NASA L'SPACE Team #13
2024 Mission Concept Review

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Table of Contents

Table of Figures

Table of Acronyms

CDH: Command and Data Handling

CPU: Central Processing Unit

CNT: Carbon Nanotube

DSN: Deep Space Network

EDL: Entry, Descent, and Landing

EZ: Exploration Zone

FIDR: Fault Detection, Isolation, and Recovery

GHz: Gigahertz

GNc: Guidance Navigation Control

HDA: Hazard Detection and Avoidance

IMU: Inertial Measurement Unit

ME: Mechanical

MHz: Megahertz

MRO: Mars Reconnaissance Orbiter

MR: Mission Requirements

PG: Power Generation

PMAD: Power Management and Distribution

RTOS: Real-Time Operating System

SRR: System Requirements Review

STM: Science Traceability Matrix

SYS: System

TBR: To Be Resolved

TCH: Thermal Control System

TRN: Terrain Relative Navigation

UHF: Ultra-High Frequency

VCE: Vision Computer Element

XRD: X-Ray Diffraction

1. System Requirements Review

1.1. Mission Statement

This mission designed by Team 13 involves the launch and operation of a small, low-cost, rover that will navigate the surface of Mars. The rover will be autonomous and will focus on conducting an examination of the Martian surface by analyzing minerals and rocks to discover the geological history of the planet and the historic presence of liquid water. Additionally, the rover will search for subsurface ice deposits which will set the stage for subsequent manned missions.

By landing within 10km of a selected volcano, the rover will be able to conduct tests with its two instruments, the mini-TES and RIMFAX, to determine the relationship between historic volcanic activity on Mars and the historical presence of liquid water that may have been formed through the outgassing of water vapor from volcanoes. Scientific instruments will analyze rocks, minerals, and volcanic deposits such as lava flows to determine the impact historical volcanic eruptions have had on the Martian atmosphere, climate, and hydrology. This can be done by identifying and testing hydrated minerals found on the Martian surface. Furthermore, the rover will continuously scan locations with a moderate to high likelihood of subsurface ice and analyze its formation and quantity, allowing for potential future extraction. The findings collected by the rover will provide key insights into the Martian geology and the historic formation of liquid water on its surface, as well as supporting future human missions by searching for suitable ice deposits.

1.2. Mission Requirements

The customer constraints outlined in Figure 1 aim to ensure the success, safety, and efficiency of the Mars exploration mission while adhering to specific guidelines and limitations. These constraints span various aspects of the mission, including payload, system, mechanical, power systems, thermal control, computer hardware, and guidance, navigation, and control (GNC). Payload Requirements focus on the compactness, weight, and cost of the payload to meet the specifications provided by the mission document and launch provider. Additionally, constraints specify the limitation of radioactive materials and instruments to ensure compliance with regulatory standards and environmental safety.

Customer constraints for the System involve mission readiness, transportation, communication capabilities, and mobility for exploration purposes. The system must be prepared for launch within specified time frames, utilize dedicated vehicles for surface transportation, relay communications effectively, and possess mobility to explore diverse terrains on Mars. Mechanical Requirements primarily address the structural integrity, load-bearing capacity, and functionality of mechanical components such as chassis, drills, and suspension systems. The mechanical system must support and enclose all instrumentation, withstand loads, and maintain stability during operation and transportation.

Constraints related to Power Systems encompass power generation, storage, fault tolerance, distribution, and management to ensure the reliability, efficiency, and resilience of the spacecraft's power systems. Solar panels, batteries, redundancy mechanisms, and distribution systems are essential components to sustain operations throughout the mission duration. Thermal Control System Requirements focus on regulating temperatures within acceptable ranges to protect onboard systems and instruments from extreme conditions on Mars. Passive and active components, cooling/heating capabilities, and temperature regulation mechanisms are integral to maintaining optimal performance.

Customer constraints for Computer Hardware encompass processor specifications, real-time operating systems, communication interfaces, and redundancy measures. Radiation-hardened processors, backup systems, and communication protocols ensure reliability, data processing efficiency, and system resilience. GNC Requirements address the rover's ability to travel, calculate distance, determine heading and tilt, map terrain, and implement hazard avoidance and path planning algorithms. These constraints are crucial for ensuring safe and effective navigation, obstacle avoidance, and terrain analysis during exploration missions on Mars. Overall, these customer constraints play a pivotal role in shaping the design, development, and operational aspects of the Mars exploration mission, emphasizing safety, reliability, and adherence to mission objectives and environmental considerations.

Figure 1. Mission Requirements Table

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met ?
MISSION REQUIREMENTS							
MR-1	The system shall have a compact configuration not exceeding a volume of 100cm x 100cm x100 cm.	Provided by Mission Document.	Launch Provider	TBD	Inspection	All	TBD
MR-2	The system shall not exceed a total mass of 45 kg.	Provided by Mission Document.	Launch Provider	TBD	Inspection	All	TBD

MR-3	The system cost shall not exceed $300M	Provided by Mission Document.	Customer	SYS-1,2,3 MEC1,1.1,1.2,1.3,2,2.1,2.2,2.3,3 PG, TCS1,2,3,3.1	Analysis		TBD
MR-4	The mission shall be ready to launch by December 31th, 2028 and arrives by August 28th, 2029	Provided by Mission Document.	Customer	All Below	Demonstration	All	TBD
MR-5	The system shall not contain more than two science instruments to achieve the science objectives.	Provided by Mission Document.	Mission Constraints		Inspection	Retractable drill (not sure what the second instrument is)	TBD
MR-6	Shall not have a Radioisotope Thermoelectric Generator.	Provided by Mission Document.	Regulatory	MR-7	Inspection	None	TBD
MR-7	The use of radioactive materials shall be kept under a cumulative mass of 5g.	Provided by Mission Document.	Regulatory	SYS-1,2? PG TCS-1,2,3,3.1	Inspection	Thermal Requirements	TBD
MR-8	The mission concept shall be transported to the surface of Mars by a separate descent vehicle.	Provided by Mission Document.	Launch Provider	MEC-1	Demonstration	All	TBD
MR-9	Allows the system to relay communications via the MRO to be received by Earth via the DSN.	Provided by Mission Document.	Communication Constraints	MR-9.1	Analysis(cannot properly test/demonstrate)	Communication	TBD
MR-9.1	The system's data shall be transmitted to the MRO every 112 minutes for a window of 6 minutes.	Provided by Mission Document.	Communication Constraints		Analysis(cannot properly test/demonstrate)	Communication	TBD
MR10	System shall have the mobility to explore areas of interest on Mars	Provided by Mission Document.	Customer	MEC-2,2.1,2.2,2.3	Test	Movement	TBD

1.3. System Definition

1.3.1. Spacecraft Overview

The spacecraft designed for the Mars rover undertaking, integrates advanced technology across its subsystems to ensure strong functionality and undertaking success. This review delineates the top-level necessities and functionalities of each vital subsystem: Mechanical, Power, Command and Data Handling (CDH), Thermal, Guidance, Navigation, and Control (GNC), and Science Instrumentation.

Power Subsystem: Central to the mission, the Power Subsystem is pivotal for presenting electrical strength vital for mobility, conversation, scientific research, and facts transmission. It encompasses three primary subassemblies: energy era, electricity garage, and strength distribution and management. Power generation is based on solar panels, particularly designed with SpectroLab XTE-SF Ga-primarily based triple junction cells for high performance. Power storage is managed through lithium-ion batteries, chosen for their excessive energy density and cycle life. The electricity control and distribution subassembly, using gadgets like the Pumpkin Space Systems EPSM 1 PMAD, ensures efficient energy goes with the flow all through the rover.

Mechanical Subsystem: This subsystem ensures the structural integrity of the rover, shielding it from Mars' harsh environmental conditions, together with intense temperatures, dirt, and choppy terrain. It includes issues for chassis assist, wheels, and suspension, focusing on redundancy and recuperation techniques to mitigate ability failures because of environmental demanding situations.

Command and Data Handling (CDH) Subsystem: It serves as the mind of the rover, managing all facts processing, storage, and command execution responsibilities. It employs sturdy computing sources, consisting of RAD750 CPUs, and a fault-tolerant software program architecture to ensure reliable operations under Mars' conditions. Redundancy and self-sufficient healing skills are integrated to address any capability device failures or information processing anomalies.

Thermal Subsystem: This subsystem is accountable for retaining operational temperatures for all onboard components, employing each passive and active thermal manage strategies. Utilizing materials like aerogel and systems including heaters, radiators, and heat sinks, it ensures the rover can withstand the bloodless Martian nights and the warmth of Martian days, with self sufficient recuperation actions in area for any system failures.

Guidance, Navigation, and Control (GNC) Subsystem: Essential for the rover's mobility and operational accuracy, the GNC subsystem consists of inertial sensors, sun sensors, and engineering cameras for navigation and environmental interaction. Redundancy is constructed into each component to ensure continuous operation, with self sufficient recuperation plans geared up to cope with any possible disasters.

Science Instrumentation: This subsystem is geared up with a collection of clinical instruments designed for Mars exploration, including contraptions for geological and atmospheric analysis. It is vital for reaching the mission's medical targets, with integrated redundancy and health tracking to ensure information integrity and device capability throughout the undertaking.

In conclusion, the spacecraft's design integrates a comprehensive method to redundancy and recovery throughout all subsystems, making sure resilience towards the Martian environment and operational anomalies. This layout philosophy enhances the mission's basic reliability, helping its bold desires for Mars exploration.

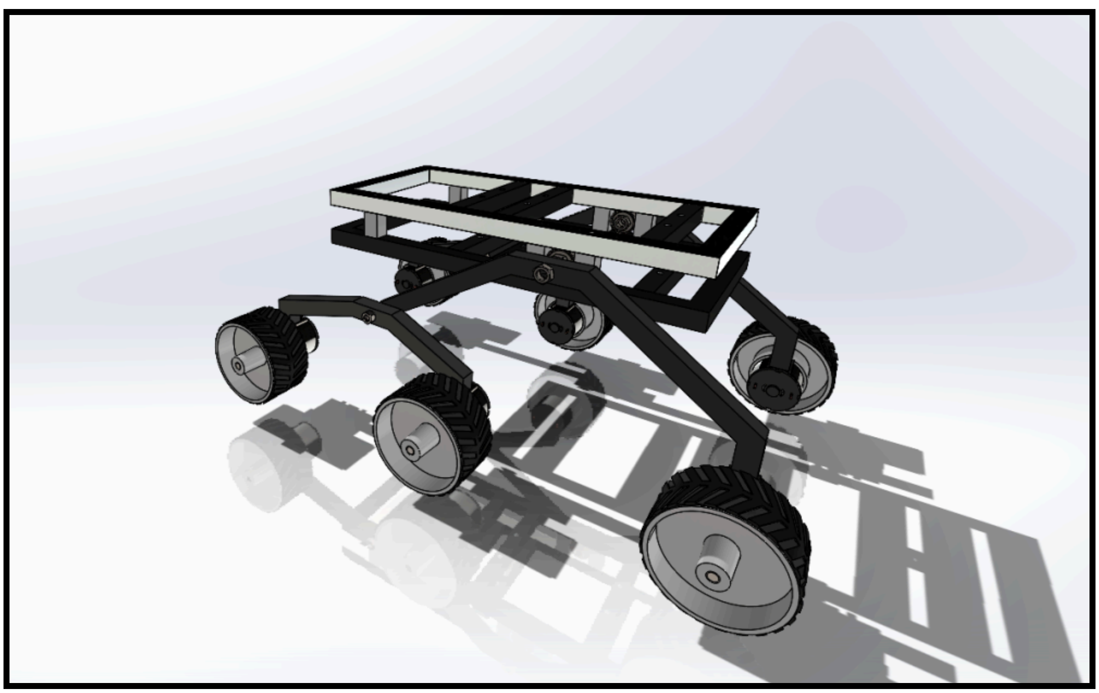


Figure 2. Rover Isometric View

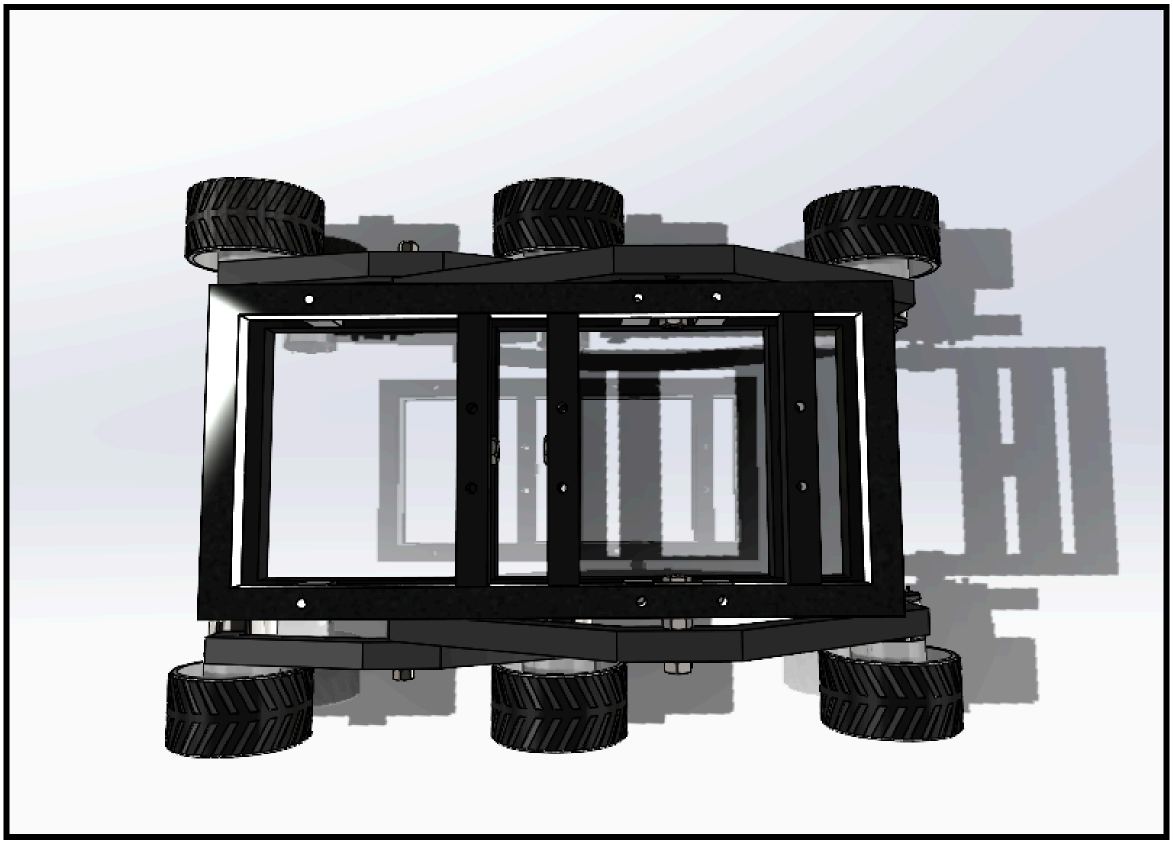


Figure 3. Rover Aerial View

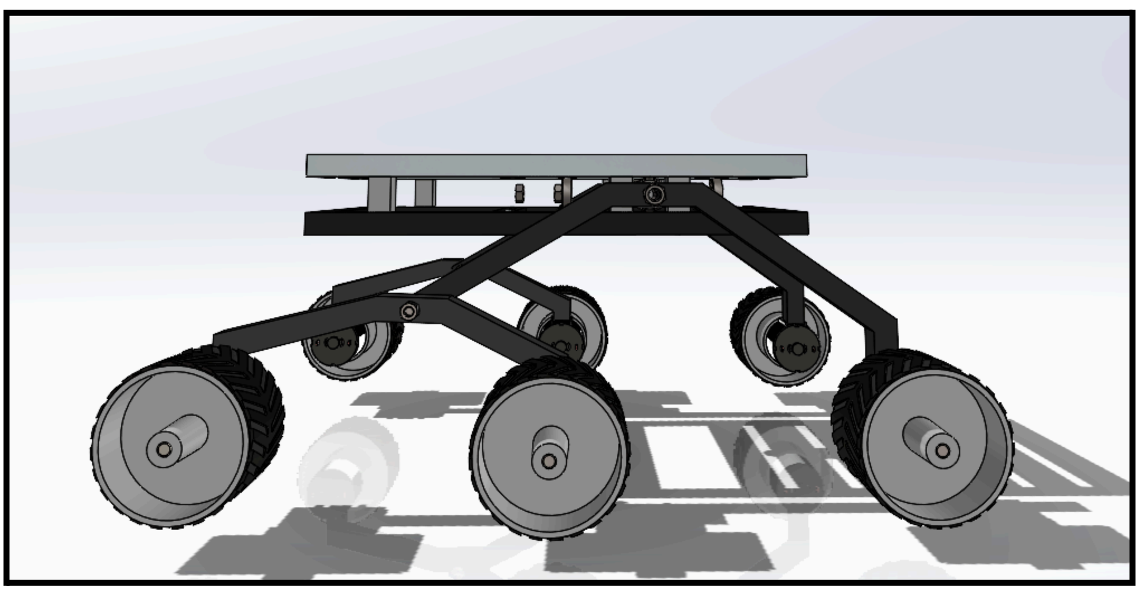


Figure 4. Rover Side View

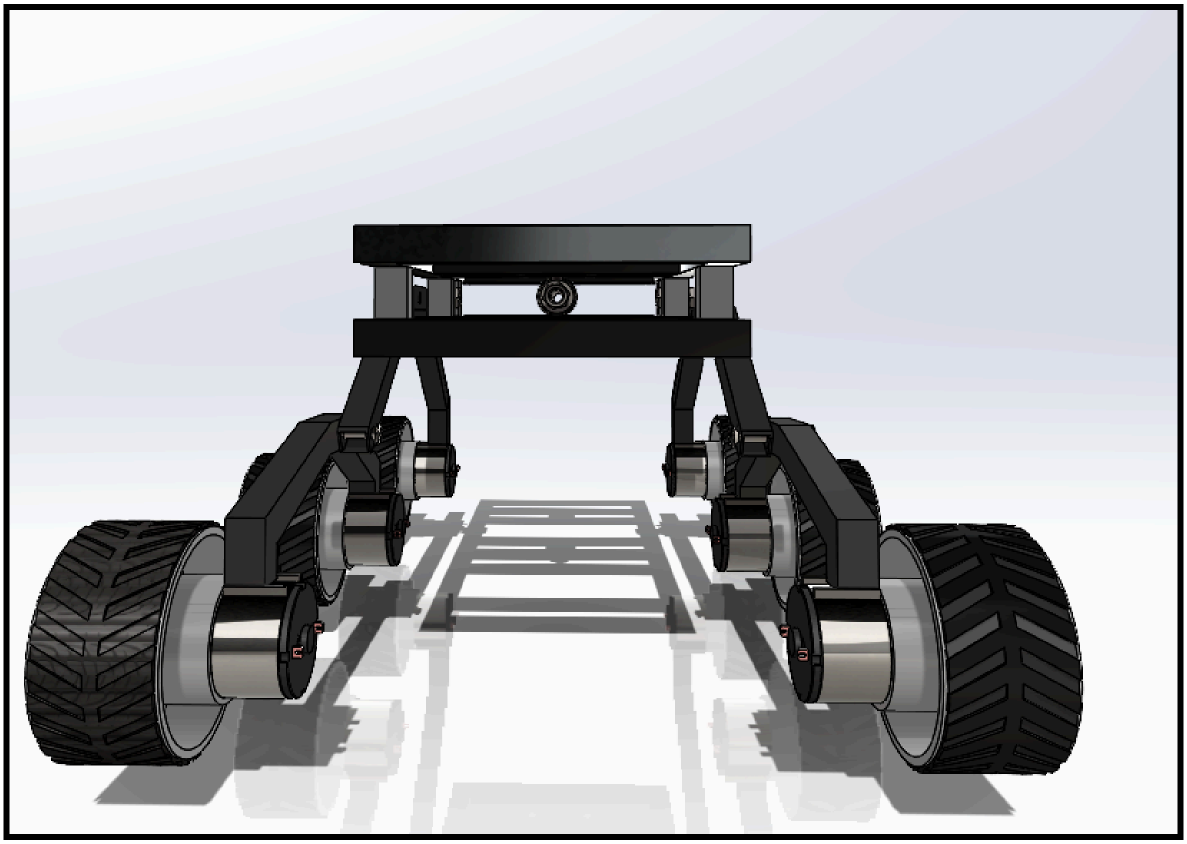


Figure 5. Rover Front View

1.3.2. Mechanical Subsystem

1.3.2.1. Mechanical Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
MEC-1	The mechanical system shall have a protective support chassis capable of surviving on the martian surface for the duration of the mission.	The chassis will serve to protect any internal spacecraft components from the hostile martian environment and landscape to ensure mission success	MR-1 MR-4	MEC-1.1 MEC-1.2 MEC-1.3 MEC-1.4	Demonstration	Mechanical	TBD
MEC-1.1	The chassis shall be made of material	This is critical for onboard component	MEC-1	MEC-1.1.1 MEC-1.1.2	Demonstration	Mechanical	TBD

	capable of withstanding the hostile martian environment	protection and stability of the spacecraft.		MEC-1.1.3 MEC-1.1.4			
MEC-1.1.1	The chassis shall be made of radiation-resistant material limited by at least 22 milirads.	The thin martian atmosphere provides large solar radiation amounts that are detrimental for electronics/material corrosion. Previous rover missions have experienced around this level over the course of a similar mission duration (Odyssey).	MEC-1	None	Testing	Mechanical	TBD
MEC-1.1.2	The chassis shall have thermal insulation protection to maintain integrity between 30*C to -160 *C.	Heat transfer loads may thermally expand/compress materials, possibly inducing cracking and brittle fracture. This is the temperature range on Mars for our location.	MEC-1	None	Testing	Mechanical	TBD
MEC-1.1.3	The selected chassis material will have a sufficient Mohs Hardness	This is a conventional property that classifies a material as abrasively resistant which is required for prevention of regolith abrasion.	MEC-1	None	Testing	Mechanical	TBD
MEC-1.1.4	The selected chassis material will have a sufficient ultimate fracture strength for the mission.	Fracture of the body will be considered failure as opposed to yielding since the chassis is meant to take the brunt forces of the martian environment while maintaining functionality.	MEC-1	None	Testing	Mechanical	TBD
MEC-1.2	The chassis shall provide adequate spacing for all onboard technology without interference.	This will ensure no component will unnecessarily affect any other onboard components in functionality while maintaining protection.	MEC-1	MEC-1.2.1 MEC-1.2.2	Inspection	Mechanical	TBD

MEC-1.2.1	The chassis shall support designated space for electronics/spacecraft subsystem components.	Capable of protecting these components while keeping intrusions between each subsystem at a minimum	MEC-1	None	Inspection	Mechanical	TBD
MEC-1.2.2	The chassis shall support designated internal space for the mobility system.	The mobility system must be protected by the chassis to ensure wear/degradation does not affect movement of the spacecraft over time.	MEC-1	None	Inspection	Mechanical	TBD
MEC-1.3	The chassis shall have a mass between 60%-70% of the allocated mass system constraint.	The chassis will make up the bulk of the spacecraft mass and weight, and so requires the most mass designation for the mechanical subsystem.	MR-2 MEC-1	MEC-2	Inspection	Mechanical	TBD
MEC-1.4	The chassis shall not cost more than 60% for the allocated budget subsystem cost.	Material selection and body size will drive the cost of the chassis which will take the bulk of the subsystem budget.	MR-3 MEC-1	None	Inspection	Mechanical	TBD
MEC-2	The mechanical system shall have a mobility system capable of traversing the martian surface for the duration of the mission.	This will ensure a steady and efficient transportation of the spacecraft to testing sites.	MR-10 MEC-2	MEC-2.1	Demonstration	Mechanical	TBD
MEC-2.1	The wheels of the spacecraft shall be physically resistant across the martian terrain.	Primarily for abrasive/frictional hazards which may be experienced at the designated exploration zone.	MEC-1.3 MEC-2	MEC-2.1.1 MEC-2.1.2	Demonstration	Mechanical	TBD
MEC-2.1.1	The wheels shall be capable of supporting the weight of the spacecraft times a safety factor.	The weight of the spacecraft according to the max designated mass, material, and additional safety factor determine this value to ensure minimal chances of tire failure.	MEC-1.3 MEC-2.1	None	Testing	Mechanical	TBD
MEC-2.1.2	The wheels shall	The Martian terrain is	MEC-1.3	None	Testing	Mechanical	TBD

	possess adequate grip to traverse the rocky martian surface for added tipping prevention	rocky and rarely flat at our chosen location. If the spacecraft is extremely tilted, it could risk tipping over.	MEC-2.1				
MEC-2.2	There will be a suspension system capable of maintaining body alignment against uneven terrain up to 30 degrees of tilt.	In the case where one wheel is not on an even surface to another, the main body will maintain a horizontally stable (relative to ground) position to prevent tipping. Inspiration taken from Perseverance rover.	MEC-2	MEC-2.2.1 MEC-2.4 MEC-2.5	Testing	Mechanical	TBD
MEC-2.2.1	The suspension system must have an adequate compressive yield stress.	The suspension system supports the weight of the chassis and will encounter uneven stress points while in operation.	MEC-2.2	None	Testing	Mechanical	TBD
MEC-2.3	The mobility system will be autonomously powered through solar battery storage.	This simplifies how the power distribution is given to all the subsystems by drawing energy from the same power system.	MEC-2 PS-2 PS-3	None	Testing	Mechanical/ Power	TBD
MEC-2.4	The mobility system will stay within 30%-40% of the allocated mass system constraint.	This mass constraint ensures there are enough mass resources for any other mechanical system categories.	MEC-2.2	None	Inspection	Mechanical	TBD
MEC-2.5	The mobility system will stay below 40% of the allocated budget system cost.	This budget constraint ensures there are enough budget resources for any other mechanical system categories.	MEC-2.2	None	Inspection	Mechanical	TBD

Figure 2. Mechanical Subsystem Table

1.3.2.2. Mechanical Subsystem Overview

The purpose of the mechanical subsystem is to ensure that the instrumentation onboard the spacecraft can perform their intended operation without significant interference from the martian environment. This includes solar radiation which may damage or alter electronic communication or cause material degradation, dust abrasion which may produce stress concentrations throughout the spacecraft's exterior support, and uneven surface terrain which may tip over the spacecraft or induce unwanted bending stresses throughout the individual support systems. Targeting these hazards is essential for the success of the mission, and so the mechanical subsystems were engineered with this in mind.

Chassis Support: The chassis serves as the protective shield which takes the brunt force of the martian environment in order to protect all onboard instrumentation. As such, the material chosen for the mission must be adequately strong for expected, as well as unexpected forces. Additionally, the thermal extremes experienced on the martian surface and at the exploration zones require a material with a low thermal expansion and high thermal effusivity. These two material properties will limit the induced thermal stresses and provide an additional insulative support layer around components which already possess reliable heat transfer properties. Depending on the chassis design geometry and material density, weight should also be considered. A chassis with a high weight will induce stresses to any support structures and make mobility difficult. Conversely, a chassis with a low weight may not be stable enough to perform well on the uneven rocky terrain.

A trade study was performed to decide on the material of the chassis which consisted of two commonly used composites and alloys used in the aerospace industry, and one newer material under current research: Alpha Titanium Alloy, Carbon Fiber, and Carbon Nanotube Composites. According to the trade study performed, the Alpha Titanium Alloy became the clear choice based on its ability to shield solar radiation due to its tightly compacted molecular structure, high stress to fracture characteristic, and low thermal expansion when compared to its counterparts. Carbon Fiber, while possessing lower cost characteristics and weight distribution, may be unreliable since if its chain-like structure is compromised, it could easily risk propagating throughout the rest of the body of the chassis. Carbon Nanotube (CNT) composites suffer from similar disadvantages, and are also a relatively new area of research still being developed which require more progress for additional reliability.

The chassis will enclose most of the volume associated with the mission system constraint. Approximately 60% of the allocated volume will be enclosed by the chassis. This will ensure that all the electronics and testing equipment possess sufficient space to operate effectively. The remaining space not enclosed by the chassis will be used for the mobility systems, particularly the wheels and parts of the suspension system, as well as solar panel extension and movement. This number is subject to change as the design is continuously updated, but is not expected to vary significantly. To keep the chassis heavy enough for stability, yet lightweight enough for the structures supporting it, and thick enough for thermal/radioactive protection, a conservative thickness of 0.2 cm was chosen as an estimate until a more updated and supported value is obtained. This system will have a TRL 4 since a Titanium chassis has not been utilized in the Martian environment, and so still requires a more well-established operation and testing method. However, Titanium frames have been tested and used extensively for other industrial applications, like bike frames and automotive designs with attention to the critical stress points imposed when in use, similar to the purpose of this particular mechanical subsystem.

Wheels: Similar to the motivations behind choosing the chassis support material, the selection of the wheel material takes into account cost, hardness parameters, and thermal expansion properties. Additionally, since the wheels will be supporting the chassis, suspension system, and all electronics, it must have a sufficient compressive yield strength to maintain elastic deformation over the duration of the mission. There must also be a consideration into fatigue strength characteristics since rolling contact fatigue will develop as the spacecraft maneuvers around the martian terrain. Abrasion is especially significant since the wheels will be in constant frictional contact against the martian surface.

There were three primary materials chosen based on previous NASA missions to Mars, as well as commonly used materials in the aerospace industry based on the criteria discussed above. These materials are Titanium, Aluminum, and Rubber. Aluminum was used as comparison in the trade study due to its previous utilization in the wheels of the Perseverance Rover, which has been active for the past three years. Rubber was also selected for comparison due to its mechanical damping advantage and cheap cost. Once again, Titanium was ultimately chosen for the wheel material due to its high compressive strength, its ability to withstand the harsh ionizing radiation imposed over the martian surface, and its high Brinell hardness against abrasion hazards. Despite its use in other NASA missions in the past, Aluminum was not chosen due to its lack of a fatigue limit and a steadily decreasing fatigue life as stress increases. Rubber was not chosen due to outgassing that could possibly occur from the little pressure that the martian environment possesses. Solar radiation also affects rubber elastomers more than the other selected materials and may harden or soften it depending on exposure which possibly induces unwanted stresses overtime.

To ensure that the wheels will function as intended, it is assumed that the max mass constraint provided by the customer (45 kg, or approximately 167 N) must be supported on Mars. To be conservative, an additional safety factor of 2 is standard for applications regarding stress analysis, so all wheels must support 334 N of force over the mission duration, which means each wheel will need to support at a minimum 55.67 N if six wheels are used. After performing stress calculations, six Titanium wheels may be used which have a diameter of 0.2 meters each. Inspiration from the Perseverance rover motivated us to add additional grooves on the outer surface of the wheel for enhanced grip. Six wheel spokes will be added for further support. Each wheel will have their own individual motor which will help to increase the power provided to the wheels as they traverse over rocky and uneven terrain. It also allows the wheels to rotate at different speeds if needing to make turns, eliminating any necessary need for a differential. This system is a TRL 6 because no research documents could be found showing that Titanium wheels were utilized on previous Mars rover missions. However, Titanium wheels have been tested to perform well in our terrestrial environment, proving to be a better lightweight and strengthened alternative to something like Aluminum.

Suspension: The suspension system will provide support to the body of the spacecraft in maintaining alignment as it traverses the uneven martian landscape. A trade study was performed with three materials for comparison: Alpha Titanium Alloy, Beryllium Copper, and a Carbon Fiber Reinforced plastic. Similar to reasons discussed above, titanium was chosen for comparison due to its ability to withstand stresses that may be imposed over time on the suspension system, particularly flexural stresses which may dominate over uneven terrain. The Carbon Fiber Reinforced Plastic was chosen based on its yield strength similar to that of Titanium as well as its ability to protect itself from solar radiation. Beryllium Copper was ultimately chosen as the suspension material since it possesses an incredible resistance to UV and solar radiation due to its packed molecular structure, is less dense than many other high strength materials, and is reliable among professional automotive industry development. However, it does possess a lower Brinell Hardness and yield strength when compared to Titanium, and so is more susceptible to surface abrasion to sections not entirely protected by the chassis design. These sections may be coated with a secondary protective layer of high hardness, such as Titanium Nitride.

The suspension system itself will consist of solid Beryllium Copper rods joined as a mechanism to a pin joint connecting two same side wheels. As one wheel moves over a platform not on the same even surface as the other, the rod connecting the uneven tire to the pin will allow itself to rotate which will limit the unbalanced movement that the spacecraft body would experience otherwise. This design is similar in comparison to the suspension system utilized on the NASA Mars rover, Sojourner, and is, in fact, a design common in many space rovers (also called the rocker-bogie suspension system). The suspension system has a TRL 7 due to its consistency in being used successfully by other rover missions mentioned previously. However, due to the material selection, a more well-established method of testing how the material behaved must still be achieved.

	Chassis	Wheels	Suspension
Mass (kg)	10	5	10
Volume (m^3)	0.0022	0.0011	0.0012
Max Power Draw (W)	Not required	200	Not required

Figure 3. Mechanical Break Down Table

1.3.2.3. Mechanical Subsystem Trade Studies

Chassis Material						
Criteria	**Explanation**	**Grade**	**Weight**	**Alpha Titanium Alloy**	**Carbon Nanotube (CNT) Composite**	**Carbon Fiber**
Cost	The chassis material chosen must remain below a budget threshold designated through the mission process.	10 = high, 5 = medium 1 = low 0 = Fail	10%	4	8	6
Fracture Strength	The spacecraft may be exposed to sudden movements that could possibly induce lasting stresses throughout the mission's duration.	10 = high, 5 = medium 1 = low 0 = Fail	18%	8	9	7
Hardness	The spacecraft may experience abrasive forces caused by martian regolith that may jeopardize the surface structure of the chassis.	10 = high, 5 = medium 1 = low 0 = Fail	15%	9	5	3
Radiation Shielding	The thin atmosphere will have the spacecraft under ionizing radiation that may affect onboard electronics if not adequately shielded.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	7	6
Thermal Expansion	As the chassis material goes into martian temperature extremes, it may expand or contract to the point of fracture or induced crack propagation.	10 = high, 5 = medium 1 = low 0 = Fail	15%	9	4	3
Thermal Effusivity	Materials possess an innate property that limits the amount of heat transfer which may occur	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	8	8

	through the median. This is ideal for insulation of the inner components.					
Density	The density of the material will dictate its weight for a given volume. The larger the weight, the more stress is imposed on the overall structure and on mobility.	10 = high, 5 = medium 1 = low 0 = Fail	17%	4	7	8
		TOTALS:		**71.2%**	68.1%	58.2%

Figure 4. Chassis Material Trade Study

Wheel Material						
Criteria	**Explanation**	**Grade**	**Weight**	**Titanium**	**Aluminum**	**Rubber Elastomer**
Cost	The wheel material chosen must remain below a budget threshold designated through the mission process.	10 = high, 5 = medium 1 = low 0 = Fail	5%	3	9	6
Hardness	A material's resistance against abrasive frictional hazards along the martian surface. This may scratch/ruin the wheel surface.	10 = high, 5 = medium 1 = low 0 = Fail	15%	7	5	7
Compressive Yield Stress	The wheels must support the weight of the entire spacecraft, including mobility and chassis system, as well as components.	10 = high, 5 = medium 1 = low 0 = Fail	15%	9	8	3
Radiation Shielding	The wheels are directly exposed to the martian atmosphere and ionizing radiation, possibly degrading the material over time.	10 = high, 5 = medium 1 = low 0 = Fail	15%	6	5	2

Thermal Expansion	May induce cracking on the wheel surface as temperatures reach extremes and materials expand/contract.	10 = high, 5 = medium 1 = low 0 = Fail	15%	7	8	3
Fatigue Strength	The wheels will constantly be under rolling contact fatigue which may weaken them over time.	10 = high, 5 = medium 1 = low 0 = Fail	20%	9	4	7
Coefficient of Friction	This will assist with grip on the surface to maintain spacecraft balance. (compare with martian regolith)	10 = high, 5 = medium 1 = low 0 = Fail	15%	3	3	7
		TOTALS:		**67.5%**	56%	50%

Figure 5. Wheel Trade Study

Suspension Material						
Criteria	**Explanation**	**Grade**	**Weight**	**Alpha Titanium Alloy**	**Beryllium Copper**	**Carbon Fiber Reinforced Plastic**
Cost	The suspension material chosen must remain below a budget threshold designated through the mission process.	10 = high, 5 = medium 1 = low 0 = Fail	20%	3	7	2
Yield Strength	The spacecraft may be exposed to sudden movements that could possibly induce lasting stresses in suspension throughout the mission's duration.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	5	8
Hardness	The spacecraft may experience abrasive forces caused by martian regolith that may jeopardize the	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	4	6

	surface structure of the suspension system.					
Radiation Shielding	The thin atmosphere will have the suspension under ionizing radiation that may degrade the suspension material over time.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	5	9
Thermal Expansion	As the chassis material goes into martian temperature extremes, it may expand or contract to the point of fracture or induced crack propagation.	10 = high, 5 = medium 1 = low 0 = Fail	15%	6	9	7
Density	The density of the material will dictate its weight for a given volume. The larger the weight, the more stress is imposed on the overall structure and on suspension mobility.	10 = high, 5 = medium 1 = low 0 = Fail	20%	3	8	6
		TOTALS:		57%	**64.5%**	61%

Figure 6. Suspension Trade Study

1.3.3. Power Subsystem

1.3.3.1. Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
PS-1	Power subsystem shall generate power to recharge and utilize its batteries	Power generation is necessary to consistently supply power to all subsystems	None	PS-1.1	Demonstration	Power System	TBD
PS-1.1	Power generation shall incorporate solar panels capable of generating 60 W (tentative) during solar exposure periods	Provides essential renewable energy source available on Mars for supporting spacecraft operations	MR-6, PS-1	PS-1.1.1	Test	Power System	TBD
PS-1.1.1	Solar panels should optimize power generation using solar tracking technology to adjust panel orientation	More power can be generated by adjusting panels to optimal solar angles	PS-1.1	None	Test	Power System	TBD
PS-2	Power subsystem shall	Adequate power storage is	None	PS-2.1	Inspection	Power System	TBD

	contain a power storage subassembly to store energy and reserve sufficient electrical power to meet operational needs of spacecraft	essential for maintaining spacecraft operations during periods of non-power generation					
PS-2.1	Power storage shall utilize a secondary battery capable of recharging after depletion	The power storage should be able to keep the rover powered during periods of non solar power generation	PS-2	PS-2.1.1, PS-2.1.2	Test	Power System	TBD
PS-2.1.1	Power storage shall have a long storage life (2+ years) and reasonable cycle life (500+ cycles)	The rover must recharge the battery daily thus it is necessary for the battery to have longevity.	PS-2.1	None	Inspection	Power System	TBD
PS-2.1.2	Power storage should include spare batteries for redundancy	To mitigate the risk of battery failure, having backup batteries is vital for continued power storage throughout the mission	PS-2.1	None	Inspection	Power System	TBD
PS-2.2	Power storage shall be able to handle extreme temperature fluctuations on Mars with a thermal management system	More temperature resistant battery technologies result in longer operational battery lifespans	PS-2	None	Test	Power System	TBD
PS-3	Power subsystem shall contain a power management and distribution subassembly to transmit power efficiently and safety to all subsystems	Ensures that all spacecraft subsystems receive the necessary power to perform their functions	None	PS-3.1	Inspection	Power System	TBD
PS-3.1	Power distribution shall utilize components to protect circuit against unstable current and voltage	Power distribution must be regulated to mitigate the risk of catastrophic electrical errors	PS-3	None	Test	Power System	TBD
PS-3.2	Power subsystem shall include a power management and distribution device to handle	Ensures the safe and efficient operation of battery cells, prolonging their lifespan and maintaining optimal performance under varying environmental conditions.	PS-3	None	Test	Power System	TBD

Figure 7. Power Subsystem Table

1.3.3.2. Power Subsystem Overview

The electrical power subsystem is fundamental for mission success, providing vital electrical energy to drive and support loads on the spacecraft throughout the duration of the mission. In this rover-based mission, it serves as an essential hub for powering the mobility, communication, scientific research instruments, and data transmission of the rover. This subsystem is divided into three subassemblies: power generation, power storage, and power distribution and management. Each subassembly plays a critical role in ensuring all electrical needs are met on the challenging Martian terrain and atmosphere. The following overview details the specifications and design decisions for each subassembly.

Power Generation Subassembly: The power generation subsystem is necessary for generating reliable electrical energy from a viable energy source. It is responsible for recharging power storage components like batteries and ensuring power is continually provided for the mission duration.

Solar panels were chosen as the primary power generation technology due to their lower cost, higher reliability, and lower complexity. Since there are little to no commercially available rover-based solar arrays for purchase, the solar array will be custom designed. To reduce research and development costs, the solar array uses a miniature UltraFlex design with one solar panel to reduce array shadowing and costs. The array will be composed of SpectroLab XTE-SF Ga-based triple junction cells, which have high BOL efficiencies and power outputs. A sun sensing algorithm, further detailed in the GNC subsystem, governs panel orientation for optimal exposure. The power generation subsystem is rated at TRL 6 due to its UltraFlex design that has had success in previous Mars surface missions like InSight, but is lowered due to custom parts.

Based on Sojourner, a slightly smaller Mars rover (65cm x 48cm x 30cm), the normal driving requirement for the micro rover is 10W with a peak panel production of 16 W. This rover is slightly larger and powers other subsystems: the CDH subsystem requires 35W, the GNC subsystem requires 15W, and payload requires 15.6 W. A liberal estimate of the power requirement is 100W with a panel production of 110W. This number is tentative and will be updated in future iterations when more information is available. According to the specifications for SpectroLab XTE-SF, 433.4 watts of power are produced per square meter of cells. Therefore, 0.230 m^2 of solar cell area is needed to generate 100W of power. Factoring in the solar array construction materials, round the area up to .25 m^2 or 2500 cm^2, and account for an estimated .03 m thickness, the total volume of 0.0075 m^3. Each rectangular cell is 27 cm^2, so that is approximately 93 rectangular cells to use. The density is 84 mg/cm^2, so the weight of the cells are at least 210.29 g. Assuming the materials to make the solar array add 200 g of weight, the total weight should be approximately 410.29 g.

- UltraFlex Solar Panel: SpectroLab XTE-SF Ge-based triple junction cells

Power Storage Subassembly: The power storage subassembly is responsible for storing electrical energy generated by the power generation subassembly to ensure continuous power supply, even during periods of little to no sunlight. A key factor this subassembly assumes is that it incorporates secondary batteries, not primary, as the need to recharge the battery is essential for longer mission durations.

The chosen battery chemistry is lithium-ion for its large energy density and great cycle life. The specific battery used is the EaglePicher NPD-002271, which incorporates advanced lithium-ion batteries with a large capacity for energy storage in a small amount of volume. These batteries are used in combination with the thermal management subsystem to withstand extreme temperature fluctuations on Mars and to ensure optimal performance. For redundancy and backup, extra EaglePicher batteries will be stored as backup energy. The TRL for this subassembly is assessed at TRL 8, with lithium-ion battery technology being well-established but with ongoing improvements and optimization and the EaglePicher NPD-002271 previously being utilized for space missions.

Assuming the same power requirements from before, the rover requires around 100W of power and will run for eight hours of operation, the batteries should store around 800Wh to maintain normal operations for one day. Based on the given volumetric energy density for the EaglerPicher of 271 Wh/L, this means 800Wh of power takes 2.95 L of space or 0.00295 m^3. In terms of mass, the given specific energy of the EaglePicher is 153.5 Wh/kg. This means 800Wh of power weighs around 5.212 kg.

- EaglePicher NPD-002271 Lithium-ion Batteries: High-capacity cells with thermal management; TRL 8

Power Management and Distribution Subassembly: This subassembly serves as the central hub for managing and distributing power safely and efficiently throughout the rover. It ensures stable voltage levels, proper power flow management, and protects against overloads.The main component assessed here is the power management and distribution (PMAD) device that are commercially available from space industry vendors. Aside from the PMAD device, subcomponents in this subassembly may include DC-DC converters, voltage regulators, and circuit protection mechanisms to ensure stable and reliable power delivery.

The chosen PMAD device for this subassembly is the Pumpkin Space Systems EPSM 1, for its very high efficiency score and relatively small mass and volume.The TRL for this subassembly is rated at TRL 9, with proven use on cubesats/smallsats flown in space.

- Pumpkin Space Systems EPSM 1 PMAD device
    - DC-DC Converters: Convert solar panel output to usable voltage
    - Voltage Regulators: Maintain stable voltage levels
    - Circuit Protection Mechanisms: Overcurrent, overvoltage protection

Subassembly	Mass (kg)	Volume (m^3)	Max Power Draw (W)
Power Generation	0.410	0.0075	110 W (from other subsystems + headroom)
Power Storage	5.212	0.00294	100 W
Power Distribution and Management	0.3	0.00018	15 W
Total	5.922	0.01224	225 W

Figure 8. Power Break Down Table

Overall, the power subsystem's TRL is determined by the lowest TRL among its subassemblies, TRL 6 for the mini UltraFlex custom power generation solar array. The table above provides a breakdown of the mass, volume, and max power draw for all power subassemblies.

This comprehensive design ensures that the rover's power subsystem is robust, efficient, and capable of supporting the demanding mission objectives on Mars. Incorporating the outlined power subsystem design will facilitate the development of a highly efficient rover tailored for the exploration of Martian volcanic activities. By integrating advanced technologies in solar power generation, lithium-ion battery storage, and power management and distribution, the resulting rover will be able to maintain sustained operations in the harsh Martian environment. This comprehensive approach ensures optimal utilization of available resources while mitigating risks associated with power supply and management, ultimately enhancing the mission's success and scientific output.

Moreover, the utilization of solar energy as the primary power source not only enhances the rover's sustainability but also extends the longevity of its batteries. The synergy between solar power generation and battery storage enables the accumulation of surplus energy during periods of ample sunlight. This surplus energy can be strategically stored in the batteries to supplement power requirements during phases when the rover is positioned in areas with limited or no direct sunlight, such as during nighttime or when traversing terrain obstructing solar exposure. This approach optimizes energy management, mitigates reliance on battery power alone, and ensures uninterrupted operation throughout the mission duration, further bolstering the rover's resilience and operational capabilities on the Martian surface.

1.3.3.3. Power Subsystem Trade Studies

Power Generation Technologies					
Criteria	**Explanation**	**Grade**	**Weight**	**Solar Panels**	**Fuel Cells**
Cost	It is crucial that our design is within our budget constraints. Less expensive is a higher score.	10 = high, 5 = medium 1 = low 0 = Fail	15%	7	5
Reliability	Power generation is fundamental to mission success, therefore failure impacts the entire mission..	10 = high, 5 = medium 1 = low 0 = Fail	35%	8	6

Efficiency	More efficient generation technologies maximize power output within available resources	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	8
Complexity	The higher the complexity of a component, the higher it will be at risk of failure. Less complexity is a higher score.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	3
		TOTALS:	**100%**	75.00%	57.50%

Figure 9. Power Generation Technologies Trade Study

Solar panels are a better generation technology than fuel cells for this mission. Radioisotopic thermogeneration technology was removed from consideration due to violations of the mission requirements. Solar panels have lower initial costs and minimal operational expenses in comparison to fuel cells. They are more reliable due to the accessibility of the Sun on Mars, while fuel cells may experience degradation over time. Additionally, solar panels have shown high reliability in previous Mars rover missions like Sojourner and Spirit. While solar panels are not as efficient as fuel cells, they are less complex, reducing the risk of unexpected failure.

Solar Cells						
Criteria	**Explanation**	**Grade**	**Weight**	**SpectroLab XTE-SF**	**SpectroLab ITJ**	**AZUR Space Silicon S 32**
BOL Efficiency	Efficiency of the solar cell at the beginning of life provides a standardized metric	10 = high, 5 = medium 1 = low 0 = Fail	45%	9 (32.2)	6 (26.8)	3 (16.8)
Pmp - Power Output (W/m^2)	More power generated in a standard area is advantageous under space constraints	10 = high, 5 = medium 1 = low 0 = Fail	35%	7 (433.4)	5 (386)	3 (229.2)
Cost	The budget is limited so it is best not to spend too much on tiny components like solar cells. (Higher = cheaper)	10 = high, 5 = medium 1 = low 0 = Fail	20%	3 (high end)	5 (mid tier)	8 (Si affordable)
		TOTALS:	**100%**	71.00%	54.50%	40.00%

Figure 10. Solar Cell Products Trade Study

For solar cells, SpectroLab XTE-SF provides the highest beginning of life solar efficiency and the greatest power output per unit area. Although it is a high cost item, being the top of the line of SpectroLab's solar cells, this is a worthwhile investment considering the solar array is a life limiting component. The Martian environment does not always have ideal solar conditions, therefore optimizing the efficiency of solar cells is important for

Battery Chemistries						
Criteria	**Explanation**	**Grade**	**Weight**	**NiCd**	**Li-Ion**	**LiPo**
Gravimetric Energy Density (Wh/kg)	Higher energy densities allows for more power to be stored in a smaller area	10 = high, 5 = medium 1 = low 0 = Fail	25%	3 (40-60)	8 (100-265)	8 (100-265)
Cycle Life (# of cycles)	Longer cycle lives increase the longevity of the battery and mitigate the risk of battery depletion	10 = high, 5 = medium 1 = low 0 = Fail	35%	7 (1000-2000)	8 (500-3000)	4 (300-500)
Temperature Performance (C°)	Mars has extreme temperatures that batteries must endure	10 = high, 5 = medium 1 = low 0 = Fail	15%	8 (-40 to 70)	6 (-20 to 60)	6 (-20 to 60)
Reliability	Batteries should not fail and must be functional for mission duration	10 = high, 5 = medium 1 = low 0 = Fail	25%	2 (memory effect)	8 (past space missions)	6 (overcharging damage)
		TOTALS:	**100%**	49.00%	77.00%	58.00%

Figure 11. Battery Chemistries Trade Study

Lithium ion battery chemistry is the best option for power storage. Compared to NiCd, it has a higher energy density and is similar to LiPo. In terms of cycle life, it has the best performance out of the three, which is important since the battery must be used throughout the whole mission. While its temperature performance is worse than NiCd, this can be mitigated by using the thermal control system as a support. Lastly, it does not suffer from serious reliability issues like the memory effect for NiCd and overcharging damage for LiPo batteries.

Lithium Ion Batteries

Criteria	Explanation	Grade	Weight	EaglePicher NPD-002271	Nanopower BP4	ArgoTech ELEKTRA
Volumetric Energy Density (Wh/L)	Higher values indicate the battery can store more energy in a given volume	10 = high, 5 = medium 1 = low 0 = Fail	35%	9 (271)	8 (239.8)	7 (228.5)
Specific Energy (Wh/kg)	Higher specific energy allows for more energy per unit weight	10 = high, 5 = medium 1 = low 0 = Fail	35%	7 (153.5)	8 (172)	9 (190.4)
Typical Capacity [Ah]	Larger Ah means one sample will have a longer battery life	10 = high, 5 = medium 1 = low 0 = Fail	15%	8 (14.5)	5 (6.0)	4 (3.4)
TRL Level	TRL levels determine the readiness of these batteries	10 = high, 5 = medium 1 = low 0 = Fail	15%	8 (7-9)	8 (7-9)	5 (5)
		TOTALS:	100%	80.00%	75.50%	69.50%

Figure 12. Lithium Ion Batteries Trade Study

Unfortunately, cost information is not publicly available, thus is not factored into this trade study. The best battery choice from this table is the EaglePicher NPD-002271 battery. It contains the largest volumetric energy density and has a larger typical capacity in comparison to other lithium ion batteries. While its specific energy is lower, it is still a fairly reasonable value. Typical capacity means one sample will not discharge as fast as the others. Having a high TRL level also means it is a fairly mature and reliable technology for space missions.

Power Management and Distribution Devices						
Criteria	**Explanation**	**Grade**	**Weight**	**Pumpkin Space Systems EPSM 1**	**GUMUSH AeroSpace n-ART EPS**	**EnduroSat Bulgaria EPS II**
Mass (kg)	Lower mass is preferable for minimizing weight and maximizing payload	10 = high, 5 = medium 1 = low 0 = Fail	20%	8 (.3)	9 (0.098)	6 (1.28)

Volume (cm^3)	Smaller volume advantageous for efficient space utilization	10 = high, 5 = medium 1 = low 0 = Fail	20%	8 (180)	8 (160)	5 (742)
Efficiency	Implies more effective power utilization (less waste)	10 = high, 5 = medium 1 = low 0 = Fail	35%	9 (99)	7 (94)	6 (89)
TRL Level	TRL levels determine the readiness of these batteries	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	6	9
		TOTALS:	**100%**	86.00%	73.50%	65.50%

Figure 13. Power Management and Distribution Devices Trade Study

Once again, cost information was not publicly available, therefore it could not be factored into the trade study. From this trade study, Pumpkin Space AMPS leads as the best PMAD device because of its relatively small volume and acceptable mass, very high efficiency, ranged output voltage, and high TRL level of 9.

1.3.4. Command and Data Handling Subsystem

1.3.4.1. CDH Subsystem Requirements

Figure 14. CDH Subsystem Table

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH-1	CDH system shall utilize a 32-bit radiation hardened processor	Radiation hardened processors are essential for the radiation filled environment of mars and space ensuring reliable operation	None	CDH-1.1	Test	Computer Hardware	TBD
CDH1.1	CDH shall contain a backup processor	Having a backup processor enhances system reliability and ensures continuity of operations in case of primary processor failure.	CDH-1	None	Inspection	Computer Hardware	TBD

CDH-2	CDH system shall implement a RTOS for data processing of real-time systems	Real-time operating systems are necessary for managing time-critical tasks and ensuring timely data processing.	None	CDH-2.1	Inspection	Computer Hardware	TBD
CDH2.1	RTOS shall be capable of monitoring all subsystems health and data	Monitoring subsystem health and data is critical for system diagnostics and fault detection.	CDH-2	CDH-2.1.1	Test	Computer Hardware	TBD
CDH2.1.1	RTOS shall communicate with other systems at a rate of TBD using SPI.	Communication at a high rate using SPI (Serial Peripheral Interface) ensures efficient data transfer between subsystems.	CDH-2.1	None	Test	Computer Hardware	TBD
CDH-3	CDH shall utilize 3 antennas to communicate between MRO and DSN	Having multiple antennas ensures redundancy and reliability in communication.	None	CDH-3.1	Inspection	Computer Hardware	TBD
CDH-3.1	CDH shall utilize an Ultra High Frequency(400MHz) transceiver for communications between MRO and the rover	Ultra-High Frequency transceivers enable high-speed communication between the rover and MRO.	CDH-3	CDH-3.1.1	Test	Computer Hardware	TBD
CDH-3.1.1	UHF transceiver shall be capable of transmitting 2 megabits per second	High-speed transmission capability ensures efficient data transfer between the rover and MRO.	CDH-3.1	None	Demonstration	Computer Hardware	TBD
CDH-3.2	CDH shall utilize a rotational X-band high gain(8 GHz) transceiver for communications between DSN and the rover	X-band transceivers enable long-range communication with the Deep Space Network.	CDH-3	CDH-3.2.1	Test	Computer Hardware	TBD
CDH-3.2.1	The X-band High Gain transceiver shall be capable of transmitting 160 bits per second, and receive 500 bits per second	High transmission and reception rates ensure efficient communication between the rover and DSN.	CDH-3.2	None	Test	Computer Hardware	TBD

CDH-3.3	CDH shall utilize a X-band Low gain transceiver(8GHz) for communications between the DSN and the rover. (this can be one used solely for reception)	X-band Low-gain transceivers provide robust communication capabilities with the Deep Space Network.	CDH-3	CDH-3.3.1	Test	Computer Hardware	TBD
CDH-3.3.1	The X-band Low Gain transceiver shall be capable of receiving data at a rate of 10 bits per second	Low data rate reception ensures reliable communication with the Deep Space Network.	CDH-3.3	None	Test	Computer Hardware	TBD
CDH-3.4	CDH shall have at least 1 receiver on at all times.	Having at least one receiver operational at all times ensures continuous communication capability.	None	None	Inspection	Computer Hardware	TBD

1.3.4.2. CDH Subsystem Overview

The CDH subsystem serves as the central nervous system of the spacecraft, orchestrating intra- and inter-communications between various subsystems while facilitating communication between the spacecraft and Earth. This pivotal overview explores the intricacies of the CDH subsystem, delving into its design, components, and functionalities, in alignment with the outlined requirements.

Subassembly Breakdown

Telecommunications: This subassembly governs all communication functions of the spacecraft, encompassing components vital for transmission and reception. It includes antennas, transceivers, and communication protocols, enabling seamless communication between subsystems within the spacecraft and facilitating exchanges with Earth or intermediary systems like orbiters. The Telecommunications subassembly ensures the reliable and efficient transmission of crucial data, commands, and telemetry, pivotal for spacecraft operations and mission success.

Components:

- X-band High Gain Transceivers: High-gain antennas optimized for long-range communication with the Deep Space Network (DSN), enabling the transmission of large data sets and high-resolution images.

- X-band Low Gain Transceivers: Low-gain antennas designed for robust communication with the DSN under varying conditions, ensuring stable links during adverse events.

Data Computing: This subassembly is dedicated to processing all onboard data, comprising components essential for computation and storage. It houses processors, memory units, and real-time operating systems, orchestrating the execution of commands, processing of sensor data, and generation of telemetry for transmission. The Data Computing subassembly ensures precise, efficient, and timely data processing to support spacecraft operations and achieve scientific objectives.

Components:

- RAD750 CPU: A radiation-hardened CPU renowned for reliability and performance in space environments.
- Aeroflex's 256 MB RAM: High-performance, radiation-hardened RAM for data storage.
- Aeroflex's 2GB NOR FLASH ROM: High-performance, radiation-hardened ROM for data storage.

Software Architecture: This subassembly encompasses the overarching software framework and structure of the CDH subsystem, comprising software components responsible for command execution, data processing algorithms, fault detection and recovery mechanisms, and interface protocols. The Software Architecture ensures seamless integration and coordination of various software modules within the CDH subsystem, facilitating communication with other spacecraft subsystems. It provides a robust and adaptable framework for developing, testing, and maintaining software applications onboard the spacecraft.

Components:

- VxWorks OS: A real-time operating system known for its modularity and performance.
- F' Software Framework: An open-source software implementing autonomous fault detection, isolation, and recovery (FIDR).

The integration of these components within the CDH subsystem establishes a robust and efficient communication and data processing infrastructure vital for the success of the spacecraft mission.

Component	Description
RAD750 CPU	A radiation-hardened CPU known for its reliability and performance in space environment
Aeroflex’s 256 MB RAM	High-performance, radiation-hardened RAM for data storage
Aeroflex’s 2GB NOR FLASH ROM	High-performance, radiation-hardened ROM for data storage
X-band High Gain Transceivers	An antenna designed to operate in the X-band frequency.
X-band Low Gain Transceivers	An antenna designed to operate in the X-band frequency.
VxWorks OS	A real-time OS known for its modularity and performance
F’ Software Framework	An open-source software implementing autonomous fault,detection,isolation and recovery (FIDR)

Component	**Mass(kg)**	**Volume(cm^3)**	**Power(W)**
RAD 750 CPU	1	500	10
Aeroflex’s 256MB DRAM	0.4	200	2
Aeroflex’s 2GB NOR FLASH	0.4	200	2
X-Band Transceivers	.27 * 2 = 0.54	270	20
Total	2.34	1170	34

Figure 15. CDH Break Down Table

1.3.4.3. CDH Subsystem Trade Studies

CPU					
Criteria	**Explanation**	**Grade**	**Weight**	**Rad750**	**Rad550**
Cost	It is crucial that our design is within our budget constraints.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	5
Power Consumption	Lower power consumption is generally preferred for space applications to conserve energy and optimize resources.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	6
Complexity	The higher the complexity of a component, the higher its will be at risk of failure.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	6
Construction	This criterion assesses the construction quality and robustness of the CPU models.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	7
		TOTALS:	**100%**	77.50%	60.00%

Figure 16. CPU Trade Study

The decision to choose the Rad750 over the Rad5500 was based on several factors. The Rad750 scored better in cost, power, and construction, indicating that it is less expensive, less complex, and more efficient to build. The overall advantages of the Rad750 made it the preferred choice. The Rad750's proven reliability and performance in space environments also contributed to this decision.

ROM

Criteria	Explanation	Grade	Weight	Aeroflex's 2GB	Generic 2GB
Cost	It is crucial that our design is within our budget constraints.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	8
Power Consumption	Lower power consumption is generally preferred for space applications to conserve energy and optimize resources.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	7
Complexity	The higher the complexity of a component, the higher its will be at risk of failure.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	7
Construction	This criterion assesses the construction quality and robustness of the CPU models.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	7
		TOTALS:	100%	75.00%	72.50%

Figure 17. ROM Trade Study

The choice between Aeroflex's 2GB ROM and a Generic 2GB ROM was a close call. Both options scored similarly across all criteria. However, Aeroflex's 2GB ROM edged out the generic option due to its slightly better scores in construction. In addition, the extensive experience of Aeroflex Systems in space missions is non-negligible.

Ram					
Criteria	**Explanation**	**Grade**	**Weight**	**Aeroflex 256 MB**	**Aeroflex 512 MB**
Cost	It is crucial that our design is within our budget constraints.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	6
Power Consumption	Lower power consumption is generally preferred for space applications to conserve energy and	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	6

	optimize resources.				
Complexity	The higher the complexity of a component, the higher its will be at risk of failure.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	7
Construction	This criterion assesses the construction quality and robustness of the CPU models.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	8
		TOTALS:	**100%**	75.00%	70.00%

Figure 18. RAM Trade Study

In the RAM trade study, the Aeroflex 256 MB was chosen over the Aeroflex 512 MB. Despite the larger capacity of the 512 MB option, the 256 MB RAM scored higher in cost, complexity, and construction. This indicates that it is less expensive, less complex, and more efficient to build. The power consumption for both options was the same. The decision was also influenced by the mission requirements, which could be met with the 256 MB option. In addition larger scale missions such as Curiosity uses the 256MB option making it a potential safe option for our discovery class mission.

RTOS					
Criteria	**Explanation**	**Grade**	**Weight**	**VxWorks**	**Linux**
Cost	It is crucial that our design is within our budget constraints.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	10
Power Consumption	Lower power consumption is generally preferred for space applications to conserve energy and optimize resources.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	7
Complexity	The higher the complexity of a component, the higher its will be at risk of failure.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	5
Construction	This criterion assesses the construction quality and robustness of the CPU models.	10 = high, 5 = medium 1 = low 0 = Fail	25%	5	5

		TOTALS:	100%	70.00%	67.50%

Figure 19. RTOS Trade Study

The decision to use the VxWorks OS over Linux was influenced by several factors. While Linux is open-source, VxWorks scored higher in complexity, power consumption, and construction. This indicates that VxWorks is less complex, consumes less power, and is more efficiently customizable. VxWorks' modularity and performance, along with its popularity in space missions, also contributed to this decision.

Software					
Criteria	**Explanation**	**Grade**	**Weight**	**F'**	**cFS**
Cost	It is crucial that our design is within our budget constraints.	10 = high, 5 = medium 1 = low 0 = Fail	25%	10	10
Power Consumption	Lower power consumption is generally preferred for space applications to conserve energy and optimize resources.	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	7
Complexity	The higher the complexity of a component, the higher its will be at risk of failure.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	6
Construction	This criterion assesses the construction quality and robustness of the CPU models.	10 = high, 5 = medium 1 = low 0 = Fail	25%	8	7
		TOTALS:	100%	80.00%	75.00%

Figure 20. Software Trade Study

The F' software framework was chosen over cFS based on its higher scores in complexity, power consumption, and construction. While both options were equally open source, F' was less complex, consumed less power, and was more efficient to customize. The F' framework's capabilities for autonomous fault detection and recovery were also a factor in this decision.

1.3.5. Thermal Management Subsystem

1.3.5.1. Thermal Subsystem Requirements

THERMAL CONTROL SYSTEM REQUIREMENTS							
Req #	**Requirement**	**Rationale**	**Parent Req**	**Child Req**	**Verification Method**	**Relevant Subsystem**	**Req Met?**
TCS-1	Thermal control system shall be capable of regulating the temperature.	Mars can have extreme temperatures.	None	TCS-1.1, TCH-1.2	Analysis Test	Thermal Control System	TBD
TCS-1.1	Thermal control system shall have a set of passive system components.	Passive components maintain a stable thermal environment, essential for the operation of onboard systems and instruments across varying mission conditions.	TCS-1	None	Demonstration	Thermal Control System	TBD
TCS-1.2	Thermal control system shall have a set of active system components.	Active components provide precise temperature control, ensuring optimal performance and adaptability to changing thermal conditions throughout the mission.	TCS-1	TCS-1.2.1	Demonstration	Thermal Control System	TBD
TCS-1.2.1	Thermal control system shall have both cooling and heating capabilities	Cooling and heating capabilities enable the spacecraft to operate effectively across a range of temperature environments encountered during the mission.	TCS-1.2	None	Demonstration	Thermal Control System	TBD
TCS-1.3	Thermal control system shall be capable of preventing as much outward heat transfer as possible.	The lower threshold of the temperature range on Mars is extremely low at -225 Fahrenheit.	TCS-1	None	Analysis Test	Thermal Control System	TBD
TCS-1.4	Thermal system should have a backup system in case the main temperature system is not operating at capacity.	If the main heater is not working, the mission vehicle might freeze over.	None	None	Demonstration	Thermal Control System	TBD

Figure 21. Thermal Control System Requirements

1.3.5.2 Thermal Subsystem Overview

Thermal System Background: The mission is being carried out on a planetary body that has a lower range of temperature than that of Earth. Due to this thermal constraint, our vehicle must be capable of regulating temperatures from low of -225 degrees Fahrenheit up to 70 degrees Fahrenheit. This extreme temperature range is caused by the thin atmosphere of Mars, which has a pressure equivalent to one sixth of that of Earth's. Due to the thinner atmosphere on Mars compared to Earth, the planet is unable to retain heat for very long, resulting in rapid temperature drops. Additionally due to the range peaking in the high positive Fahrenheit temperature values, the mission vehicle must have both heating and cooling capabilities.

Thermal System Overview: In the endeavor of exploring Mars, the thermal system plays a pivotal role in ensuring the success and sustainability of the vehicle mission. The mission vehicle should be designed to withstand the harsh and fluctuating environment on Mars' surface. The temperature ranges between the day and night cycle will largely provide a heating challenge rather than a cooling one. At the core of the system, it is used to regulate the internal temperature of the vehicle, and safeguarding sensitive electronic equipment and scientific instruments from fluctuating temperatures. Mars experiences temperature variations ranging from sub-zero temperatures during the night to relatively warmer conditions during the day, posing a significant challenge to the vehicle's operation. To counteract these fluctuations, the vehicle will contain a range of passive and active thermal management systems. Passive thermal regulation systems will be equipped onto vehicles to mitigate outward heat transfer.

Thermal Regulation System: The current design of our thermal control system includes a set of passive and active components. Our vehicle's thermal regulation in the passive form will mainly depend on components to minimize outward heat transfer. Power generated from the sun or from the power system team will be highly valued. Passive insulation materials such as aerogels and multi-layer insulation blankets form a protective barrier around critical components, minimizing outward heat transfer and maintaining stable internal temperatures on Mars' harsh environment. For our active thermal control mechanisms, we will be taking advantage of heaters, radiators, and heat sinks that are strategically integrated into our vehicle's design to actively manage temperature fluctuations. During the frigid nights on Mars, the heaters are employed to keep vital systems warm, ensuring the functionality and longevity of the equipment. The radiators and heat sinks dissipate the excess heat generated by the vehicle's activities during the day and prevents it from overheating.

Passive System: With our current list of passive system regulation methods, including the use of aerogels, we can ensure that our vehicle can maintain as much of its interior heat as possible while minimizing outward heat transfer. Aerogel is derived from a gel, where the liquid component is replaced with fas, resulting in a solid material that is incredibly lightweight and possesses exceptional insulation capabilities. Aerogel is made of 99% of air with an incredibly low density; however, it has remarkable thermal insulation abilities, blocking heat transfer through conduction. By implementing aerogel into our vehicle design, we can minimize outward heat transfer during the frigid night and inward heat transfer during the day. Not only does aerogel serve as an excellent thermal insulator, it also serves as an excellent absorber of cosmic radiation due to its nanoporous structure, thus providing further protection for sensitive electronics onboard. Our vehicle will also use heat pipes to distribute excess heat generated by onboard electronics to the radiators or heat sinks which can be dissipated into Mars' atmosphere.

Active System: While we have a general plan for the active thermal management system, we are still waiting on components of other subsystems to be chosen and tested before our active management components will be finalized. We have planned for the mission vehicle in general to have a system of heats, radiators, heat exchangers, and coolers to be installed. During the frigid nights on Mars, the heaters will be used to maintain optimal operational temperatures to prevent critical components from freezing. For the upper ranges of temperatures on Mars, our vehicle will be utilizing the radiators and heat exchangers to dissipate excess heat generated by its electronics and power systems. There will also be a system of sensors that will relay thermal data to a heating/cooling system. However, at the current stage of development of our mission, decisions of other subsystem teams have to be made first in order for us to be accurate and detailed about our active thermal management system. Compared to our passive thermal management system, these active systems are less desirable as they likely require more power to maintain and operate. We will also have to take into consideration volume constraints of our vehicle when choosing our active thermal systems. Our mission vehicle's final design will come after more research, heat transfer analysis, and finalization of our components.

TRL: At this point of our design process, the Technology Readiness Level (TRL) of the entire thermal system is likely to be around a 5. Many of the components we have implemented on our mission vehicle have been used on previous rover missions such as the system of heaters, radiators, and thermostats on the Perseverance. Applications of aerogel have also been tested on the Perseverance rover, as well as previous rovers sent to Mars. Due to the similarities between the environment of which the Perseverance rover was sent to and that of which our vehicle will be sent to, it meets the description of the "component and/or breadboard validation in relevant environment". However, until we can test our final design system and a full system with heat transfer calculations and data showing its effectiveness, we will be unable to go past a technology readiness level of 5. Once our vehicle systems are completely installed, our TRL should read an 8 once the vehicle goes through a series of tests and demonstrations either on ground or space.

1.3.5.3. Thermal Subsystem Trade Studies

Insulating Materials						
Criteria	**Explanation**	**Grade**	**Weight**	**Aerogel**	**Foam Insulation**	**Thermal Blankets**
Cost	It is crucial that our design is within our budget constraints.	10 = low cost 5 = medium cost 1 = high cost 0 = Fail	15%	5	8	10
Risk	The selected component must demonstrate robust reliability and durability to withstand the entirety of the mission duration.	10 = low risk 5 = medium risk 1 = low risk 0 = Fail	20%	8	8	8
Complexity	The higher the complexity of a component, the higher its will be at risk of failure.	10 = low complexity, 5 = medium complexity 1 = high complexity 0 = Fail	25%	5	7	7
Performance Criteria	The component needs to regulate the temperature of the mission vehicle on Mars.	10 = high 5 = medium 1 = low 0 = Fail	40%	10	5	6
		TOTALS:	**100%**	76%	65.5%	72.5%

Figure 22. Insulating Materials Trade Study

Heat Pipes						
Criteria	**Explanation**	**Grade**	**Weight**	**Loop Heat Pipes**	**Grooved Heat Pipes**	**Vapor Chamber Heat Pipes**
Cost	It is crucial that our design is within our budget constraints.	10 = low cost 5 = medium cost 1 = high cost 0 = Fail	15%	5	8	6
Risk	The selected component must demonstrate robust reliability and durability to withstand the entirety of the mission duration.	10 = low risk 5 = medium risk 1 = low risk 0 = Fail	20%	7	9	8
Complexity	The higher the complexity of a component, the higher its will be at risk of failure.	10 = low complexity, 5 = medium complexity 1 = high complexity 0 = Fail	25%	6	7	8
Performance Criteria	The component needs to regulate the temperature of the mission vehicle on Mars.	10 = high 5 = medium 1 = low 0 = Fail	40%	8	7	9
		TOTALS:	**100%**	68.5%	75.5%	81.0%

Figure 23. Heat Pipes Trade Study

Cooling System

Criteria	Explanation	Grade	Weight	Thermoel-ectric Coolers	Active Liquid Cooling	Vapor - Compre-ssion Cooling
Cost	It is crucial that our design is within our budget constraints.	10 = low cost 5 = medium cost 1 = high cost 0 = Fail	15%	4	7	8
Risk	The selected component must demonstrate robust reliability and durability to withstand the entirety of the mission duration.	10 = low risk 5 = medium risk 1 = low risk 0 = Fail	20%	7	8	9
Complexity	The higher the complexity of a component, the higher its will be at risk of failure.	10 = low complexity, 5 = medium complexity 1 = high complexity 0 = Fail	25%	8	6	5
Performance Criteria	The component needs to regulate the temperature of the mission vehicle on Mars.	10 = high 5 = medium 1 = low 0 = Fail	40%	6	8	9
		TOTALS:	**100%**	64.0%	73.5%	78.5%

Figure 24. Cooling System Trade Study

1.3.6 GNC Subsystem

1.3.6.1 GNC Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met ?
GNC-1	The spacecraft shall contain a Guidance, Navigation and Control system that allows for traversing the Martian terrain and precise collection of scientific data	The rover will need to be able to navigate the hazardous martian terrain and accurately collect samples in order to successfully perform the science needed	None	GNC-1.1,1.2	Demonstration	Guidance, Navigation, Control	Met
GNC-1.1	The GNC system shall be capable of determining its location on the Martian surface using a combination of sensors	Knowing the location will enable mapping of the environment, distances traveled, and ensure the rover is accurately navigating to the destination.	GNC-1	GNC-1.1.1, 1.1.2, 1.1.3, 1.1.4	Test	Guidance, Navigation, Control	Met
GNC-1.1.1	The GNC system shall be capable of finding the direction the rover is facing within 0.5 degrees of accuracy	Knowing the direction the rover is facing will help with path planning, and ensure the rover is heading in the right direction.	GNC-1.1	None	Test	Guidance, Navigation, Control	Met
GNC-1.1.2	The GNC system shall be capable of determining the amount of distance it has traveled using Visual Odometry with 99% accuracy	Visual Odometry will ensure the rover hasn't misinterpreted the distance traveled by using images as a reference.	GNC-1.1	None	Test	Guidance, Navigation, Control	Met
GNC-1.1.3	The GNC system shall be capable of determining the rovers heading, tilt, and the direction of gravity with a bias stability of 1.5 degrees/hr & 500 micro-g	The rover should be capable of determining the direction of gravity and its tilt in order to prevent rollover.	GNC-1.1	None	Test	Guidance, Navigation, Control	Met
GNC-1.1.4	The GNC system shall be capable of capturing images with a resolution of 0.82 milliradians, of the rovers' immediate area to provide information regarding the surrounding terrain	The rover should be able to capture images of the terrain features in its area for the ground team or itself to determine best routes, and potential hazards	GNC-1.1	None	Test	Guidance, Navigation, Control	Met
GNC-1.2	The GNC system shall implement hazard avoidance and path planning software.	The rover should be capable of determining and avoiding obstacles in its path, such as rocks, cliffs, and sand dunes	GNC-1	GNC-1.2.1, 1.2.2	Inspection	Guidance, Navigation, Control	Met
GNC-1.2.1	The hazard avoidance software shall be capable of determining when the environmental conditions are too hazardous for the rover to travel	The rover shouldn't be capable of traveling during extreme dust storms or during the night as they are too	GNC-1.2	None	Test	Guidance, Navigation, Control	Met

		hazardous and pose too great of a risk					
GNC-1.2.2	The GNC system shall have two navigation levels to promote efficiency and autonomy	In order to preserve power for the rest of the subsystems, the rover will utilize an “efficient navigation” mode where the terrain is relatively safe , and a “full navigation” mode when the terrain has become increasingly hazardous.	GNC-1.2	GNC-1.2.2.1, 1.2.2.2	Inspection	Guidance, Navigation, Control	Met
GNC-1.2.2.1	The GNC system will have an “efficient navigation” mode to traverse in safe environments	This will allow for preservation of power and the ability to control the spacecraft form a ground station	GNC-1.2.2	None	Inspection	Guidance, Navigation, Control	Met
GNC-1.2.2.2	The GNC system shall have a “full navigation” mode for hazardous terrains	The ability to control the rovers every move in hazardous terrain is next to impossible due to latency. This mode will allow for autonomous navigation of the rover.	GNC-1.2.2	None	Inspection	Guidance, Navigation, Control	Met

Figure 25. GNC Subsystem Requirements

1.3.6.2. GNC Subsystem Overview

The Guidance, Navigation, and Control subsystem of the rover will need to be designed in such a way that will enable the rover to navigate the hazardous Martian environment, and accurately collect samples to successfully meet the science goals of the mission. The subassemblies of the GNC system will need to be carefully considered in order for the spacecraft to perform reliably.

Inertial Sensing subassembly:

This subassembly is responsible for measuring the velocity and angular change of the rover, providing essential data for navigation, attitude control, and motion estimation. The rover will have a primary Inertial Measurement Unit and a backup IMU that is powered down unless a malfunction occurs in the primary. This will ensure that the rover will be capable of continuing its mission even if the first fails.

The primary IMU will be an Emcore SDI50x-AF00. This IMU was chosen due to the fact it's the highest performance MEMS- based IMU and the only MEMS based IMU to demonstrate 1 degree/sqrt(hr) gyro bias stability and 100 microgram accelerometer bias stability. This IMU was specifically designed to withstand demanding, mission critical, rugged environments. The main drawback of this IMU is its TRL level of 5. Due to the medium TRL level, the rover shall include a backup HG1930 IMU manufactured by Honeywell. This IMU is lightweight, draws little power, and has a TRL level of 7, making it a great backup IMU.

Sun sensing subassembly:

The sun sensing subassembly is responsible for tracking the position of the sun for determining the orientation of the rover in relation to the sun, and when it is morning/night so the rover can know when to start/stop traveling. The sun sensors will need to cover 180 degrees in order to figure out where the sun is at all times throughout the day. When the sun sensor no longer sensed the sun, the rover will know it is time to stop traveling for the day. In order to obtain the most accurate orientation, the sun sensor will need to be capable of determining the position of the sun within 0.5 degrees. Due to the concerns with radiation, the sun sensor will also need to be radiation tolerant of up to 100 krads.

The rover shall have 3 Redwire Digit Sun Sensors(+-64). This sun sensor was chosen due to its spectral range of 128 degrees, +-0.25 degrees accuracy, and having a rad tolerance of 100 krads. This particular sensor has a long history of being used for space applications as well with a TRL of 9, further solidifying it as being the best choice for the mission. Two sensors will be placed on the sides of the rover in order to obtain a spectral range of 180 degrees , and one placed on top to serve as a backup in case the main two malfunction.

Engineering Cameras subassembly:

This subsystem includes all the cameras the rover uses to navigate its environment. The rover will have a Navcam stereo camera mounted on the rotatable mast. The Navcam chosen will be a MCSE MCAMv3. This camera is a proven camera with a large flight heritage, having a TRL of 8. The camera has been developed to be light, compact, low power consuming, and to withstand harsh environmental conditions for resource critical applications. With a FOV of 83 degrees, depth of field of 500mm to infinity, this Navcam will be used to aid in path planning, and the autonomous navigation of the rover.

The rover will also have 4 Hazcam cameras, mounted on the front, back, and both sides. These cameras have a wider FOV of 120 degrees, with one on each side allowing complete coverage of the rovers' surrounding area. These cameras will be mounted directly to the rover body, disabling any independent movement of the cameras. The purpose of these cameras is to provide nearby range data coverage of the surrounding terrain to enable the Hazard avoidance software to map out any potential obstacles.

Navigation Controller:

The rover will need to have software that enables it to traverse the environment, accurately arrive at its destination, and collect samples all while avoiding any obstacles and potential hazards along the way. In order to achieve this, the environmental conditions will need to be monitored by the rover and ground station and ranked into three categories, level 1 - easy, level 2 - difficult, and level 3 - dangerous. The rover shall operate using two different navigation modes depending on the environment.

The first navigation mode, referred to as “efficient navigation” mode, will be used while traversing in level 1 environments. This mode will operate the same way many of the past rovers have, the destination and path will be sent from a ground station, and the rover will navigate using Visual Odometry from the Navcam to keep track of the localization and make sure it is following the right path. In parallel, the hazard avoidance software will be checking for hazards in the area using the Hazcams. If a hazard is detected, the rover will stop and reassess the path with help from the ground team.

When the rover enters a level 2 environment, it will switch to the more advanced “full navigation” mode, which will implement AutoNav software to navigate the terrain without the need for a ground station to continuously monitor every hazard the rover comes across. This mode will also continuously monitor the area, leaving the Hazcams on until its back in a level 1 environment, meaning a higher power draw for the system. This will be handled in collaboration with the CDH system by making sure there is sufficient power that can be supplied.

Level 3 entails environments that are too hazardous for the rover to travel such as dust storms and when the sun is down. Due to the high potential for the rover to be damaged when the environment reaches this level, the GNC system will go into a low power mode and the rover will cease to travel. The rover will “wake up” and return to normal operation when it is safe to do so.

TRL:

The TRL for the entire GNC system is 5. Most of the components in the GNC hardware and software have been to Mars and are flight proven, except for the Emcore IMU, which sits at a TRL of 5. There is a Honeywell HG1930 IMU backup, however, the Emcore is a more advanced component and will better serve future missions if it can be flight proven.

Subassembly	Mass (kg)	Volume (m^3)	Max Power Draw (W)
Inertial Sensing	0.75 SDI50x-AF00(0.59)	0.00038 SDI50x-AF00(3e-4)	5

	HG1930(0.16)	HG1930(0.00008)	
Sun sensing	1.62	0.000201	0.4
Engineering Cameras	1.635	0.001205	9
Total	4	0.001786	14.4

Figure 26. GNC Break Down Table

1.3.6.3. GNC Subsystem Trade Studies

Primary Inertial Sensor						
Criteria	**Explanation**	**Grade**	**Weight**	**Northrop Grumman Ln-200S**	**Honeywell HG1930**	**Emcore SDI50x-AF00**
Gyro & Accelerometer Bias Stability	degrees/hr & micro-g	10 = high, 5 = medium 1 = low	30%	7 (1 & 300)	5 (1.5 & 500)	9 (1 & 100)
Angle & Velocity Random Walk	degrees/sqrt(hr) & (m/sec)/sqrt(hr)	10 = high, 5 = medium 1 = low	20%	7 (0.07 & 0.2)	4 (0.175 & 0.4)	8 (0.02 & 0.059)
Bandwidth	Hz	10 = high, 5 = medium 1 = low	15%	7 (200)	8 (100)	8 (100)
Power Consumption	Watts	10 = high, 5 = medium 1 = low	20%	2 (12)	9 (<3)	5 (5)
TRL	Scale 1-9	9 = high, 5 = medium 1 = fail	15%	9	7	5
		TOTALS:	**100%**	63%	63.5%	72.5%

Figure 27. Primary Inertial Sensor Trade Study

Secondary Inertial Sensor						
Criteria	**Explanation**	**Grade**	**Weight**	**Northrop Grumman Ln-200S**	**Honeywell HG1930**	**Emcore EN-300-5**

Gyro & Accelerometer Bias Stability	degrees/hr & micro-g	10 = high, 5 = medium 1 = low	20%	7 (1 & 300)	5 (1.5 & 500)	9 (0.4 & 300)
Angle & Velocity Random Walk	degrees/sqrt(hr) & (m/sec)/sqrt(hr)	10 = high, 5 = medium 1 = low	20%	7 (0.07 & 0.2)	4 (0.175 & 0.4)	9 (0.03 & 0.2)
Power Consumption	Watts	10 = high, 5 = medium 1 = low	10%	2 (12)	9 (<3)	1 (18)
TRL	Scale 1-9	9 = high, 5 = medium 1 = low	25%	9	7	5
Mass	Kilograms	10 = high, 5 = medium 1 = low	25%	5 (0.748)	9 (0.16)	3 (0.907)
		TOTALS:	**100%**	65%	67%	57%

Figure 28. Secondary Inertial Sensor Trade Study

Sun Sensor							
Criteria	**Explanation**	**Grade**	**Weight**	**NSS Aquila D02**	**RedWire Digital Sun Sensor(6 4+-)**	**Bradford Fine Sun Sensor**	**Cube Sense Sun**
Spectral Range	Degrees	10 = high, 5 = medium 1 = low	20%	8 (140)	7 (128)	7 (128)	9 (166)
Accuracy	Degrees	10 = high, 5 = medium 1 = low	30%	5 (0.5)	8 (0.25)	7 (0.3)	9 (0.2)
Power Consumption	Watts	10 = high 5 = medium 1 = low	10%	6 (0.3)	5 (0.5)	7 (0.25)	6 (0.3)
Temperature Range	Degrees Celsius	10 = high, 5 = medium 1 = low	10%	8 (-2 to 70)	9 (-50 to 85)	9 (-50 to 85)	7 (-20 to 80)
Rad Tolerance	krad	10= high 5= medium 1=low	30%	3 (20)	7 (100)	7 (100)	4 (24)
		TOTALS:	**100%**	54%	73%	72%	70%

Figure 29. Sun Sensor Trade Study

Engineering Cameras						
Criteria	**Explanation**	**Grade**	**Weight**	**MCSE MCAMv 3**	**MSSS LCAM**	**MSSS ECAM-P 50**
Field of View	Degrees	10 = high, 5 = medium 1 = low	25%	7 (83)	8 (90)	8 (90)
Mass	Kilograms	10 = high, 5 = medium 1 = low	25%	8 (0.327)	5 (0.88)	6 (0.7)
Rad Tolerance	krad	10 = high, 5 = medium 1 = low	25%	7 (35)	7 (35)	7 (35)
Power Consumption	Watts	10 = high, 5 = medium 1 = low	25%	9 (1.8)	4 (5.5)	5 (3.25)
		TOTALS:	**100%**	77.5%	60%	65%

Figure 30. Engineering Cameras Trade Study

1.3.7. Payload Subsystem

1.3.7.1. Payload Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
PLS-1	The system shall not contain more than two science instruments to achieve the science objectives.	Provided by mission document	Mission constraints	PLS-1.1	Inspection	RIMFAX, Mini-TES	TBD
PLS-1.1	The system shall not exceed a mass of 45Kg	Provided by the mission document	PLS-1		Inspection	All subsystems	TBD
PLS-2	The payload shall have the ability to investigate subsurface ice deposits on the martian surface	Provided by the mission document	Mission constraints	PLS-2.1	Test (analytical techniques not adequate)	RIMFAX	TBD
PLS-2.1 /3.1	The payload must maintain permissible	Ensure that the instruments are	PLS-2 / 3	PLS-2.2 / 3.2	Test	RIMIFAX, Mini-TES	TBD

	operating temperatures throughout the mission	capable of functioning correctly					
PLS-2.2	RIMFAX must point to the ground	Allows RIMFAX to properly conduct research	PLS-2		Test	RIMFAX	TBD
PLS-3	The payload shall have the ability to investigate and test relevant mineral, rock, and lava deposits on the martian surface	First mission objective. Inspired by Q5.4 of planetary science decadal.	Planetary Science Decadal	PLS-3.1	Test (analytical techniques not adequate)	Mini-TES	TBD
PLS-3.2	Mini-TES must be able to rotate/swivel	Allows Mini-TES to capture data from various angles	PLS-3		Test	Mini-TES	TBD
PLS-4	The payload must have an operating life of TBD years	Ensure that the instruments can conduct sufficient research	Customer		Demonstration	RIMIFAX, Mini-TES	TBD
PLS-5	The instruments must only consume power within the capacity of the vehicle (225W)	Ensure that the instruments are capable of functioning correctly	Power Constraints		Test	RIMIFAX, Mini-TES	TBD

Figure 31. Payload Subsystem Table

1.3.7.2. Payload Subsystem Overview

The purpose of the payload subsystem is to provide the necessary instruments to gather scientific data by performing tests, experiments, and analyses of the Martian surface and subsurface. The established scientific objectives for the mission include the search and characterization of subsurface ice deposits and the analysis of rocks and minerals, specifically those resulting from volcanic activity. Equipped with two scientific instruments, the Radar Imager for Mars' Subsurface Experiment (RIMFAX) and the Miniature Thermal Emission Spectrometer (Mini-TES), the rover will continuously seek large subsurface ice deposits and will examine Scanning for subsurface ice is an important part of the human exploration goal for Mars, which includes characterizing accessible Martian resources and analyzing potential reserves that enable the use of resources in future operations and manned missions. Likewise, the analysis of volcanic deposits gathers scientific research data that not only uncovers the historic volcanic activity on Mars but can also contribute to understanding the formation of liquid water on Mars and the quantity released through the outgassing of water vapor from volcanoes. Both of the instruments have demonstrated successful operations on previous Mars missions. As a result, the TRL of both the RIMFAX and Mini-TES are 9. Thus, the overall TRL of the payload subsystem is 9.

Radar Imager for Mars' Subsurface Experiment (RIMFAX): The RIMFAX is the first of two instruments supported by the rover. Its primary purpose is to locate geologic features beneath the Martian surface by sending ground-penetrating radar waves under the rover. Thus, it must be located on the bottom of the rover with a direct line of sight to the Martian surface. For the selected mission, the RIMFAX will be used to locate and characterize subsurface ice deposits. Because of the rover's small size, it is not feasible to equip it with a drill to dig for subsurface ice. Consequently, the RIMFAX was selected because of its ability to remotely and continuously scan for ice deposits, taking measurements every 4 inches traveled by the rover. RIMFAX can scan greater than a depth of 30 feet or 10 meters depending on the material. Various materials under the Martian surface, such as ice, rocks, and water reflect and scatter the radar waves in different ways, allowing RIMFAX to create a 2-dimensional image of the subsurface from the returned radar pulses. Similarly, the speed at which the radar pulses return can also be used to identify the materials beneath the surface. The radar pulses range from 150 to 1200 megahertz. These frequencies can be adjusted to reach different depths as lower-frequency waves travel deeper into the surface. This will allow the rover to focus the instrument on specific areas of interest, such as ice located at a certain depth. The vertical resolution of these measurements mostly ranges between 3 and 12 materials, providing data on layering in the rocks and sediments it detects. For subsurface pure liquid water ice, the radar pulses emitted by RIMFAX are expected to pass straight through the ice.

A trade study was performed to select an instrument that would best meet the mission requirement of detecting subsurface ice. Consisting of RIMFAX, the Near Infrared Volatile Spectrometer System (NIRVSS), and the Neutron Spectrometer System (NSS), the trade study determined which instrument was capable of remotely scanning for subsurface ice while meeting the existing requirements for the rover and mission. The criteria for the trade study involved the range of the instrument, the power consumption, the mass, and the technology readiness level with the range being the primary basis for selection, weighted at 50%. RIMFAX was superior with its 30-foot range, compared to the 4-foot range of NSS and the 0-foot range of NIRVSS which required samples to be excavated with a drill. The technology readiness level of each instrument was also assessed. NSS was assigned a TRL of 8 as the instrument demonstrated successful qualification tests for the Peregrine 1 mission but never operated on the Moon due to a propellant leak. NIRVSS was assigned a TRL of 7 as it was also a part of the Peregrine 1 mission. RIMFAX was assigned a TRL of 9 as it was equipped on the Perseverance rover and has successfully operated on Mars. Because of RIMFAX's sensing range and technology readiness level, it was the optimal instrument for subsurface ice detection, despite not being the lightest or most energy-conservative of the three.

Miniature Thermal Emission Spectrometer (Mini-TES): The Mini-TES is the second of the two instruments selected to be supported by the rover. The primary purpose of Mini-TES is to determine the mineralogy of Martian rocks, soils, and minerals. For the designed mission, the Mini-TES will be used to analyze volcanic deposits to determine the relationship between historic volcanic eruptions and the outgassing of water vapor which may have contributed to large quantities of liquid water on the Martian surface. This mission objective is inspired by question 5.4 of the Planetary Science Decadal. Mini-TES is an advantageous instrument because it is specially created to look for minerals formed in water. It is capable of identifying carbonates and clays and can even detect water vapor in the atmosphere. Similarly, it can effectively identify and analyze hydrated minerals which may provide insight into historic outgassing. Mini-TES is an infrared spectrometer. However, unlike many other spectrometer instruments, Mini-TES is ranged and is capable of analyzing materials up to 10 meters away. It works by detecting thermal radiation emitted by different objects. The wavelengths it can detect range from 5 to 29.5 micrometers and it has a scan resolution of 10 cm-1. Additionally, its field of view can toggle between 8mrad and 20mrad. Optimally, the instrument will be attached to a rotating mast which will allow it to conduct tests in all directions from the rover. This is important as the rover may traverse rough terrains because of lava flows and many rocks. The ranged ability of the instrument allows data to be gathered from the difficult but necessary landscape.

A trade study was performed to select an instrument that would best meet the mission goal of analyzing Martian rocks and volcanic deposits to uncover the historic formation of liquid water. Three instruments were compared: Mini-TES, ChemCam LIBS, and SHERLOC. The criteria used to assess the instruments included the detection accuracy, the range, the power consumption, and the mass with the accuracy and range being the most vital, weighted at 40% and 30% respectively. Mini-TES was the most accurate of the three, with a percent accuracy within 5% as defined by its requirements when undergoing testing. LIBS had an accuracy within 10% and SHERLOC within 30%. Further, the Mini-TESS had the greatest range of 10 meters. Thus, Mini-TESS was the optimal instrument because it could accurately analyze Martian rocks and minerals from a distance. This is vital in rough terrains characteristic of volcanic landscapes.

	RIMFAX	Mini-TES
Mass	3 kg	2.4 kg
Volume	19.6 x 12.0 x 6.6 cm	23.5 x 16.3 x 15.5 cm
Max Power Draw	10 W	5.6 W

Figure 32. Payload Break Down Table

1.3.7.3. Payload Subsystem Trade Studies

Ice Detection Instrument

Criteria	Explanation	Grade	Weight	RIMFAX	Near Infrared Volatile Spectrometer System (NIRVSS)	NSS: Neutron Spectrometer System
Power Consumption	Watts	10 = low power draw 5 = medium power draw 1 = high power draw	20%	6 (10 W)	2 (30 W)	9 (1.5 W)
Mass	Kilograms	10 = low mass 5 = medium mass 1 = high mass	10%	6 (3 kg)	5 (3.57 kg)	9 (1.6 kg)
TRL	Scale 1-9	9 = high 5 = medium 1 = low	20%	9 (TRL 9)	7 (TRL 7)	8 (TRL 8)
Range	Feet	10 = high range 5 = medium range 1 = low range	50%	10 (30 feet)	1 (0 feet)	4 (3 feet)
		TOTALS:	**100%**	88.00%	29.56%	64.78%

Figure 33. Ice Detection Instrument Trade Study

Rock and Mineral Analysis Instrument						
Criteria	**Explanation**	**Grade**	**Weight**	**Mini-TES**	**ChemCam LIBS**	**SHERLOC**

Power Consumption	Watts	10 = low power draw 5 = medium power draw 1 = high power draw	20%	8 (5.6 W)	3 (30 W)	1 (48.8 W)
Mass	Kilograms	10 = low mass 5 = medium mass 1 = high mass	10%	7 (2.4 kg)	2 (10.79 kg)	4 (4.72 kg)
Accuracy	Percent	10 = high accuracy 5 = medium accuracy 1 = low accuracy	40%	10 (+-/- 5%)	8 (+/- 10%)	6 (+/- 30%)
Range	Meters	10 = high range 5 = medium range 1 = low range	30%	8 (10 meters)	6 (7 meters)	1 (0.05 meters)
		TOTALS:	**100%**	87.00%	58.00%	33.00%

Figure 34. Rock and Mineral Instrument Trade Study

1.3.8. Recovery and Redundancy

Mechanical Subsystem:

Purpose:

- The mechanical subsystem is designed to safeguard the instruments of the spacecraft from Mars' environmental hazards. This includes having the protection against solar radiation, dust abrasion, and uneven surface terrain, ensuring mission success.

Chassis Support:

- *Redundancy:* The chassis support will have additional rib supports within the compartment enclosing the primary volume. These ribs are not necessary at a bare minimum standard, but in the instance that larger than expected forces are imposed over the structure, the ribs help to distribute those forces over a larger area which will decrease stresses throughout the spacecraft body. Additionally, a more conservative estimate to the thickness was chosen to account for any

unexpected loading conditions to prevent catastrophic fracture failure and openings into the critical electronic/testing components within the spacecraft.
- *Recovery:* The chassis is directly connected with the suspension system, which is directly connected with the wheel system. These individual subsystems each have their own autonomous methods of recovery that are discussed in the next sections. Their purpose is to ensure the chassis maintains stability over an uneven surface and through mobility across the terrain.

Wheels:

- *Redundancy*: Similar to the perseverance rover, using narrower- 0.2 meters in diameter- yet more robust titanium wheels will ensure that the wheels can properly navigate the harsh martian surface. Additionally, the titanium wheels can withstand harsh ionizing radiation, high compressive strength, and abrasion hazards. The redundancy of a standard safety factor of 2 was applied to the design ensuring that each wheel could support a minimum of 55.67 N of force.
- *Recovery:* Autonomous recovery is guaranteed through AutoNav, an autonomous navigation system which creates a 3D image of the martian surface before it, identifies potential hazardous terrain, and works around obstacles. AutoNav allows for enhanced efficiency and a real-time tracker of potential danger ensuring proper navigation.

Suspension:

- *Redundancy:* Beryllium copper was chosen as the material for the suspension as it has copious resistance to UV and solar radiation due to its compact molecular structure. A redundant thin layer of titanium nitride (less than five micrometers thick) will be applied to increase Brinell hardness and yield strength, thereby preventing surface abrasion.
- *Recovery:* A six wheel rocker-bogie suspension system will be used which will allow the vehicle to maintain balance and upright position even in uneven and rocky terrain. Additionally, an autonomous system such as Enhanced Nav or Vision Computer Element (VCE) will be implemented to provide real-time tracking of possible hazards for the suspension. A more well-enhanced selection process must be conducted prior to a decision on either system.

Overall Considerations:

- Mission-Critical Infrastructure- Integrating both redundancy and recovery in the mechanical subsystem are vital to mission success. Redundancy allows room for unforeseen hazards and obstacles in the Martian terrain and climate, especially crucial for the near equator zone being discussed as a landing-site. Recovery allows for real time response to difficulties of navigation on Mars that would be otherwise impossible to properly control from Earth.

Redundancy and Recovery in Power Generation Subsystem:

Power Generation Subassembly:

- *Redundancy:* Using advanced GaAs-based multijunction cells, solar panels are put into different networks. This design makes sure that the failure of a single panel won't have a negative impact on the overall energy production, making sure that critical energy demand is trying to always be maintained.
- *Recovery:* Autonomous recovery is guaranteed through the Sun Tracker Algorithm in the power management and control subsystem. If a panel malfunctions, the algorithm adjusts other panels' orientation, making sure that the continuous and efficient energy is still harvesting.

Power Storage Subassembly:

- *Redundancy:* Robust lithium-ion batteries with enhanced durability are backed by redundancy, adding multiple batteries capable of lone operation. This redundancy can make sure of a backup power source in case of battery failure.
- *Recovery:* The Power Management and Control Subassembly makes an autonomous recovery by monitoring battery health in real-time. In the chance of a battery issue, the system newly puts the power load among working batteries, keeping overall energy storage capacity.

Power Management and Distribution Subassembly:

- *Redundancy:* Vital parts like DC-DC converters, voltage regulators, and circuit protection mechanisms make sure that the power has a stable distribution. Redundancy in these parts prevent a single failure from causing damage or any disruption of the overall power delivery, keeping a stable voltage output.
- *Recovery:* Autonomous recovery, managed by the Power Management and Control Subassembly, involves dynamic rerouting of power flow during errors or component failures, to keep having an unbothered power distribution to important systems.

Overall Considerations:

- Mission-Critical Infrastructure: including redundancy in critical components can make sure of preparation against failures. Autonomous recovery plans, primarily driven by the Power Management and Control Subassembly, can help us adapt to any challenges that catch us off-guard, maintaining a good ongoing and stable power supply on Mars.

Redundancy and Recovery in CDH Subsystem:

Telecommunications Subassembly:

- *Redundancy:* The Telecommunications subassembly includes redundancy, especially in X-band High Gain Transceivers, to keep a continuous and reliable communication with the Deep Space Network (DSN) under any conditions.
- *Recovery:* Autonomous recovery plans, guided by the Software Architecture, enable the CDH subsystem to address errors or disruptions and restore good communication through error detection, isolation, and recovery (FIDR) protocols.

Data Computing Subassembly:

- *Redundancy:* Acknowledging the central role, the Data Computing subassembly has redundancy in important components like the RAD750 CPU, making sure of an unbothered and good execution of commands and data processing.
- *Recovery:* Autonomous recovery plans, allowed by the F' Software Framework, make real-time error detection and recovery mechanisms, so that we can operate with efficient data processing and system stability.

Software Architecture Subassembly:

- *Redundancy:* The Software Architecture subassembly creates a redundancy through parts like the VxWorks OS, enhancing the reliability of command execution and data processing.
- *Recovery:* The F' Software Framework plays a great role in autonomous error detection, isolation, and recovery, allowing the CDH subsystem to correct software-related issues without external intervention.

Overall Considerations:

- Mission-Critical Infrastructure: Integrating redundancy in the CDH subsystem creates a strong communication and data processing infrastructure. Balancing redundancy and autonomy makes sure that we have adaptability to unpredicted challenges, positioned with mission requirements for reliable and autonomous systems.

Redundancy and Recovery in Thermal System Subsystem:

Thermal System Overview:

- *Redundancy*: The Thermal System acknowledges the need to strengthen the system in the face of Mars' changing environment. Both passive and active thermal management systems are used, to ensure redundancy in maintaining stable internal temperatures. Passive systems, including aerogels, form protective barriers, while active systems with heaters, radiators, and heat sinks actively manage temperature changes.

- *Recovery*: Collaborating with the software team, the Thermal System shows autonomous recovery plans for both passive and active systems. In the case of freezing Martian nights, heaters are autonomously used to prevent important components from freezing. This collaboration ensures that the spacecraft can fix issues without direct commands from mission control.

Passive Thermal Regulation System:

- *Redundancy*: Passive systems, such as aerogels, play an important role in minimizing outward heat transfer. While redundancy in these reliable parts may not be necessary, their integration makes sure that the interior heat is maintained during cold nights and prevents inward heat transfer during the day.

- *Recovery*: Autonomous recovery plans for passive systems involve leveraging the different properties of aerogels, keeping the heat transfer through conduction to a minimum. Additionally, heat pipes distribute extra heat generated by onboard electronics to radiators or heat sinks, which can be scattered into Mars' atmosphere.

Active Thermal Regulation System:

- *Redundancy:* Active components, including heaters, radiators, and heat sinks, are integrated with redundancy considerations with the subsystem decisions.
- *Recovery:* Autonomous recovery plans focus on maintaining the best and optimal temperatures during extremely cold Martian nights and scattering excess heat during warmer periods. Sensors relay thermal data to start corrective actions autonomously.

Overall Considerations:

- Collaboration with the software team ensures autonomous recovery plans for both passive and active thermal management systems. The careful balance between redundancy and autonomy aligns with the mission's science goals, emphasizing strong and adaptable systems for successful exploration on Mars.

Redundancy and Recovery in Guidance, Navigation, and Control Subsystem:

Inertial Sensing Subassembly:

- *Redundancy:* Incorporating a primary Emcore SDI50x-AF00 IMU and a backup HG1930 IMU makes sure of dual IMU configuration for navigation, enhancing reliability in the Martian environment.
- *Recovery:* Autonomous recovery plans switch to the backup IMU in case of primary system malfunction without any issues, making sure of continuous navigation and sample collection capabilities.

Sun Sensing Subassembly:

- *Redundancy:* Three Redwire Digit Sun Sensors, each of them placed strategically, give redundancy for accurate sun tracking. In case of sensor malfunctions, the third sensor serves as a backup.
- *Recovery:* Autonomous recovery involves software readings of sun sensor data, making sure that we have accurate sun tracking for navigation and operational timing, even in the event of sensor malfunctions.

Engineering Cameras Subassembly:

- *Redundancy:* Multiple Hazcam cameras and a reliable Navcam stereo camera provide redundancy for all-inclusive coverage of the rover's surrounding areas.

- *Recovery:* Autonomous recovery plans involve revised navigation algorithms based on available camera inputs, making sure of continuous path planning and hazard avoidance.

Navigation Controller:

- *Redundancy:* Operating in two navigation modes, the navigation software makes sure of adaptability through redundancy – "efficient navigation" for level 1 environments and "full navigation" for level 2 environments.
- *Recovery:* Autonomous recovery plans involve assessing hazards we may come across in real-time using Hazcams, with the GNC system entering low power mode in level 3 environments for the rover's safety.

Overall Considerations:

- Preparing for redundancies creates a better reliability in the challenging Martian environment. Autonomous recovery plans, guided by complex software, make sure that the rover's adaptability and continuous mission progress are constantly being overseen by mission control. The comprehensive approach lines up with the mission's science goals, prioritizing strong and adaptable systems for exploration and sample collection on Mars.

1.3.9. Interface Control

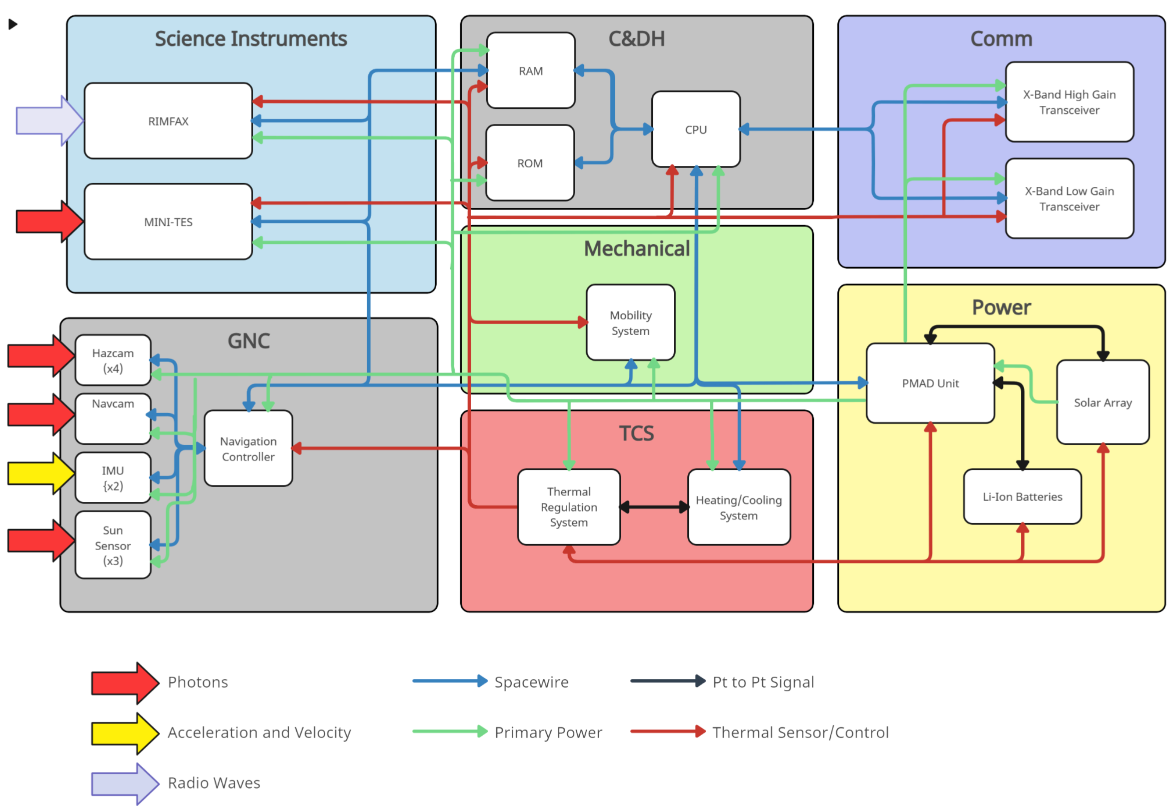


Figure 35. Interface Control Table

Science Instruments:

The two science instruments (RIMFAX, and Mini-TES) will send data collected via spacewire to the CPU where it will be stored in RAM until the data is ready to be sent back to earth.

Figure 36. Block Diagram

Command & Data Handling:

The CPU is the brains of the subsystem, carrying out all instructions and commands via spacewire in the rover. Inside the C&DH subsystem, it will store data into RAM, and retrieve instructions from the flight software stored in ROM. The C&DH subsystem will be capable of sending commands to the science instruments, mobility and PMAD subassembly, the thermal state of all the subsystems to the TCS, the navigation plan to the navigation controller, and all instrument/telemetry data to the MRO via the x-band antennas.

Science Instruments	Instrument Science					
Navigation Command	Command & Data Handling	Instrument Data Telemetry Data Autonomous Check	Navigation Plan	Navigation Command	Rover Thermal State	PMAD Command
	Inbound Transmissions	Comm				
	Telemetry Navigation Data		GNC			
	Telemetry			Mechanical		
TCS	Telemetry TCS	TCS	TCS	TCS	Thermal	TCS
Power	Power	Power	Power	Power	Power	Power

Telecommunication:

The Telecommunications subsystem will be responsible for receiving inbound transmissions sent from the MRO with its two x-band antennas and relaying it to the C&DH system via spacewire.

Guidance, Navigation, and Control:

The Navigation Controller is the brains of the subsystem, responsible for receiving, and sending data to the CPU via spacewire. Inside the GNC subsystem, the Navigation Controller will interpret the data from the sensors via spacewire.

Mechanical:

The Mechanical subsystem will send telemetry data and receive navigation commands via spacewire from the CPU.

Thermal:

The thermal system is responsible for regulating temperatures of all subsystems via sensors. It will also send telemetry to the CPU via spacewire. Inside the subsystem, the heating/cooling subassembly communicates directly with the regulation subassembly

Power:

The power subsystem is responsible for powering all the subsystems via the primary power wire. Inside the subsystem, the solar arrays communicate directly with the PMAD, which communicates directly with the lithium ion batteries to store the power generated from the arrays.

1.4 Risk Analysis

Mechanical Subsystem:
In the development of the spacecraft's Mechanical Subsystem, the team has identified two major risks. First, there is a concern regarding potential chassis material failure due to unknown Martian environmental factors. To mitigate this risk, the team plans to conduct rigorous testing of potential materials in simulated Martian conditions and implement continuous monitoring of the chassis during the mission. Additionally, redundancy will be integrated into critical areas to provide a safety net. The second risk involves the possibility of wheel abrasion or fatigue

impacting mobility. To address this, the team will carefully select wheel materials, continuously monitor wheel health, and incorporate autonomous recovery plans, such as adjusting wheel configurations or redistributing loads as needed.

Power Generation Subsystem:
Within the Power Generation Subsystem, a major risk involves the potential malfunction of solar panels, impacting energy production. To mitigate this risk, the team has implemented advanced GaAs-based multijunction cells with redundancy. Continuous monitoring through the Sun Tracker Algorithm ensures early detection of panel malfunctions, and autonomous recovery plans are in place to adjust the orientation of other panels to maintain continuous and efficient energy harvesting. Another identified risk pertains to lithium-ion battery failure leading to power loss. The mitigation strategy includes employing robust batteries with redundancy, real-time monitoring of battery health by the Power Management and Control Subassembly, and autonomous recovery plans that redistribute power load among working batteries.

CDH Subsystem:
In the Communication and Data Handling (CDH) Subsystem, a significant risk is associated with the potential failure of X-band High Gain Transceivers, impacting communication. To address this risk, the team has incorporated redundancy in the Telecommunications subassembly. Autonomous recovery plans guided by the Software Architecture include error detection, isolation, and recovery (FIDR) protocols to ensure continuous and reliable communication with the Deep Space Network (DSN). Additionally, there is a risk related to software-related issues affecting data processing. The team has mitigated this by incorporating redundancy in components like the RAD750 CPU and implementing autonomous recovery through real-time error detection and recovery mechanisms provided by the F’ Software Framework.

Thermal System Subsystem:
The Thermal System Subsystem addresses the challenging Martian environment with a focus on both passive and active thermal management systems. A major risk involves the potential inefficiency of the passive thermal regulation system during extreme temperature changes. To mitigate this, the team integrated aerogels for passive regulation, implemented autonomous recovery plans leveraging aerogel properties, and collaborated with the software team for additional measures during Martian nights. Another risk pertains to active thermal regulation component failure. Redundancy in heaters, radiators, and heat sinks, along with autonomous recovery plans for maintaining optimal temperatures and scattering excess heat during various Martian environmental conditions, serves as the team's strategy for risk mitigation.

GNC Subsystem:
In the Guidance, Navigation, and Control (GNC) Subsystem, the team has identified a major risk associated with the potential failure of the Inertial Sensing Subassembly, which could impact navigation. To mitigate this risk, a dual IMU configuration has been implemented, incorporating both a primary Emcore SDI50x-AF00 IMU and a backup HG1930 IMU. Autonomous recovery plans are in place to switch to the backup IMU in case of a primary system malfunction, ensuring continuous navigation and sample collection capabilities. Another risk involves Sun

Sensing Subassembly malfunctions affecting sun tracking. The team has mitigated this by incorporating three redundant sun sensors strategically placed, with autonomous recovery plans involving software readings for accurate sun tracking even in the event of sensor malfunctions.

Instrumentation Subsystem:
In the Instrumentation Subsystem, the team has considered the risk of critical scientific instrument failure impacting mission objectives. To mitigate this risk, redundancy has been integrated into key instruments, and continuous monitoring of instrument health will be conducted throughout the mission. Autonomous recovery plans are in place to reconfigure instrument operations as needed. Another risk involves data processing issues affecting scientific data collection. The team has addressed this by incorporating redundancy in the Data Computing subassembly components and implementing autonomous recovery through real-time error detection and recovery mechanisms provided by the F’ Software Framework.

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Mechanical	3	5	NEW	W	Wheel abrasion and Material Failure	Active
2	Power Generation	2	5	NEW	W	Malfunction of Solar Panels	Active
3	CDH	3	4	NEW	M	Failure of Transceivers causing no communication	Active
4	Thermal	1	4	NEW	R	Failure during extreme Temperatures	Active
5	GNC	2	5	NEW	R	Failure to Navigate correctly	Active
6	Instrumentation	1	4	NEW	M	Failure of proper data collection	Active
7	Budget	3	5	NEW	W	Mission cost is over $300M Budget	Active
8	Schedule	3	5	NEW	W	Unexpected delays cause changes in schedule	Active

Figure 37. Risk Table

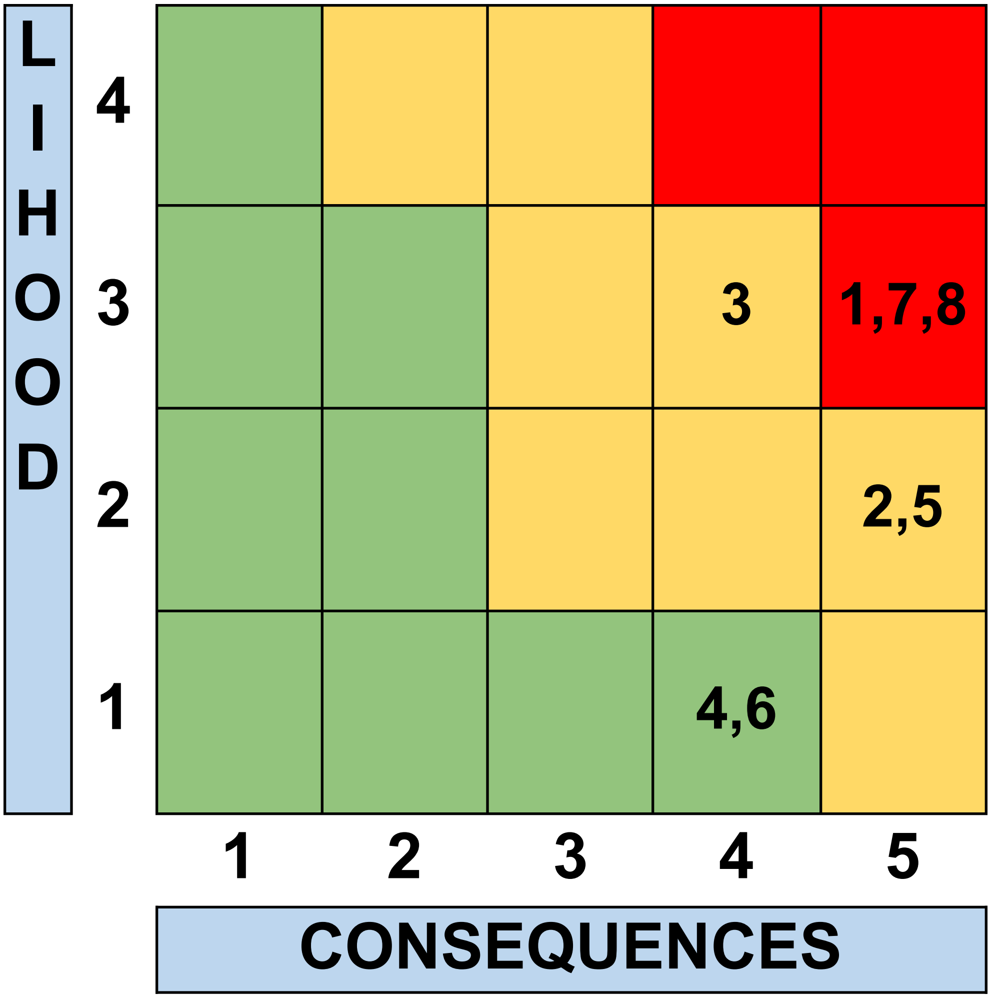


Figure 38. Consequence Table

1.5. Programmatics

1.5.1. Team Organization

The team will handle the delegation of workload, team organization, and decision-making by designating lead roles and assigning all team members to one primary and one secondary role. The team hierarchy is ordered from up to down meaning the highest decision-making power is on the left. Team members either report directly to the Project Manager/Deputy Project Manager or to a lead who then reports to the PM/DPM. Team organization is shown below).

In the instance of a conflict the conflict will be reported to the PM or DPM and a meeting will be scheduled with all individuals associated with the conflict and the PM or DPM will make a verdict resolving the conflict.

The team currently has the experience of writing documentation and many of the members are currently not knowledgeable in specific instrumentation. Still, there are many documents that each member has access to for educating how to build this mission to Mars.

Issues or disagreements may arise within the team. In the event, the team will use live discussion via Discord voice chat in order to express those differences and come to an amicable solution to any disagreements or differences in ideas and opinions.

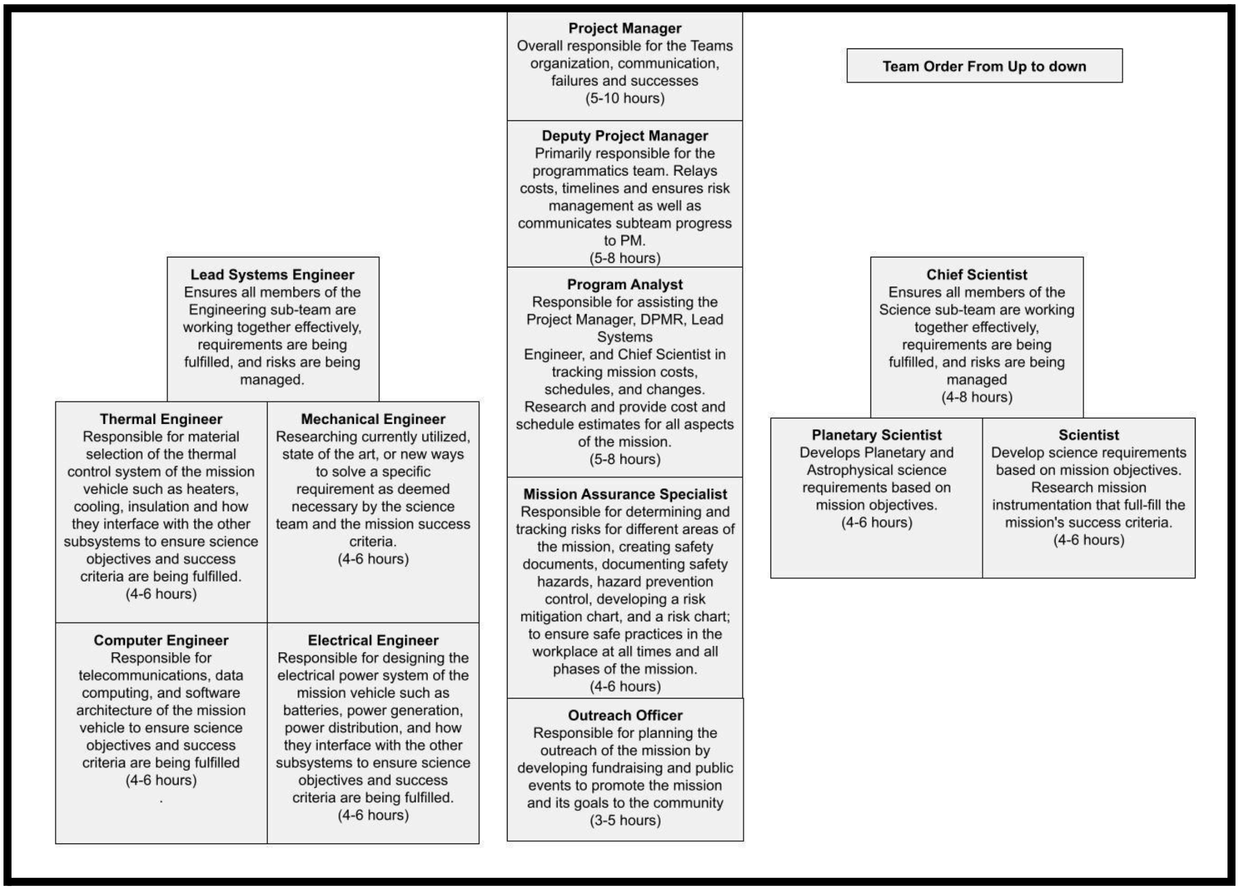


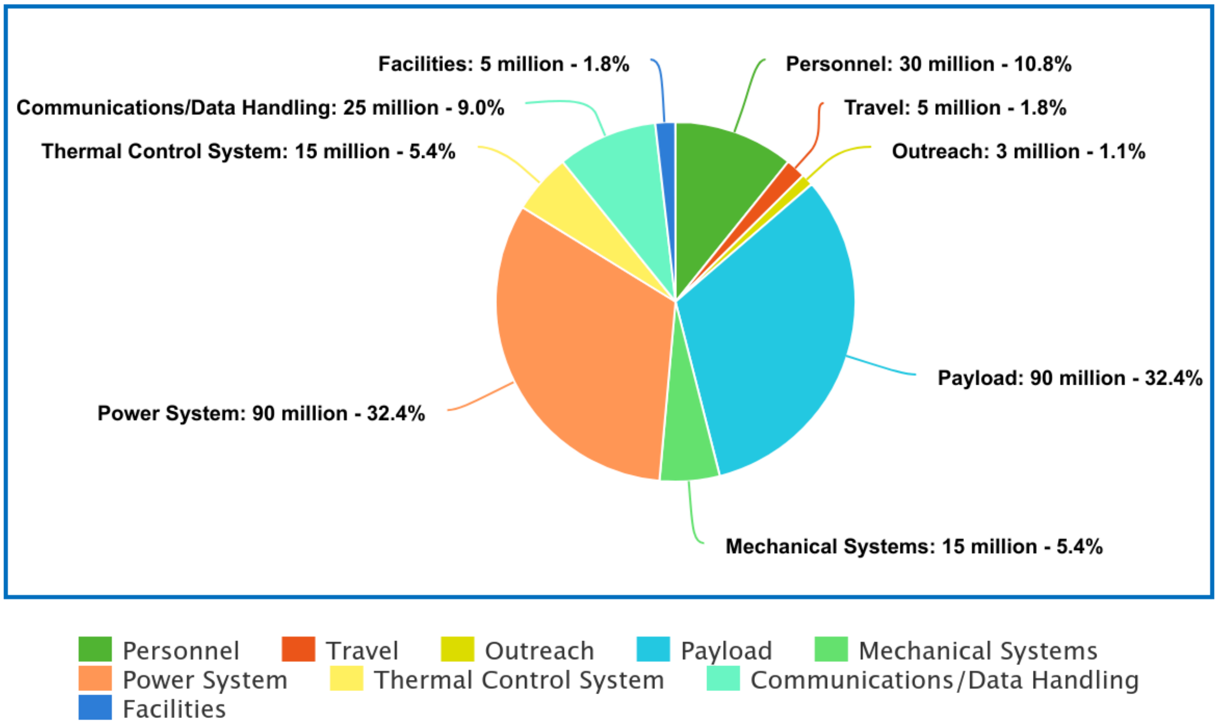
Figure 39. Organization Table

1.5.2. Cost Estimate

Mission Budget Overview

The successful execution of any space mission hinges not only on scientific and engineering prowess but also on the financial planning. The mission budget serves as the fiscal roadmap, providing a comprehensive breakdown of anticipated costs across various domains including personnel, travel, outreach, payload, mechanical systems, power system, thermal control system, communications/data handling, facilities. In this section, we delve into the intricacies of the budget, exploring the allocation of resources and the diverse methods employed to derive accurate estimates.

MCA Budget



Costs	**Budget**
Personnel	Total = **$9.96 million (min) - $16.6 million (max)** 30-50 people needed. 6-10 people per position Scientists - Need during Phases A-B and E-F. - $1,440,000 - $2,400,000 Engineers - Need during all stages (A-F) - $2,400,000 - $4,000,000 Technicians - Need during Phases C-D - $720,000 - $1,200,000 Administration - Amount remains the same during all phases - $1,800,000 - $3,000,000 Project Management - More people = more management - $3,600,000 - $6,000,000
Travel	Total = **$5 million** $2500 per person per week Account for highest costs

<table>
<tr><td>Outreach</td><td>Total = $3 million

Outreach to the audience we want to inform</td></tr>
<tr><td>Direct Costs (Payload)</td><td>Total = $90 million

WIll use NICM to get a better estimate further into the mission</td></tr>
<tr><td>Direct Costs (Vehicle)</td><td>Total = $145 million

<table>
<tr><td>Mechanical Systems</td><td>$15 million

Structure, material, mobility, robotic arms, etc.</td></tr>
<tr><td>Power System</td><td>$90 million

Batteries, solar panel, harness, distribution system, etc.</td></tr>
<tr><td>Thermal Control System</td><td>$15 million

Heaters, radiators, thermal straps, etc.</td></tr>
<tr><td>Communications/Data Handling</td><td>$25 million

Antennas, data storage, software, etc.</td></tr>
</table>

Cost estimating methods
NASA Instrument Cost Model (NICM)</td></tr>
<tr><td>Facilities</td><td>Total = $5 million</td></tr>
</table>

Figure 40. Cost Estimate Table

Margin cost

F&A %	10%
Manufacturing Margin	50%
Total Cost Margin	30%
ERE - Staff	28%

Cost Categories: Personnel

A pivotal component of the mission budget is the allocation for personnel, constituting a substantial portion of the total expenditure. With a budget of $30 million, the workforce is estimated to require 30 to 50 individuals throughout the mission phases (A-F). Scientists are crucial during Phases A-B and E-F, engineers play a continuous role from A to F, technicians contribute predominantly during Phases C-D, and administrative roles remain consistent across all phases. For scientists, we will need 6-10 people who will work for around 3 years, so this will cost $80,000 salary/year * 3 years * 6-10 people = $1,440,000 - $2,400,000. For engineers, we will need 6-10 people who will work for around 5 years, so this will cost $80,000 salary/year * 5 years * 6-10 people = $2,400,000 - $4,000,000. For technicians, we will need 6-10 people who will work for around 2 years, so this will cost $60,000 salary/year * 2 years * 6-10 people = $720,000 - $1,200,000. For administration, we will need 6-10 people who will work for around 5 years, so this will cost $60,000 salary/year * 5 years * 6-10 people = $1,800,000 - $3,000,000. For managers, we will need 6-10 people who will work for around 5 years, so this will cost $120,000 salary/year * 5 years * 6-10 people = $3,600,000 - $6,000,000. The intricacies of project management necessitate additional staffing as the team size increases.

Cost Categories: Travel

For a mission of this magnitude, the budget reserves $5 million for travel expenses. This figure accounts for a per-person weekly expense of $2500. Recognizing that travel often incurs the highest costs, this allocation ensures a robust financial buffer.

Cost Categories: Outreach

With a dedicated outreach budget of $3 million, the mission underscores the importance of communicating its endeavors to the intended audience. Effective outreach activities during each phase are vital for informing the public, stakeholders, and the scientific community.

Cost Categories: Direct Costs (Payload and Vehicle)

Direct costs encompass both payload and vehicle considerations. The payload, estimated at $90 million, employs the NASA Instrument Cost Model (NICM) to refine estimates as the mission progresses. This model, renowned for its accuracy, ensures a thorough understanding of instrument costs. Meanwhile, the vehicle, with a total budget of $145 million, breaks down into distinct components like Mechanical Systems ($15 million), Power System ($90 million), Thermal Control System ($15 million), and Communications/Data Handling ($25 million). Each subset reflects the diverse technical requirements inherent in a Martian exploration mission.

Cost Categories: Facilities

Finally, the budget reserves $5 million for facilities. These funds support the infrastructure needed for effective mission execution, encompassing testing, integration, and operational spaces.

In conclusion, the mission budget serves as a financial blueprint, intricately outlining the resources needed for a successful journey to Mars. The adoption of proven cost estimating methods, the careful allocation of funds across personnel, travel, outreach, and direct costs, attests to the meticulous planning essential for the realization of this ambitious venture. As the mission progresses, continuous evaluation and adaptation of the budget will be vital to ensure financial prudence and mission success.

1.5.3. Schedule Estimate

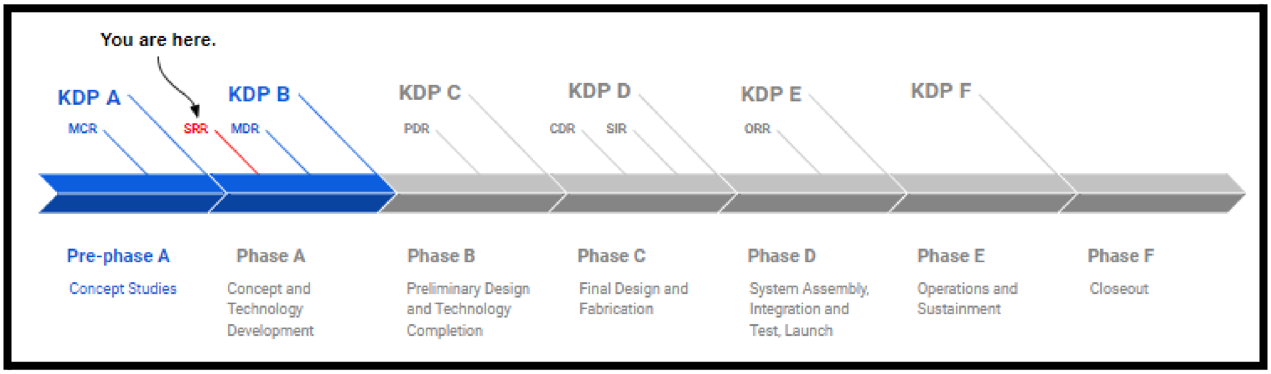


Figure 41. Schedule Table

Phase C: 12 months

- Review and update documents in previous phases (MCR, SRR, MDR, and PDR).
- Refine the preliminary design and finalize the detailed design of all components and subsystems.
- Develop/refine plans for implementation, integration, and operations.

Phase D: 12 months

- Integrate/assemble components according to the integration plans.
- Perform comprehensive system testing, including functional, environmental, and performance testing.
- Launch vehicle
- Launch date will be December 31st, 2028.

Phase E: 12 months

- Conduct launch vehicle performance assessment.
- Coordinate with launch service providers and prepare for launch campaign.
- Prepare for deactivation, disassembly, and decommissioning as planned.
- Develop final mission report
- Account for a cruise time of 240 days to Mars for an arrival date of August 28th, 2029.

Phase F: 24 months

- Archive data.
- Capture lessons learned.
- Performed analysis of returned data.

1.6. Conclusion

In conclusion, our System Requirements Review (SRR) has provided a comprehensive overview of the spacecraft design, encompassing detailed subsystem requirements, trade studies, risk analysis, and programmatic considerations. We have meticulously outlined the mission statement and requirements, laying the groundwork for subsequent stages of development.

Through rigorous trade studies and risk analysis, we have identified critical design decisions and mitigation strategies to enhance mission success probabilities. Our team has demonstrated adaptability and cohesion in handling workload, organizational structures, and decision-making processes, paving the way for efficient project management and execution.

Looking ahead, our focus shifts towards the Mission Definition Review (MDR) and subsequent milestones. We are committed to refining system designs, integrating emerging technologies, and further enhancing subsystem capabilities to meet evolving mission objectives. Additionally, ongoing cost estimation and schedule planning efforts will ensure alignment with project timelines and resource allocations.

As we embark on the next phase of development, collaboration, innovation, and strategic foresight will remain pivotal in achieving our overarching mission goals. With dedication and perseverance, we are poised to realize the full potential of our spacecraft design and contribute meaningfully to scientific exploration and discovery.

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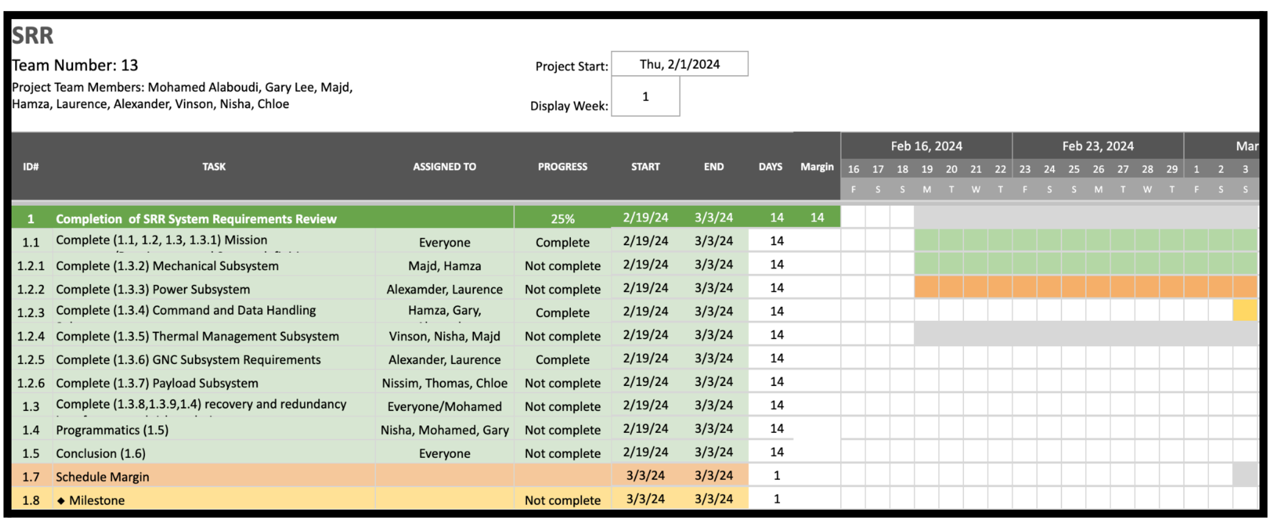
Appendix

TBD / TBR #	Item or Requirement to Complete	Timeline	Plans for Resolution
1	Complete NX CAD Drawing for Rover	2 Weeks	• Delegate NX CAD task to those interested to refine the drawing of the rover.
2	Finalize selection of landing zone	1 week	• Continue to analyze potential landing zones through JMARS. • Consider factors such as terrain, accessibility and resource availability.
3	Concept of Operations Figures	2 weeks	• Review the TBD in the Concept of Operations. • Determine which avenues to pursue in order to figure out the TBD.
4	Further Develop Cost Estimates	2 Weeks	• Implement the use of Gantt Charts • Further research cost options and look at templates provided by stakeholders.
5	Risk Assessment and Mitigation Strategy Review	1 Week	• Evaluate current risk and identify any gaps. • Develop mitigation strategies to ensure alignment with project objectives.
6	Resolution of TBDs	2 Weeks	• Resolve any remaining TBDs. • Review MCR and SRR for any fixes to be made before completion of MDR.
7	Refinement of Risk Analysis	2 Weeks	• Review methods used for identifying risks and re estimate for MDR.



SRR

Team Number: 13

Project Team Members: Mohamed Alaboudi, Gary Lee, Majd, Hamza, Laurence, Alexander, Vinson, Nisha, Chloe

Project Start: Thu, 2/1/2024

Display Week: 1

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	Margin
1	Completion of SRR System Requirements Review		25%	2/19/24	3/3/24	14	14
1.1	Complete (1.1, 1.2, 1.3, 1.3.1) Mission	Everyone	Complete	2/19/24	3/3/24	14	
1.2.1	Complete (1.3.2) Mechanical Subsystem	Majd, Hamza	Not complete	2/19/24	3/3/24	14	
1.2.2	Complete (1.3.3) Power Subsystem	Alexamder, Laurence	Not complete	2/19/24	3/3/24	14	
1.2.3	Complete (1.3.4) Command and Data Handling	Hamza, Gary,	Complete	2/19/24	3/3/24	14	
1.2.4	Complete (1.3.5) Thermal Management Subsystem	Vinson, Nisha, Majd	Not complete	2/19/24	3/3/24	14	
1.2.5	Complete (1.3.6) GNC Subsystem Requirements	Alexander, Laurence	Complete	2/19/24	3/3/24	14	
1.2.6	Complete (1.3.7) Payload Subsystem	Nissim, Thomas, Chloe	Not complete	2/19/24	3/3/24	14	
1.3	Complete (1.3.8,1.3.9,1.4) recovery and redundancy	Everyone/Mohamed	Not complete	2/19/24	3/3/24	14	
1.4	Programmatics (1.5)	Nisha, Mohamed, Gary	Not complete	2/19/24	3/3/24	14	
1.5	Conclusion (1.6)	Everyone	Not complete	2/19/24	3/3/24	14	
1.7	Schedule Margin			3/3/24	3/3/24	1	
1.8	◆ Milestone		Not complete	3/3/24	3/3/24	1	