000.00	?
Product Assurance Costs	$2,340,000.00	?
Integration & Test Costs	$8,370,000.00	?

Final manufacturing cost per unit (manufacturing + wraps)	$54,600,000.00	Rounded up to the nearest $100K

Test Facility Cost	Cost Estimate	Info
TVAC	$8,190,000.00	?
EMI	$4,100,000.00	?
VIBE	$2,050,000.00	?
Ambient	$2,050,000.00	?

This cost is per unit. You will need to test each unit at least once and then one more time with everything assembled together

The cost for the final test is the sum of all the other individually conducted tests and then doubled

Final testing facility cost per unit	$16,400,000.00	Rounded up to the nearest $100K

Total cost breakdown per phase	Phase B (4% of total cost)	Phase C (57% of total cost)	Phase D (39% of total cost)
Manufacturing Costs	$2,184,000.00	$31,122,000.00	$21,294,000.00
Testing Costs	$656,000.00	$9,348,000.00	$6,396,000.00

Rounded up to the nearest $1K
Sums to total manufacturing and testing costs

Schedule Estimate Relation (SER)	Time in months
Planetary, Remote Sensing Instruments (Optical and Microwave)	47.5
Planetary, Remote Sensing Instruments (Fields and Particles)	62.4
Planetary, in situ Instruments	40.6

This information is only available for these hardware types

Figure A.6 (Mechanical Subsystem MCCET)

Schedule Estimate Relation (SER)	Time in months
Planetary, Remote Sensing Instruments (Optical and Microwave)	22.6
Planetary, Remote Sensing Instruments (Fields and Particles)	29.6
Planetary, in situ Instruments	29.3

Figure A.7 (SER for Mini-TLS)

Schedule Estimate Relation (SER)	Time in months
Planetary, Remote Sensing Instruments (Optical and Microwave)	27.8
Planetary, Remote Sensing Instruments (Fields and Particles)	36.5
Planetary, in situ Instruments	32.1

Figure A.8 (SER for Rimfax)

Schedule Estimate Relation (SER)	Time in months
Planetary, Remote Sensing Instruments (Optical and Microwave)	16.1
Planetary, Remote Sensing Instruments (Fields and Particles)	21.1
Planetary, in situ Instruments	25.2

Figure A.9 (SER for Gamma Neutron Probe)

Schedule Estimate Relation (SER)	Time in months
Planetary, Remote Sensing Instruments (Optical and Microwave)	30.9
Planetary, Remote Sensing Instruments (Fields and Particles)	40.5
Planetary, in situ Instruments	33.6

Figure A.10 (SER for Spectrometer)

Enter the inflation rate (Default for 2023 is 154.44%)	188.97%	Inflation rate calculator
Enter the number you recieved from the CER formula	1,719.72	The CER provides a cost that is orginally in 2004 dollars and in thousands of dollars. It needs to be multiplied by a percentage to account for inflation, and then 1000 to be turned into millions. This tool does the math for you.
Estimated cost with inflation (Without Wraps)	$3,249,754.88	

Wrap Costs	Cost Estimate	Info
Management Costs	$170,000.00	?
Systems Engineering Costs	$150,000.00	?
Product Assurance Costs	$150,000.00	?
Integration & Test Costs	$510,000.00	?

Final manufacturing cost per unit (manufacturing + wraps)	$4,300,000.00	Rounded up to the nearest $100K

Test Facility Cost	Cost Estimate	Info
TVAC	$650,000.00	?
EMI	$320,000.00	?
VIBE	$160,000.00	?
Ambient	$160,000.00	?

This cost is per unit. You will need to test each unit at least once and then one more time with everything assembled together

The cost for the final test is the sum of all the other individually conducted tests and then doubled

Final testing facility cost per unit	$1,300,000.00	Rounded up to the nearest $100K

Total cost breakdown per phase	Phase B (4% of total cost)	Phase C (57% of total cost)	Phase D (39% of total cost)
Manufacturing Costs	$172,000.00	$2,451,000.00	$1,677,000.00
Testing Costs	$52,000.00	$741,000.00	$507,000.00

Schedule Estimate Relation (SER)	Time in months
Planetary, Remote Sensing Instruments (Optical and Microwave)	20.1
Planetary, Remote Sensing Instruments (Fields and Particles)	26.4
Planetary, in situ Instruments	27.8

This information is only available for these hardware types

Figure A.11 (Thermal Subsystem MCCET)

Enter the inflation rate (Default for 2023 is 154.44%)	188.97%	Inflation rate calculator
Enter the number you recieved from the CER formula	1,155.88	The CER provides a cost that is orginally in 2004 dollars and in thousands of dollars. It needs to be multiplied by a percentage to account for inflation, and then 1000 to be turned into millions. This tool does the math for you.
Estimated cost with inflation (Without Wraps)	$2,184,266.44	

Wrap Costs	Cost Estimate	Info
Management Costs	$120,000.00	?
Systems Engineering Costs	$110,000.00	?
Product Assurance Costs	$90,000.00	?
Integration & Test Costs	$330,000.00	?

Final manufacturing cost per unit (manufacturing + wraps)	$2,900,000.00	Rounded up to the nearest $100K

Test Facility Cost	Cost Estimate	Info	
TVAC	$440,000.00	?	This cost is per unit. You will need to test each unit at least once and then one more time with everything assembled together
EMI	$220,000.00	?	
VIBE	$110,000.00	?	The cost for the final test is the sum of all the other individually conducted tests and then doubled
Ambient	$110,000.00	?	

Final testing facility cost per unit	$900,000.00	Rounded up to the nearest $100K

Total cost breakdown per phase	Phase B (4% of total cost)	Phase C (57% of total cost)	Phase D (39% of total cost)
Manufacturing Costs	$116,000.00	$1,653,000.00	$1,131,000.00
Testing Costs	$36,000.00	$513,000.00	$351,000.00

Schedule Estimate Relation (SER)	Time in months	
Planetary, Remote Sensing Instruments (Optical and Microwave)	17.6	This information is only available for these hardware types
Planetary, Remote Sensing Instruments (Fields and Particles)	23.1	
Planetary, in situ Instruments	26.2	

Figure A.12 (Software MCCET)

Enter the inflation rate (Default for 2023 is 154.44%)	188.97%	Inflation rate calculator
Enter the number you recieved from the CER formula	8,331.00	The CER provides a cost that is orginally in 2004 dollars and in thousands of dollars. It needs to be multiplied by a percentage to account for inflation, and then 1000 to be turned into millions. This tool does the math for you.
Estimated cost with inflation (Without Wraps)	$15,743,090.70	

Wrap Costs	Cost Estimate	Info
Management Costs	$760,000.00	?
Systems Engineering Costs	$610,000.00	?
Product Assurance Costs	$830,000.00	?
Integration & Test Costs	$2,920,000.00	?

Final manufacturing cost per unit (manufacturing + wraps)	$20,900,000.00	Rounded up to the nearest $100K

Test Facility Cost	Cost Estimate	Info
TVAC	$3,140,000.00	?
EMI	$1,570,000.00	?
VIBE	$780,000.00	?
Ambient	$780,000.00	?

This cost is per unit. You will need to test each unit at least once and then one more time with everything assembled together

The cost for the final test is the sum of all the other individually conducted tests and then doubled

Final testing facility cost per unit	$6,300,000.00	Rounded up to the nearest $100K

Total cost breakdown per phase	Phase B (4% of total cost)	Phase C (57% of total cost)	Phase D (39% of total cost)
Manufacturing Costs	$836,000.00	$11,913,000.00	$8,151,000.00
Testing Costs	$252,000.00	$3,591,000.00	$2,457,000.00

Schedule Estimate Relation (SER)	Time in months
Planetary, Remote Sensing Instruments (Optical and Microwave)	34.4
Planetary, Remote Sensing Instruments (Fields and Particles)	45.2
Planetary, in situ Instruments	35.2

This information is only available for these hardware types

Figure A.13 (Electronics MCCET)