Team 26: Endurance

Preliminary Design Review (PDR)

15 April 2024

Table of Contents

Table of Figures

Table of Acronyms

EOL	End Of Life
IO	Input/Output
MRO	Mars Reconnaissance Orbiter
DSN	Deep Space Network
UHF	Ultra High Frequency
CDH	Command and Data Handling
TRL	Technology Readiness Level
EPS	Electrical Power System
TCS	Thermal Control System
VCHP	Variable Conductance Heat Pipe
MOMA	Mars Organic Molecule Analyzer
MI	Microscopic Imager
DPMR	Deputy Project Manager of Resources
PM	Project Manager
MCCET	Mission Concept Estimate Tool
KDP	Key Decision Points
GNC	Guidance, Navigation, and Control
CDH	Command and Data Handling
FMEA	Failure Mode and Effect Analysis

MGS	The Mars Global Surveyor
JPL	Jet Propulsion Laboratory
HGA	High Gain Antenna
EEL	Endurance Exploration Laboratory
NASA	The National Aeronautics and Space Administration
PPE	Personal Protective Equipment
HGA	High Gain Antenna
MUREP	Minority University Research and Education Project
MAIANSE	Minority University Research and Education Project American Indian and Alaska Native STEM Engagement
CoECI	Center of Excellence of Collaborative
KMP	Knowledge Management Plan
RFAs	Request for Actions
UHF	Ultra-High Frequency
XHG	X-Band High-Gain
XLG	X-Band Low-Gain
PDR	Preliminary Design Review

1. Mission Overview

1.1. Mission Statement

The Endurance mission aims to investigate the surface and subsurface of Mars to better understand its geological history and the planet's potential for fostering past and present life. The mission will deploy a rover equipped with onboard instruments, including the mass spectrometer from the Mars Organic Molecule Analyzer (MOMA) instrument suite and the Microscopic Imager (MI). The MOMA-MS will analyze the chemical composition of organic compounds, while the MI will gather data through high-resolution surface imaging. By detecting certain sediment isotope fractionations such as sulfur, carbon, and hydrogen, and determining the mineral composition of Martian regolith near ice deposits, the Endurance mission seeks to analyze the possibilities of strong biosignatures on Mars and reveal insights into locations and periods when Mars may have supported life. Data on ice deposits layering, age, composition, and origin will also provide insights into Mars' climatic and geologic history. The onboard instrument suite is optimized to provide essential data to achieve customer constraints and mission goals of assessing past habitability potential and resources to support future human exploration through subsurface ice characterization. Each subsystem is designed to operate under harsh Martian conditions and address the technical challenges of Mars exploration, ensuring the rover's ability to conduct in-depth analysis and fulfill all three scientific objectives. The mission adheres to strict budget and deadline constraints by following a comprehensive schedule estimate and cost analysis, ensuring efficient resource utilization and timely completion of milestones. Findings from this mission will determine future Mars landing sites and guide the search for life and water resources as understanding of the red planet's potential for past or present habitability grows.

1.2. Science Traceability Matrix

The Science Traceability Matrix (STM) demonstrates the flow down from science goals and objectives to mission requirements and instrumentation selection. It is used to track whether the science objectives of the Endurance mission align with NASA's goals and assesses the suitability of the selected instruments for achieving these objectives. Science objectives are derived from the science goals and are attained through science measurement requirements, which are the parameters and observables. The performance requirements of each instrument onboard the payload were evaluated to determine the optimal performance needed to collect valuable data during the Endurance mission.

Figure 1: Science Traceability Matrix

Science Goals	Science Objectives	Science Measurement Requirements

		Physical Parameters	Observables
Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions. Investigate the chemical compositions and chemical reactions in or around the subsurface ice of terrestrial planetary bodies to advance knowledge about the resources that support habitability beyond Earth.	Detect certain sediment isotopic fractionation to determine possibilities of strong potential biosignatures on Mars	Define the isotopic fractionation of carbon, nitrogen, oxygen, hydrogen, and sulfur within different stratas of a Martian evaporite	Detect and record the isotopic ratios of elements within a 1m depth
	Determine the mineral composition of Martian regolith found near subsurface ice deposits	Identify carbon-containing minerals in the thick regolith	Detect biomarkers like amino acids in carbon-containing minerals under 210-900 nm of UV irradiation
	Determine the age of subsurface ice deposits, erosion, and volcanic activity on Mars	Identify sedimentary layers from erosion and volcanic activity entrained in ice	Collect absorbance bands from ice deposits

Figure 2: Instrument Performance

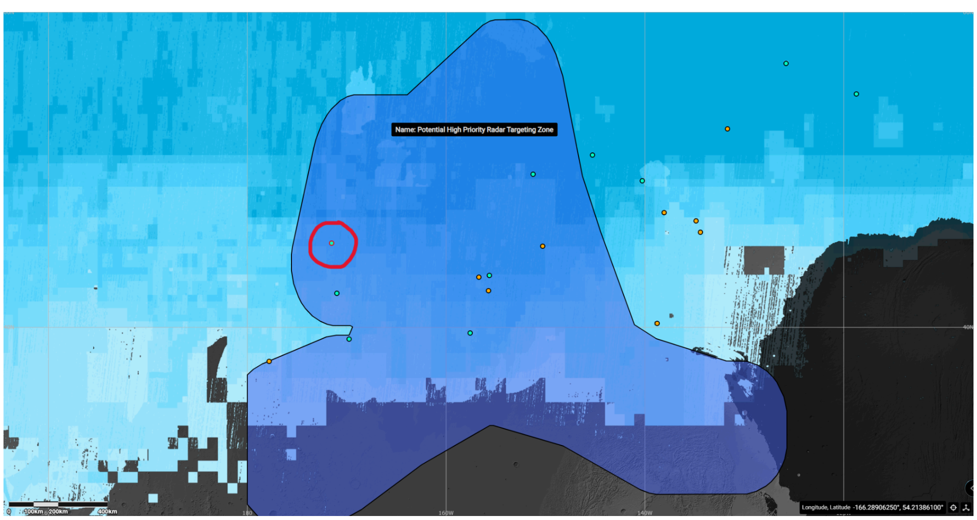
Instrument Performance Requirements		**Predicted Instrument Performance**	**Instrument**	**Mission Requirements**
Resolution:	10 ppb	10 ppb	MOMA Mass Spectrometer	MR-1 The Endurance rover shall investigate regions of Mars that demonstrate potential suitability for past and present habitability.
Mass range:	50-500u	50-450u		
Output wavelength:	266 nm	266 nm		
Peak irradiance:	>30 MW/cm2	>30 MW/cm2		MR-2 The Endurance rover shall analyze Martian water sources to understand their composition and potential for supporting life.
Spectral Range	415-650 nm	400-700 nm	Microscopic Imager	
Field of View	1024 x 1024	1024 x 1024 pixels		
Depth of Field	>±3 mm	>±3 mm		PAY-1 The science objectives shall be achievable with no more than two science instruments.
Spatial resolution:	<100 µm	<100 µm		
				PAY-2 Instruments shall not exceed physical constraints.

1.3. Summary of Mission Location

In selecting the optimal landing site for the Martian ice deposits investigation mission, various criteria such as geological diversity, subsurface ice potential, mineralogical signatures, atmospheric conditions, regolith thickness, accessibility/safety, and biosignature potential were considered. Mineralogical signatures provide insights into past water activity, while atmospheric conditions help assess the impact of solar radiation and dust on water cycling. Greater regolith thickness reduces vulnerability to cosmic radiation, crucial for preserving potential signs of ancient Martian life. Aligned with the Mission Task Criteria, the selected landing site adheres to specific latitude and longitude constraints, focusing on areas no greater than 60 degrees latitude, north or south. It falls within a Potential High Priority Radar Targeting Zone, and is at depths of 0-1m or within 10km of impact-exposed ice locations. This criterion is coupled with the essential requirement for remote sensing data, particularly CRISM data from JMARS, to provide solid evidence of water ice at the chosen site.

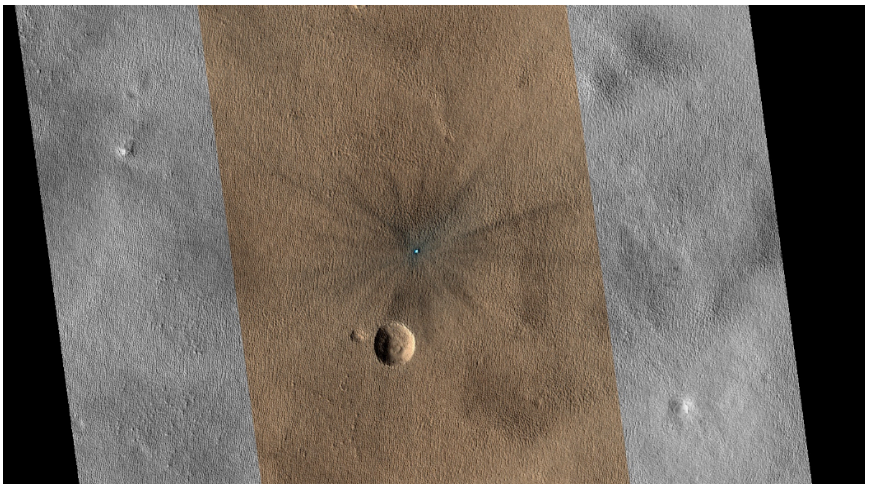
The chosen landing site is a fresh impact site formed between July 2004 and June 2008 located within Arcadia Planitia. The main motivation behind selecting a location within the greater Arcadia Planitia is the presence of shallow subsurface water ice. Arcadia Planitia, named after the Arcadia region of ancient Greece, features lava flows and aeolian materials, spanning roughly 40–60° North and 150–180° West. It transitions from thinly to heavily cratered terrain and shows signs of glaciation, indicating potential ground ice. Expanded secondary craters suggest widespread ice presence, making it a target for Endurance's landing and science sites. The impact crater of interest is located at a latitude (centered) of 46.151° and a longitude (East) of 188.501°.

Figure 3: SWIM map of Arcadia Planitia, with ice-exposing impact circled in red (Credit: SWIM2020)



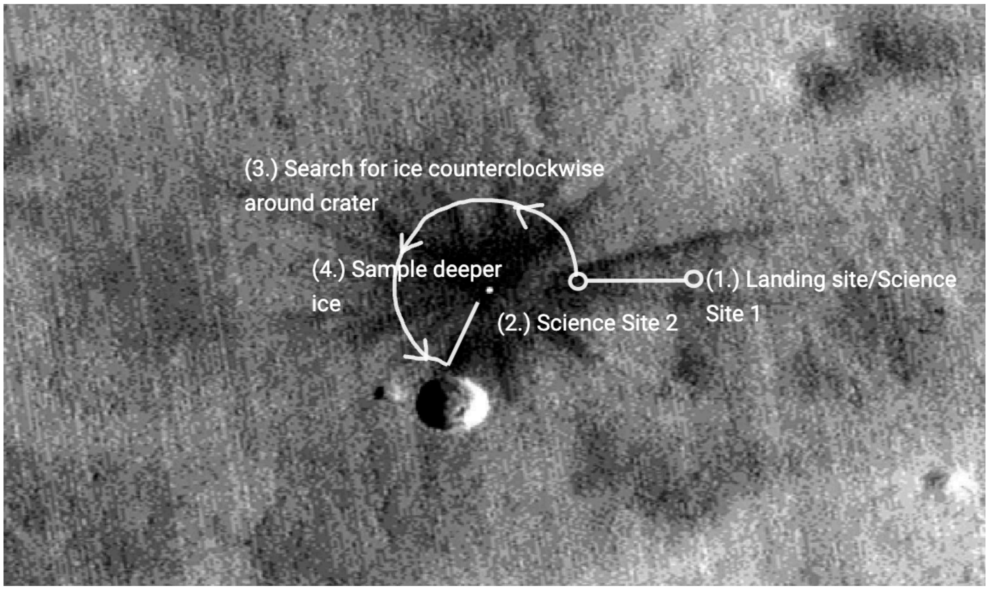
Impact craters, particularly secondary craters, are crucial locations for identifying exposed surface ice on Mars. Primary craters can act as windows revealing subsurface properties, including the presence and abundance of water ice. Models suggest that the observed sublimation of ice implies a relatively pure subsurface ice layer, potentially overlying ice-rich regolith. This particular secondary crater shows expanded morphologies, likely caused by sublimation of excess ice.

Figure 4: HiRISE image of crater PSP_010861_2265



Overall, this mission site will allow the team to investigate the chemical compositions and chemical reactions in or around the subsurface ice of Mars to advance knowledge about the resources that support habitability beyond Earth. The following shows the site location's mission events (image is ~2000m across for reference):

Figure 5: Mission Site & Path of Operations (Credit: JMARS)



1.4. Mission Requirements

The Mission Requirements table, shown in Figure 1, outlines the highest-level requirements necessary for the success of the Endurance Rover mission. This table highlights constraints and parameters specified by NASA, with several constraints related to the spacecraft mass, volume, cost, and science instrumentation; parameters regarding transportation, site selection, and landing specifications; and clarification of prohibited material and the spacecraft's launch date. In addition to customer-specific requirements, Figure 1 includes requirements derived by Team 26, which outlines constraints and parameters related to the mission lifespan and top-level requirements for each sub-system, including Mechanical, EPS, Thermal, GNC, CDH, and Payload. These sub-system requirements highlight aspects of the cost, size, and mass of each system, as well as other aspects, such as outlining their primary function, and identifying what duration of time they are expected to remain operational. This table partitions the derived requirements into sections, which include the following: Mission Reqs, Mechanical Reqs, EPS Reqs, Thermal Reqs, GNC Reqs, Payload Reqs, Transportation Reqs, Landing Site and Operations Reqs, and CDH Reqs. In addition to defining the requirement and the rationale for each, the Figure 1 also defines the parent and child requirements, as these high level requirements are expected to be further broken down as the mission progresses. Furthermore, the Mission Requirements table provides a "Verification Section", conveying how Team 26 plans on verifying that a specific requirement has been sufficiently satisfied, a "Relevant Subsystem" section, outlining the subsystem a particular requirement may pertain to, and a "Req met?" which defines whether a certain requirement has been met.

Figure 6 - Mission Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mission Reqs							
MR-1	The Endurance rover shall investigate regions of Mars that demonstrate potential suitability for past and present habitability.	Provided by Mission Document.	Customer	All	Demonstration	Science	Met
MR-2	The Endurance rover shall analyze Martian water sources to understand their composition and potential for supporting life.	Provided by Mission Document.	Customer	All	Demonstration	Science	Met
MR-3	The launch date shall be no later than December 31st, 2028, to ensure an arrival date of August 28th, 2029.	Provided by Mission Document.	Customer	All	Analysis	All	Met
MR-4	The total mission cost shall not exceed $250M, excluding launch or cruise costs.	Provided by Mission Document.	Customer	All	Analysis	All	Met
MR-5	The Endurance rover shall have a mission lifespan of 240 days.	Minimum amount of time required to acquire sufficient data to satisfy the mission objectives.	MR-1, MR-2	All	Demonstration	All	Met
MR-6	The spacecraft shall not exceed a total mass of 45 kg.	Provided by Mission Document.	Customer	All	Analysis	All	Met
Mechanical Reqs							
MEC-1	The spacecraft shall not exceed a stored configuration volume of 100 cm x 100 cm x 100	Provided by Mission Document.	Customer	All	Analysis	All	Met

	cm.						
MEC-2	All mechanical components shall maintain structural integrity throughout the duration of the mission.	Mechanical component degradation could impair all rover operations.	MR-1, MR-2, MR-5	MEC-1	Demonstration	MEC	Met
EPS Reqs							
EPS-1	The spacecraft shall not include an RTG, and any radioactive material used shall not exceed a cumulative mass of 5g.	Provided by Mission Document	Customer	All	Inspection	EPS	Met
EPS-2	All hardware for the Electrical Power System shall not exceed a total mass of 12kg	The rover must remain at or below the 45 kg threshold.	MR-1	EPS	Inspection	EPS	Met
EPS-3	The Endurance Rover shall supply continuous power to subsystems as needed for the entire mission duration.	All subsystems require electrical power to operate.	MR-1, MR-2, MR-5	EPS-3.1, 3.2, 3.3, 3.4, 3.5	Demonstration	EPS	Met
Thermal Reqs							
TCS-1	The spacecraft shall not exceed extreme temperatures -40ºC to 50ºC.	The spacecraft has to be able to withstand the temperatures on Mars	MR-5	All	Test	TCS	Met
TCS-2	The spacecraft shall be resistant to IR radiation.	The spacecraft has to avoid being destroyed by radiation	MR-5	TCS-2.1	Test	TCS	Met
GNC Reqs							
GNC-1	The GNC subsystem shall not exceed a mass of 2.25kg	Less than 5% of total rover mass.	MR-1	GNC	Inspection	GNC	Met
GNC-2	The GNC subsystem shall not exceed a stored configuration volume of 36^3cm.	Less than 5% of total rover volume.	MEC-2	GNC	Inspection	GNC	Met
GNC-3	The total GNC subsystem cost shall not exceed $15M	Less than 5% of total rover cost.	MR-4	GNC	Inspection	GNC	Met
GNC-4	Ensure the rover can autonomously navigate, guide, and control movements on Mars.	Enables thorough investigation of Mars.	MR-1, MR-2	GNC	Test	GNC	Met
GNC-5	The rover shall gather real-time and accurate data on terrain and obstacles throughout the mission.	Enables the rover to autonomously navigate and operate on mars terrain.	MR-1, MR-2	GNC-5.1, GNC-5.2	Test	GNC	Met
Payload Reqs							
PAY-1	The science objectives shall be achievable with no more than two science instruments.	Provided by Mission Document.	Customer	All	Analysis	Science	Met
PAY-2	Instruments shall not exceed physical constraints	Adhere to rover constraints	MR-1	PLD-2.1, PLD-2.2, PLD-2.3, PLD-2.4	Inspection	Science, Mechanical	Met
Transportation Reqs							
TR-1	The spacecraft shall be designed for transportation to Mars as a secondary payload on a primary launch vehicle.	Provided by Mission Document.	Customer	All	Test	All	Met
TR-2	The spacecraft shall be maintained in minimal power and thermal conditions during transit by the primary vehicle's power supply.	Provided by Mission Document.	Customer	All	Test	EPS, Thermal	Met
TR-3	The spacecraft shall not collect science data during transit.	Provided by Mission Document.	Customer	All	Demonstration	Science	Met
Landing Site & Operations Reqs							
LSO-1	The spacecraft's mission operation shall begin after landing at the target destination on the Martian surface.	Provided by Mission Document.	Customer	All	Demonstration	All	Met
LSO-2	The mission team shall design the rover in accordance to the selected landing site.	Provided by Mission Document.	Customer	All	Demonstration	All	Met
LSO-3	The landing site shall be at any longitude and no greater than 60 degrees latitude, north or south.	Provided by Mission Document.	Customer	All	Demonstration	All	Met
LSO-4	The landing site shall be within a Potential High Priority Radar Targeting Zone.	Provided by Mission Document.	Customer	All	Demonstration	All	Met
LSO-5	The landing site shall be within 10km (radial) area that the SWIM Maps show as having water subsurface ice at 0-1m depth or be within 10 km of one of the identified impact-exposed ice locations.	Provided by Mission Document.	Customer	All	Demonstration	All	Met

LSO-6	The landing site shall have remote sensing data that suggests evidence of water ice identified using JMARS.	Provided by Mission Document.	Customer	All	Demonstration	All	Met
CDH Reqs							
CDH-1	The spacecraft shall send and receive communications to and from Earth via the MRO and DSN.	Provided by Mission Document.	Customer	CDH	Test	CDH	Met
CDH-2	The spacecraft shall adhere to the communication window and data volume allocated by the MRO.	Provided by Mission Document.	Customer	CDH	Test	CDH	Met
CDH-3	The rover shall utilize radiation-hardened components to meet defined Martian radiation exposure thresholds.	Protects the rover's electronic systems against the harmful Martian solar and cosmic radiation.	MR-5	CDH	Inspection	CDH	Met
CDH-4	The rover shall have an onboard computer.	Provides the primary computational power needed for all rover functions.	MR-1, MR-2	CDH-4.1, CDH-4.2, CDH-4.3, CDH-4.4, CDH-4.5	Test	CDH	Met
CDH-5	The Endurance Rover's CDH sub-system shall remain operational for the duration of the mission.	Guarantees the rover's sustained operation throughout the entire mission life.	MR-1, MR-2, MR-5	CDH	Demonstration	CDH	Met

1.5. Concept of Operations (ConOps)

Launch & Transit

The Endurance Mission is scheduled to launch on December 31, 2028, from Cape Canaveral. Following a 240-day cruise through space, the mission's Entry, Descent, and Landing (EDL) vehicle will arrive at Mars and touchdown in Arcadia Planitia on August 28, 2029.

Initial Operations at Landing Site - Crater Commencement Point

Upon landing, the Endurance rover will initiate a series of health and communication checks to ensure all systems, including power distribution, thermal controls, sensor telemetry, and communication capabilities with the Mars Reconnaissance Orbiter (MRO) and Earth-based mission control, are fully operational. The rover will capture initial panoramic images of its immediate surroundings to document the EDL vehicle and landing terrain. Endurance will then conduct its first scientific investigations at the Crater Commencement Point. This includes deploying its robotic arm to test the drill and instruments on Martian soil to verify operational integrity and the rover's ability to transmit scientific data back to mission control.

Site 2 - Permafrost Plateau

Endurance will traverse approximately 1 km to reach the Permafrost Plateau. Upon arrival, the rover will explore a 20 x 20 meter designated area to identify an optimal drilling site. The rover's primary task here will be to drill through the Martian regolith to access subsurface ice. Images of the drill site will be sent to mission control for confirmation before sampling begins. The collected samples will be analyzed using the onboard mass spectrometer to study the chemical composition of the ice, which could provide insights into the historical climatic conditions of Mars. The solar panels will be deployed throughout this operation to maximize energy intake.

Site 3 - Glacier Gateway

After completing studies at Permafrost Plateau, Endurance will make its way to Glacier Gateway. This site will involve extensive use of the Microscopic Imager to capture detailed textures of the Martian surface and subsurface ice. The focus will be on detecting sediment layering and understanding the stratigraphy, which can reveal past environmental conditions and potential habitability. The rover will stay stationary for extended periods to conduct thorough imaging and chemical analysis of collected samples.

Final Phase – Ice Core Cove (Crater Interior Exploration)

In the final phase of the mission at Ice Core Cove, Endurance will descend into the crater itself, navigating steep and challenging terrain to reach scientifically significant locations within the crater rim. This phase will focus on in-depth geological and mineralogical studies, utilizing all onboard instruments to conduct a comprehensive survey of the crater's interior. Over approximately 10 days, the rover will collect, analyze, and transmit data on the mineral composition and potential biosignatures from different layers exposed within the crater.

Communication Protocol

As described by NASA, the communications from the Endurance Rover will be sent to Earth via the MRO, which will be received by the DSN. The MRO will pass overhead every 112 minutes for a communication window of 6 minutes, and the rover may only relay 250 MB worth of data to Earth every 24 hours. Provided these constraints, the Endurance Rover will be relaying routine health checks every 112 minutes, which provide a comprehensive status summary evaluating its power systems, communication links, data processing units, navigation sensors, environmental controls, structural integrity, and onboard instruments. In tandem to relaying routine health checks, the Endurance Rover will consistently offload any science data that may be collected. Data offloading to the MRO will occur continuously throughout the duration of the mission for a total of 12 data relays every 24 hours, where 240 MB will be allocated to science data and 10 MB dedicated to health checks. Allocating 10 MB to health checks, which are relatively light-weight, will ensure health evaluations are always received and not impeded by reaching data caps.

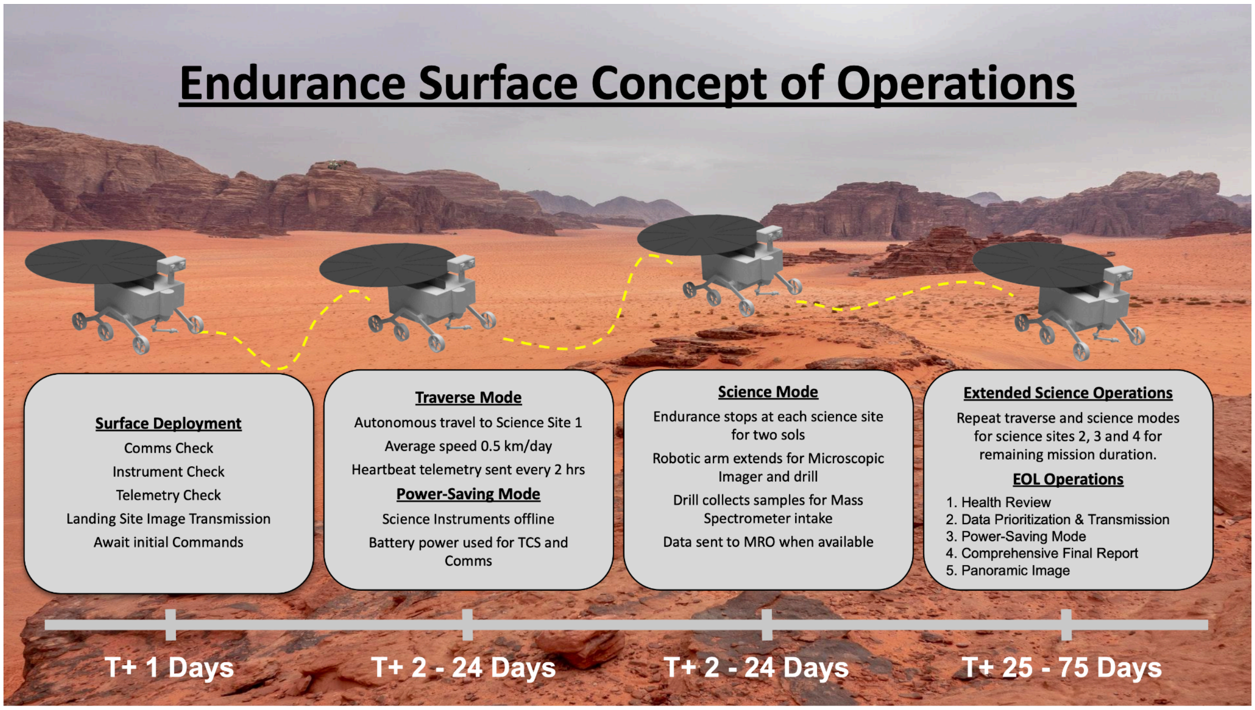
End-of-Life (EOL) Operations

In the unfortunate event where the Endurance Rover loses significant functionality or encounters insurmountable obstacles, various EOL operations have been outlined to address such instances. These functionalities prioritize redundancies and automated safeguards to protect the rover and its scientific data, taking into account the harsh Martian environment and the inevitable delay in communication between Mars and Earth. The first step in EOL operations is to perform a mission assessment. The Endurance Rover will conduct a comprehensive health review, determining the operational status of all subsystems and payloads. This information will enable Mission Control and the Endurance Rover to evaluate ongoing science objectives versus remaining capabilities. In the event communication is lost, the rover will perform pre-programmed routines to re-establish contact. This may include driving in circles until connection is made with Earth or backtracking to prior locations where connection was established. If it has been determined that functionality has been compromised, data prioritization and transmission will ensue. This entails prioritizing the transmission of all valuable scientific data stored on the rover where optimizing communication windows with Earth to ensure maximum data retrieval will be crucial. As data prioritization and transmission is underway, the Endurance Rover will initiate Power-Saving Mode where it will shut down non-essential systems and instruments to conserve energy and extend the life of whatever crucial functionality that may still be available. Once the rover has transmitted all vital data and it has been determined that the rover is approaching inoperability, the Endurance Rover will send a comprehensive final report of the mission’s scientific findings and rover status. The rover will then proceed to capture one last panoramic image and that position will be the rover’s final resting place.

Surface Concept of Operations Graphic

Accompanying the detailed description of the Endurance Mission's Concept of Operations above, the graphic below provides an essential visual aid that complements the text with a timeline and operational modes of the rover. This illustration includes key modes such as Surface Deployment, Traverse Mode, Power-Saving Mode, Science Mode, Extended Science Operations, and the End-of-Life (EOL) operations. This graphic serves to present a simplified yet comprehensive overview of how the Endurance Rover will manage its tasks, energy, and scientific objectives over the course of its journey on Mars.

Figure 7: Surface Concept of Operations



1.6. Vehicle Design Summary

Figure 8: Render of Endurance CAD Model

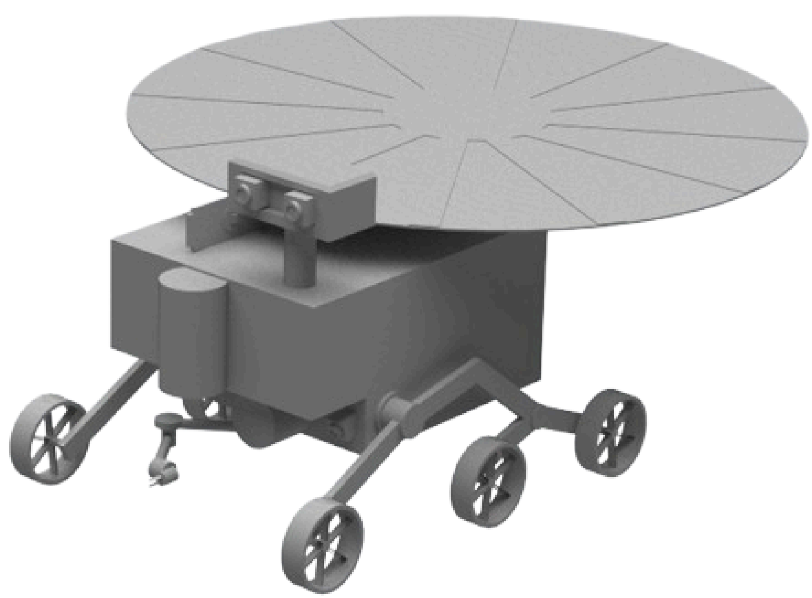


Figure 9: Mass Volume Power Table

Subsystem	Mass (kg)	Stowed Volume Container (cm)	Max Power Draw (W)	CER (Budget)
EPS	8.2	20x20x5 + 2*(4x4x6)	N/A	7193.188678
TCS	5	10 x 10 x 10	50	1741.391542
MECH	10	58 x 52 x 38 (chassis shelled)	90	5843.192845
CDH	4	20 x 20 x 15	30	4843.096152
GNC	3	17 x 17 x 17	10	3921.621702
Payload	12	20 x 20 x 25	70	17121.2825
TOTAL	**42.2**	**WILL FIT IN 100x100x100cm**	**250**	

1.7. Science Instrumentation Summary

The Endurance mission employs two science instruments, the first being the Mars Organic Molecule Analyser Mass Spectrometer (MOMA-MS) and the second being the Microscopic Imager (MI). Both the MOMA-MS and the Microscopic Imager are uniquely equipped to fulfill the mission's science objectives revolving around the search for biosignatures, the analysis of Martian geology, and the study of the Martian environment.

The MOMA is a multi-faceted instrument that is highly capable at analyzing organic Martian materials. It utilizes a combination of advanced techniques including a Laser Desorption Mass Spectrometer in order to perform its tasks. The LDMS approach involves the use of ultraviolet (UV) laser pulses to desorb and ionize organic compounds. In this way, the molecular bonds of the organic compound are preserved, empowering the MOMA to detect complex organic compounds in low concentrations. Its capabilities here empower the Endurance Mission's objective to detect potential biosignatures and understand the environment of Mars.

The Microscopic imager is a highly reputable high-resolution imaging tool designed to capture detailed visual data of the Martian surface at a microscopic level. It maintains a resolution capability of 30 microns per pixel across a 31 x 31 mm field of view. The MI enables the Endurance Mission to obtain quality geological and mineralogical insights. It operates using solar illumination and incorporates a retractable dust cover with a tinted orange Kapton window to enhance color information capture within a specific spectral bandpass. By providing reliable imaging, the MI enables better understanding of the characteristics of subsurface ice deposits, erosion patterns, and volcanic activity. The extra context provided by the MI also aids in interpreting data collected by MOMA, linking visual geological features with chemical analyses.

These two instruments, MOMA and MI, are seamlessly integrated into the rover's payload subsystem, and operate within the stringent constraints of weight, power, and environmental conditions imposed by the Martian landscape. Their combined capabilities will significantly advance humanity's understanding of Mars, potentially revealing conditions favorable for past life and informing future manned missions to the Red Planet. Their combined capabilities embody the scientific heart of the Endurance mission, positioned to investigate and unlock the secrets of Martian geology and atmosphere.

1.8. Programmatic Summary

1.8.1. Team Introduction

Anna Diaz

Anna Diaz is a Business Administration student at California State University, Northridge. Anna is a research fellow at the CSUN Autonomy Research Center, and served as the Project Manager and a Mechanical Engineer during her time participating in the NASA L'SPACE MCA Academy. Anna has had extensive leadership experience as part of a winning MITTIC MUREP competition team and as the President of the Rotaract Business Club at Santa Monica College. Anna is a former NASA and Boeing intern with a passion for innovation, leadership, and aerospace.

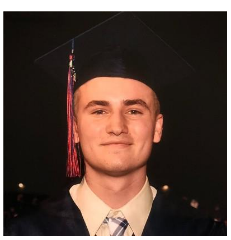
Jimmy Fowler

Based in Seattle, Washington, Jimmy Fowler is an Aerospace Engineering student at the University of Washington. Throughout the NASA L'SPACE MCA Academy, Jimmy served as the Lead Systems Engineer, demonstrating his leadership skills and extensive engineering knowledge. He is a lead at the University of Washington's Husky Flying Club, serving as the Flight Operations Manager. He previously interned with Boeing as a Configuration Aerodynamics Engineer. Jimmy has also served as a Controls and Electronics Engineer at the Society for Advanced Rocket Propulsion.

Tiffany Au

Tiffany Au is a biological sciences and computer science undergraduate student at the University of California, Irvine. Tiffany has dutifully served as a senior advisor for the United Abacus Arithmetic Youth Association, empowering middle and high school students to enhance their logical reasoning and mathematical skills for over four years. Tiffany was the lead scientist during her time at the NASA L'SPACE MCA Academy, working alongside team members fostering her professional and academic leadership experience.

Bryce Verberne



Bryce Verberne holds an Associate of Science in Computer Science and is pursuing a Bachelor's Degree in the same field at Arizona State University, concentrating in Software Engineering. He has appeared on both Dean's List and the President's Honor List, and is a member of the Phi Theta Kappa Honor Society. As a Computer Science teacher at Generation Tech Support, Bryce taught various tech-related subjects to students, including programming, networking, algorithms, IT, and more. At NASA's L'SPACE MCA Academy, he served as a CDH engineer and Deputy Project Manager of Resources, enhancing his leadership and interdisciplinary skills.

Jason Chau

Jason Chau is a Computer Engineering undergraduate student at the University of California, Riverside. During his time in the NASA L'SPACE MCA Academy, he served as the team's Outreach Officer and a scientist. Jason has prior experience serving as a volunteer for the Monterey Park Historical Museum, where he exhibited his strong passion for education and historical preservation. Jason is also a member of the Highlander Space Program and the Association for Computing Machinery, where he participates in engaging meetings and events discussing programming and rocketry.

Yuval Noiman

Yuval Noiman is an undergraduate student at California State University, Fullerton. During his time at the NASA L'SPACE MCA Academy, Yuval served as the team's Mission Assurance Specialist and as a thermal engineer. Yuval developed comprehensive communication, leadership, and interdisciplinary skills working with both engineering and programmatics. Yuval has also appeared on the Dean's List multiple times. In addition, as a Computer Science Tutor at his school, Yuval has assisted multiple students in programming and understanding difficult concepts.

Daniel Kang

Daniel Kang is an aerospace engineering undergraduate student at California State University, Long Beach. As a member of CSULB's liquid bi-propellant rocketry club, Daniel is serving as a member of the computational fluid dynamics team. Daniel is shadowing for the Beach Launch Team, preparing for his role as the business lead. During his time at the NASA L'SPACE MCA Academy, Daniel served as a mechanical engineer and scientist, enhancing his research and communication skills.

Jesse Ramirez

Jesse Ramirez is a Mechanical Engineering student at the University of California, Berkeley. Jesse has extensive experience working on engineering projects throughout his time as a student at Berkeley. Notably, Jesse has participated in a break analysis subteam through the Solar Vehicle Team and the propulsion subteam of Space Technologies and Rocketry (STAR), both hosted by UC Berkeley. During his time at the NASA L'SPACE Academy, Jesse served as a thermal and mechanical engineer.

Natalia Moreno

Natalia Guillen Moreno is an undergraduate Aerospace Engineering student at California State Polytechnic University, Pomona. Natalia interns at Dicronite, contributing to NASA's space program, and is active in her university's UAV club. She also is an online tutor through Peerlinc, where she teaches calculus and physics to highschool students. Natalia was a GNC Engineer during her time at the L'SPACE MCA Academy, growing her knowledge in navigation and control systems and collaborating with other inspiring students.

Henok Woldesenbet

Henok Woldesenbet is a Computer Science student at the University of Washington. Henok served as a CDH engineer and scientist during his time at the NASA L'SPACE MCA Academy. Henok is an alumni of the NASA L'SPACE NPWEE Academy, where he worked as a software engineer. Henok is an ambassador for Extern, has held the position of Student Government Officer for Technology at Edmonds College, and has prior experience as a software engineer through his tenure in the Google Summer of Code program. Henok volunteers as an Open Source Developer for GitHub, and actively participates in the organizations Management Leadership for Tomorrow and ColorStack.

Ali Kayani

Ali Kayani is an Informatics undergraduate student at the University of California, Irvine. During his time participating in the NASA L'SPACE MCA Academy, Ali served as a CDH and GNC engineer. During his time as a social media manager for KicksOnFire.com, Ali developed keen problem solving abilities and communication skills. Ali has grown his teamwork and organizational skills extensively during his time with L'SPACE.

Edward Henriquez

Edward Henriquez is a Computer Software Engineering student at the University of California, Irvine. Edward has worked as a data analyst for CSU

Fullerton, supply chain manager for DaVita Kidney Care, and as a technical support engineer intern for Tenant. During his time at the NASA L'SPACE MCA Academy, Edward served as the Program Analyst and a CDH engineer. Edward has developed extensive experience in research, data handling, and engineering.

1.8.2. Team Management Overview

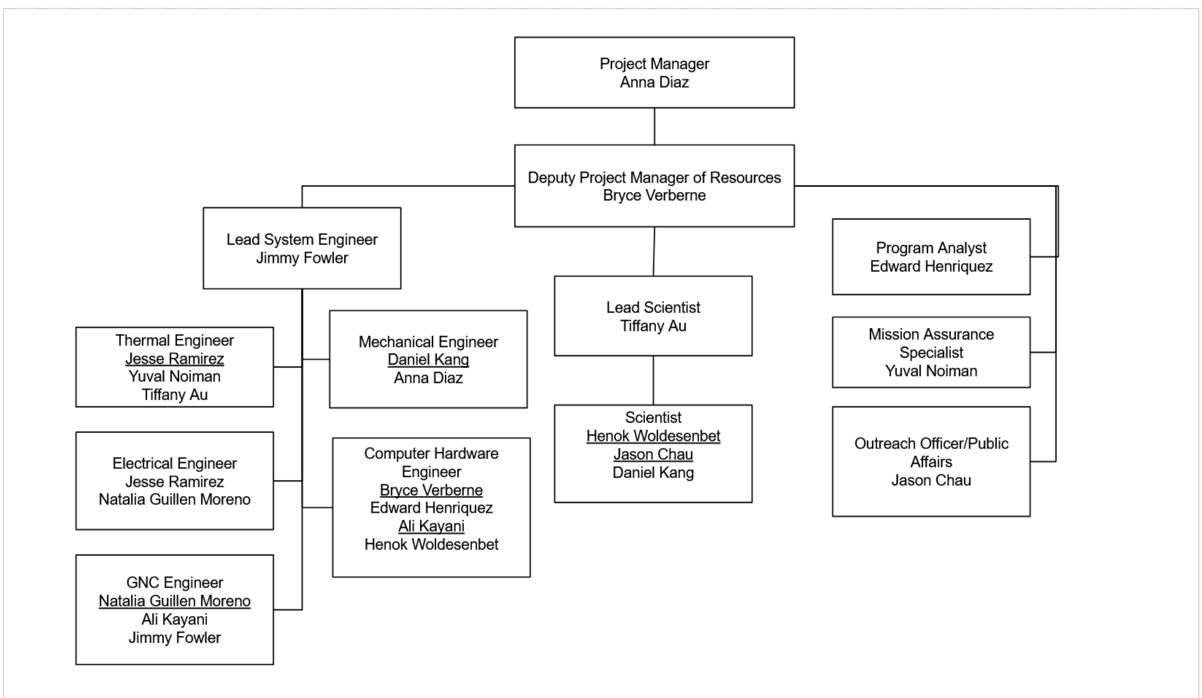
The team has handled the workload by implementing organizational tools, conducting regular meetings, and following an established decision-making process. To increase member productivity and work distribution, assignment trackers have been created with Google Sheets to allow team members to voluntarily assign themselves to sections of each deliverable and keep live updates on their progress. The status of the project was kept up through four core status updates. "Not started," "In progress," "Need help," and "Done" where the primary statuses team members could utilize to notify the team leads and other team members about their progress. Each week, the team gathered in an "All-Hands Meeting," which consisted of all subsystems. Throughout the week, three slotted times were identified by the team leads for utilizing the Discord Voice Channel feature so that team members could join in if they had questions or worked on tasks alongside one another.

The decision-making process employed relies upon the importance of tasks. Short, non-mission critical tasks are made through autocratic decision-making led by the lead systems engineer, lead scientist, deputy project manager of resources, and project manager. Tasks determined to be non-mission critical have no direct impact on the mission's success, such as deciding upon a team name. Consultative decision-making entails consulting the team for input, but ultimately, making the final decision depends on the lead. Meeting times, location, and duration are made through consultative decision-making, considering general team member availability, but are ultimately decided at the discretion of a team leader. Democratic decision-making occurs when the team provides input on a decision and eventually votes for the direction taken. Team members directly impact decisions on critical, mission-altering tasks such as mission deliverables. The task assignment monitoring tool has been optimized and will continue to be optimized for future deliverables to increase ease of use and accuracy. The assignment monitoring tool has actively evolved based on each deliverable's needs. During the development of the MCR, all sections were elective, and all members were allowed to pick and choose which sections to complete and how many to develop actively. Moving forward into the SRR, the team leads concluded that assigning sections to all team members would balance the amount of work conducted by team members. While the team worked on the MDR deliverable, the team leads implemented a draft system reinforcing internal deadlines.

A peer review process was implemented to increase the quality and detail of section completion. For the PDR, the draft and peer review process deadlines were spaced out to allocate more time for team members to address more complicated aspects of the writing process sooner strategically. Accurate updates on task progression were utilized, and an active progress tracker was implemented.

While the current decision-making process is effective, periodic reviews and adjustments can ensure that the leadership process evolves with changing demands and needs. Refining the assignment tracker system could lead to more accurate, real-time team productivity and project status tracking. Integrating additional project management and collaboration tools can further streamline team communication and task coordination. Through continuous monitoring and evaluation of assignment monitoring tools and decision-making strategies, the team can proactively consider and implement process improvement changes that further optimize performance and deliverable quality.

Figure 10: MCA Team Org Chart



1.8.3. Major Milestones Schedule

The Endurance team, with their dedicated efforts, has meticulously developed a comprehensive project schedule estimate for mission phases C through F. This mission schedule evaluates the implementation stage of the mission life cycle, which involves

major reviews and processes involving the design. Fabrication, assembly, launch, operations, and closeout of the project. Major milestones within each phase include highlighting the completion of project reviews and major project differentials such as the finalization of rover design, the finished manufacturing of the rover, and launch.
Phase C entails the project implementation of the final fabrication and design of the rover and the completion of the CDR, PRR, and SIR. The final design will be completed and documented in this phase, testing and product and fabrication measures will be completed, and integration plans will be developed. ("NASA Space Flight Program and Project Management Handbook," n.d.) During Phase C, which accounts for two of the project's fiscal years, notable milestones include finalizing preliminary designs and refining all procedures and plans for implementation, V&V, operations, integration, assembly, and manufacturing. The culminating milestone of Phase C is the completion of the CDR on 6/4/24, which is a review designed to demonstrate the appropriate design maturity to continue into assembly, fabrication, and testing. The PRR is set for completion by 1/10/25 and will detail the readiness of the system development production plans and requirements. The SIR, set for completion by 9/20/25, will determine the readiness of any remaining project development that can occur with the team's available resources, as well as the maturity level of the project to move forward into Phase D.

Phase D involves system assembly, integration, testing, launching, and checkout activities of the rover and the completion of TRR 1, TTR 2, TRR 3, ORR, and FRR reviews. Phase D will span three fiscal years for the team and includes major milestones such as assembling and integrating all components in compliance with the previously established integration plans, performing V&V, and preparing all operations, ground support, and launch activities. The three scheduled TRRs are designed to evaluate the project's support personnel, test procedures, test facilities, and chosen software and hardware. The TRRs will be conducted through three stages of Phase D, evaluating the project as development continues. Manufacturing is set to be complete by 4/13/25, and final authentication of rover functionality will be performed at KSC after shipment on 11/15/28. The culminating milestones of Phase D are the successful launch of the rover per the December 31st, 2028 deadline and the planned performance of V&V on-orbit.

The previously established Mission Operations Plan is implemented for phases E and F, and feedback from the returned data from the rover is analyzed to fulfill science mission objectives. In addition, the completion of the DR and DRR verify and prepare for the termination and disposal process for the rover. Other notable milestones include the vehicle launch performance assessment, which will begin once the rover lands on Mars on 8/27/29. Developing a final mission report and capturing lessons learned from the mission are integral milestones for this phase. The end of primary scheduled surface operations is projected to occur on 9/23/29. Major milestone reviews conducted afterward include a life-cycle review to determine that all objectives and project maturity dates have been met satisfactorily. ("NASA Space Flight Program and Project Management Handbook," n.d.).

1.8.4. Budget Overview

The Endurance team mission final cost estimate totals $219,596,000, meeting the budget cap of $250,000,000. The total estimated personnel cost totals $22,072,000, accounting for 10% of the allocated budget. In the allocation of team funds, budget assumptions were made to express projected values and take into account certain factors that could affect the budget throughout each phase of development. The budget assumptions assist in monitoring budget performance when project performance and actual performance are evaluated. The current team budget assumptions allow for the creation of a reliable and realistic spacecraft that adheres to the mission's constraints and goals. At this stage in formulation, budget assumptions include accounting for potential supply chain disruptions, salary differentials for employees with multiple positions, and the accounting for year-over-year inflation fluctuations.

The personnel budget encompasses costs for science, engineering, technicians, administration, and management personnel. The personnel price has been factored into the mission development through phases C to F. The amount of personnel per phase fluctuates given the fluidity of mission phase needs. The varying personnel distribution is vital for addressing the changing needs of each mission phase. Throughout phases C and D, which involve the preparation and implementation of system assembly, test, integration, and launch, engineering personnel are most needed and thus account for most of each fiscal year's spending within those phases. In contrast, phases E and F involve the data collection from the spacecraft post-launch, resulting in the population of science personnel increasing and engineering personnel decreasing.

Final travel costs total $224,000, totaling roughly 1% of the total mission budget. The final travel cost projections have been carefully considered, taking into account potential interstate meetings, trips to NASA HQ, and the final witnessing of launch at Cape Canaveral. An allocated amount of $ has been allocated for each fiscal year to account for additional meetings, visits, team-building trips, and more to occur each year. The Cape Canaveral trip will have an increased budget, taking into consideration increased prices for flight, hotel, transportation, and per diem costs. Outreach costs total $ 2,686,000, 1% of the total mission budget. Outreach materials and venue costs are factored into an allocated budget for each fiscal year. The Endurance team outreach initiatives include emphasizing inclusivity and community engagement through various online and in-person collaborations. By participating in activities such as STEM Fairs, K-12 events, and creating outreach plans for further mission exposure and education, the Endurance team can emphasize the importance and value of the mission. The allocated budget for outreach includes the costs for each of these initiatives.

The direct costs total $107,904,000, accounting for 50% of the total budget. Direct costs relate to the rover's development, manufacturing, and testing. They entail the procurement, manufacturing, and testing costs associated with the mechanical, power, thermal control, communications and data handling, guidance, navigation, control subsystems, and science instrumentation. Parametric estimation and CERs from the MCCET were utilized to calculate direct costs. Direct expenses accounted for a manufacturing margin.

2. Overall Vehicle and System Design

2.1. Spacecraft Overview

The top-level spacecraft requirements define what each subsystem should accomplish or be capable of once assembled. There are constraint allocations, functional requirements, and performance requirements between each subsystem that drive trade studies and design decisions. These top-level requirements mostly stem from the mission requirements, and have many child requirements within each subsystem that are more specific constraints and goals.

Figure 11: Top-level System Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mechanical							
MEC-1	The spacecraft shall not exceed a stored configuration volume of 100 cm x 100 cm x 100 cm.	Provided by Mission Document.	Customer	All	Analysis	All	Met
MEC-2	All mechanical components shall maintain structural integrity throughout the duration of the mission.	Mechanical component degradation could impair all rover operations.	MR-1, MR-2, MR-5	MEC-1	Demonstration	MEC	Not Met
MEC-3	All mechanical components shall maintain structural integrity throughout the duration of the mission.	Mechanical component degradation could impair all rover operations.	MR-1, MR-2	MEC-3.1	Demonstration	All	Not Met

MEC-4	The rover shall have on-site mobility to access regions of interest.	The rover may need to traverse terrain in order to take scientific measurements.	MR-1, MR-2, LSO-2	MEC-4.1	Test	GNC	Not Met
MEC-5	There shall be mechanical systems in place to deploy subassemblies that require mechanical motion.	Deployment may be required by instruments and solar arrays.	MR-1, MR-2, EPS-?	MEC-5.1	Test	Payload, EPS	Not Met
EPS							
EPS-1	Any radioactive material used shall not exceed a cumulative mass of 5g.	Provided by Mission Document.	Customer	TBD	Inspection	EPS	Met
EPS-2	All hardware for the Electrical Power System shall not exceed a total mass of 12kg	This has been allocated from MR-6: "The spacecraft shall not exceed a total mass of 45 kg."	MEC-1	TBD	Inspection	EPS	Met
EPS-3	The Endurance Rover shall supply continuous power to subsystems as needed for the entire mission duration	All subsystems require electrical power to operate.	MR-1, MR-2	EPS-3.1, 3.2, 3.3, 3.4, 3.5	Demonstration	All	Met
TCS							
TCS-1	The spacecraft shall not exceed extreme temperatures -40ºC to 50ºC.	The spacecraft has to be able to withstand the temperatures on Mars	MR-5	All	Test	TCS	Met
TCS-2	The spacecraft shall be resistant to IR radiation.	The spacecraft has to avoid being destroyed by radiation	MR-5	TCS-2.1	Test	TCS	Met
TCS-3	The spacecraft shall have an internal heating/cooling system	Components within the rover must be kept at their respective safe operating temperatures	N/A	TCS-3.1, TCS-3.2	Test	Thermal	Met
GNC							
GNC-1	The GNC subsystem shall not exceed a mass of 2.25kg	Less than 5% of total rover mass.	MR-1	GNC	Inspection	GNC	Met
GNC-2	The GNC subsystem shall not exceed a stored configuration volume of 36^3cm.	Less than 5% of total rover volume.	MEC-2	GNC	Inspection	GNC	Met
GNC-3	The total GNC subsystem cost shall not exceed $15M	Less than 5% of total rover cost.	MR-4	GNC	Inspection	GNC	Met
GNC-4	Ensure the rover can autonomously navigate, guide, and control movements on Mars.	Enables thorough investigation of Mars.	MR-1, MR-2	GNC	Test	GNC	Met
GNC-5	The rover shall gather real-time and accurate data on terrain and obstacles throughout the mission.	Enables the rover to autonomously navigate and operate on mars terrain.	MR-1, MR-2	GNC-5.1, GNC-5.2	Test	GNC	Met

Payload							
PAY-1	The science objectives shall be achievable with no more than two science instruments.	Provided by Mission Document.	Customer	All	Analysis	Science	Met
PAY-2	Instruments shall not exceed physical constraints	Adhere to rover constraints	MR-1	PLD-2.1, PLD-2.2, PLD-2.3, PLD-2.4	Inspection	Science, Mechanical	Met
PLD-3	Instruments shall support scientific objectives and goals of mission	Mission needs to find insightful information	N/A	PLD-3, PLD-3.1, PLD-3.2, PLD-3.3, PLD-3.4, PLD-3.5, PLD-3.6, PLD-3.7, PLD-3.7.1	Analysis	All	Not Met
CDH							
CDH-1	The spacecraft shall send and receive communications to and from Earth via the MRO and DSN.	Provided by Mission Document.	Customer	CDH	Test	CDH	Met
CDH-2	The spacecraft shall adhere to the communication window and data volume allocated by the MRO.	Provided by Mission Document.	Customer	CDH	Test	CDH	Met
CDH-3	The rover shall utilize radiation-hardened components to meet defined Martian radiation exposure thresholds.	Protects the rover's electronic systems against the harmful Martian solar and cosmic radiation.	MR-5	CDH	Inspection	CDH	Met
CDH-4	The rover shall have an onboard computer.	Provides the primary computational power needed for all rover functions.	MR-1, MR-2	CDH-4.1, CDH-4.2, CDH-4.3, CDH-4.4, CDH-4.5	Test	CDH	Met

The Endurance Rover, from a preliminary design perspective, is a downsized combination of many technologies demonstrated from past Mars missions. Spirit and Opportunity, Curiosity, Perseverance, and Phoenix all carried engineering solutions to similar challenges that the Endurance rover will face on the red planet, so it is natural to use and build upon their successes.

The Mechanical Subsystem includes the design of the chassis, wheels, suspension, arm, and collection device. These components together determine the rover's structural integrity, maneuverability, and how the rover physically interacts with its surroundings. Aluminum 7075 was the material of choice for the chassis, wheels, and arm. Aluminum was a clear choice as it is strong and extremely lightweight for being a metal. The 7075 alloy was decided on mostly by its heritage in past Mars missions. The rocker-bogie suspension system was chosen due to its incredible maneuverability and reliability, as well as its unmatched heritage and success on every Mars rover made by NASA to date. A drill was chosen over a scooper to collect and deliver samples to the mass spectrometer as it will be a better tool to get samples of the ice itself, and not just ice-dust-mixed regolith at the surface. Since drills have been failure points in past missions, a newer, laboratory tested drill will be used, bringing the TRL of the mechanical subsystem down to 4.

The Electrical Power System (EPS) consists of power generation, storage, and distribution to all power-consuming components. Endurance's EPS has taken significant inspiration from Mars Phoenix, among other missions, because it paved the way for solar power generation in the northern polar region. The solar array will be the UltraFlex-175, designed by ATK Space Systems (absorbed by Northrop Grumman). The UltraFlex-175 is a thin-film array with triple-junction, GaAs/GaInP/Ge solar cells. The array will stow and deploy like a folding fan into a full ring. Power generated by the array will be distributed by the power distribution unit, which is custom made to interface with all power-needing components and satisfy their power needs. The distribution unit will utilize 3 lithium-ion batteries, designed and manufactured by EaglePicher Technologies for space applications. These batteries will store extra charge while it is being generated by the solar panels and distribute that power to the necessary components overnight, while power cannot be generated. The UltraFlex-175 has not yet been flight-tested, and the PDU must be partially customized to meet the precise power requirements of Endurance's subsystems. Both of these TRLs would likely be around 4, while the batteries would be 5.

The Command and Data Handling Subsystem sends commands to and saves data from all subsystems. The telecommunication sub-assembly consists of three antennas with different gains, and a transponder connecting all of them. This allows the rover to communicate with MRO and mission control, with redundancy in place in case there is an anomaly with one or two of the antennas. A central computer communicates with all subsystems via SpaceWire and utilizes a BAE RAD75 processor with DRAM for volatile memory as well as non-volatile Flash Memory to store data long-term. These components are used by the Perseverance Rover, and have proven to work reliably, but they have yet to be tested with Endurance's specific subsystems, so the TRL is assessed to be 6.

For thermal control, the rover will use variable conductance heat pipes to transfer heat between components. Excess heat will be directed to a passive structure radiator on the external surface on the chassis. Patch heaters will be used to generate heat directly in contact with components like external navigation and hazard cameras that may get very cold. Aerogel will be used to insulate the chassis and all internal components from the extremely cold Martian atmosphere. All of these technologies have been used in past missions in different configurations, so the current TRL is 5.

The rover's guidance and navigation system will utilize an engineering camera (ECAM) imaging system with 6 external cameras; 2 for navigation and 4 for hazard detection. These cameras will feed data into the navigation system processor which will run an integrated Ship's Internal Navigation System and Celestial Navigation System (SINS/CNS). Most of these systems are used on Perseverance, and will be used similarly in the Endurance mission, but the exact SINS/CNS integrated system hasn't gone through testing in space, so the TLR is 5.

The detailed process for reaching these design decisions will be explained in the proceeding sections for each subsystem.

Figure 12: Spacecraft Overview Table

Subsystem	Mass (kg)	Stowed Volume Container (cm)	Max Power Draw (W)	TRL
EPS	6.2	20x20x5 + 2*(4x4x6)	N/A	4
TCS	5	10 x 10 x 10	50	5
MECH	10	58 x 52 x 38 (chassis shelled)	90	4
CDH	4	20 x 20 x 15	30	6
GNC	3	17 x 17 x 17	10	5
Payload	9.2	20 x 20 x 25	70	4
TOTAL	**37.4**	**WILL FIT IN 100x100x100cm**	**250**	

CAD drawings of the rover and hazcam part are shown below. Engineering drawings of each modeled component can be found in Appendix 3.

Figure 13: CAD Drawing of the Endurance Rover

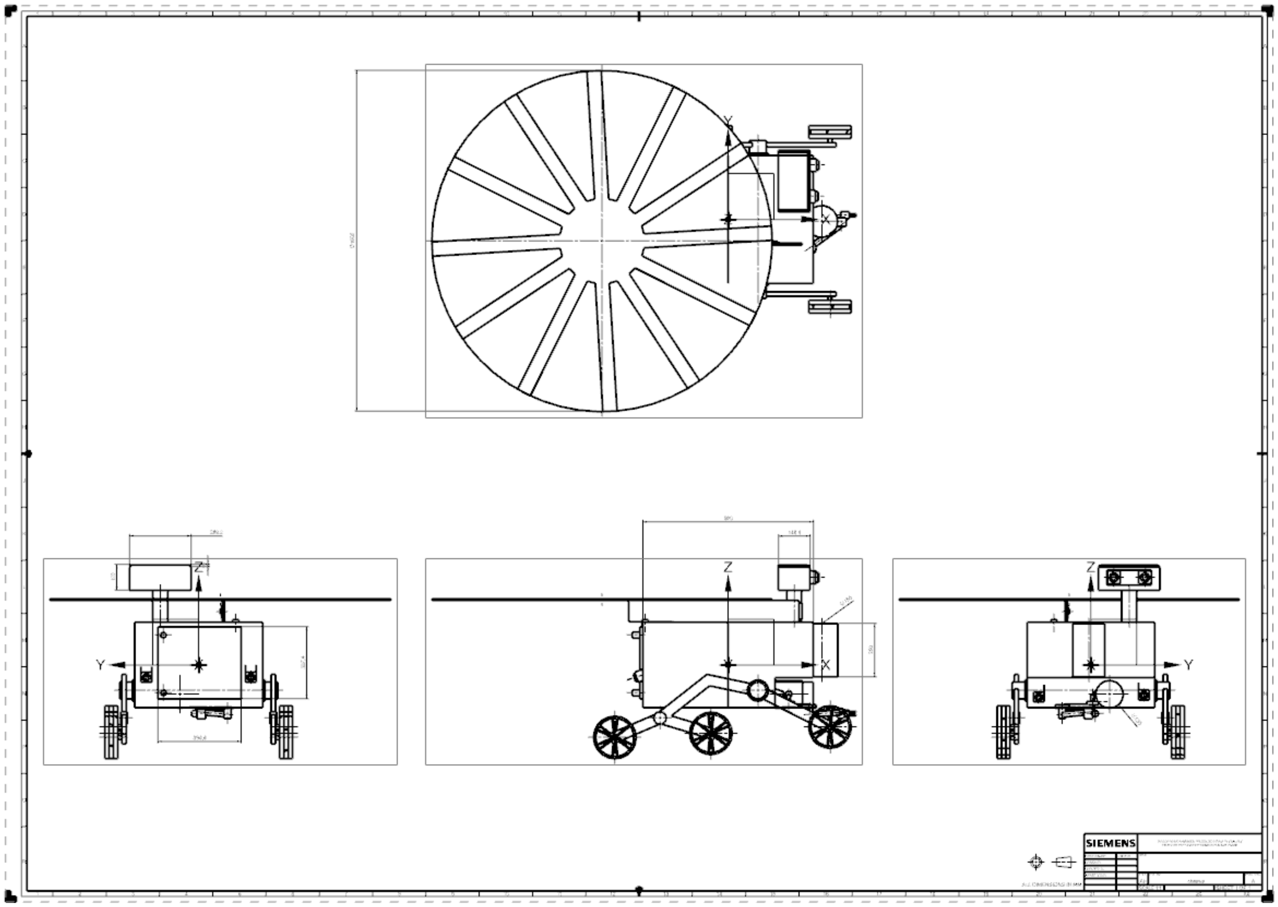
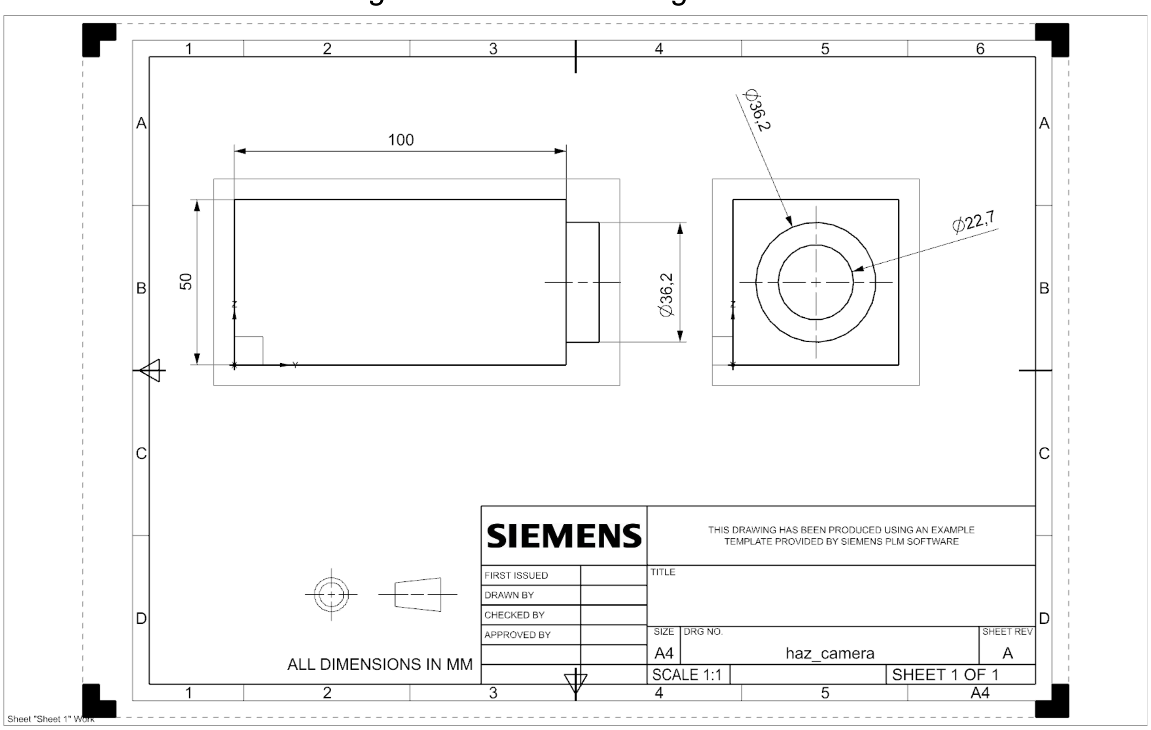


Figure 14: CAD Drawing of the Hazcam

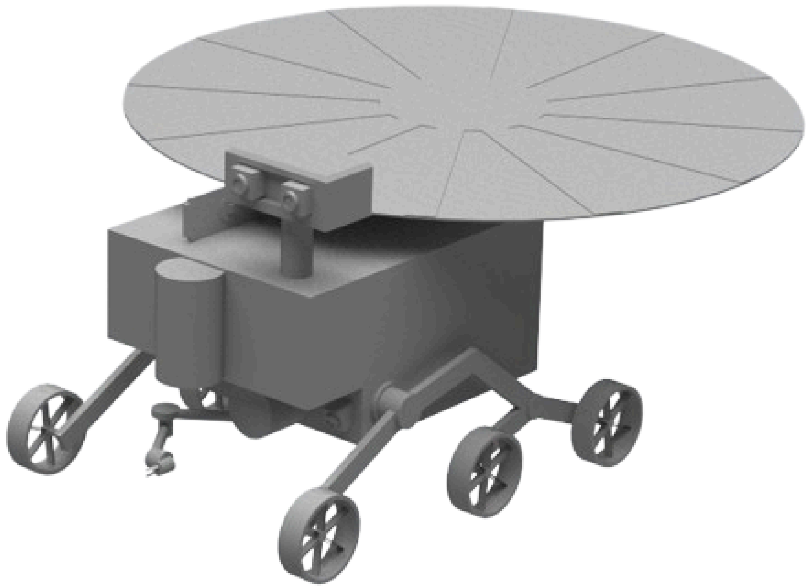


2.1.1. Mechanical Subsystem Overview

The Endurance rover's mechanical subsystem has been developed to withstand harsh Martian climates, traverse tough terrain, protect internal components, and ensure that all mission mass and cost constraints are upheld through strategic design, procurement, and manufacturing decisions. The mechanical subsystem protects all other subsystems within the chassis, and works in tandem with the power and GNC subsystems to control the speed, degrees of rotation, and functionality of the wheels and robotic arm. Each component of the rover has been designed to contain the components of each subsystem to ensure the integrity of the rover. In terms of capability, the rover can go a top speed of less than 1 mph. This top speed ensures that the rover maintains balance and does not tip over attempting to increase speed. The rover can climb an elevation of 45 degrees without the risk of losing balance. The rover's mechanical subsystem has taken into account the extreme temperatures present on Mars and can withstand temperature fluctuations of ____ degrees celsius while maintaining an internal temperature of ____ due to the thermal subsystem design.

The enhanced balance the rover has is largely attributed to the inclusion of the rocker-bogie mechanical suspension system. The mechanical subsystem addresses the robotic functionality and mobility of the rover and attached robotic arm, incorporating proven design and technology methods from previous Mars rover missions. The speed and rotational abilities of the arm were chosen to account for the power subsystem and energy usage, ensuring that power draw did not exceed determined values. Each component of the mechanical subsystem works in tandem to maintain structural integrity, balance, and ease of maneuverability of the rover.

Figure 15: Render of Endurance CAD Model



The chassis of the Endurance rover is made of aluminum alloy 7075, a proven lightweight and durable aerospace-grade metal with a proven, high TRL due to the heritage of past Mars rover missions. The Endurance rover utilizes the rocker-bogie mechanical suspension system for ease of terrain navigation and the aluminum alloy chassis to achieve lighter mass while maintaining structural integrity of internal subsystem components. The chassis material being lightweight and durable maximizes the potential of the rocker-bogie system, allowing the suspension to function with proper fluidity and resistance. The incorporation of all-wheel drive wheels and flat line tires reduce the risk of wheel damage due to navigating over rough terrain. Taking from the lessons of the Perseverance rover, this tire tread decision has been incorporated into the Curiosity rover to prevent the noted wear and tear experienced by Perseverence’s tires.

The robotic arm and drill for scientific collection have been chosen and designed after conducting trade studies to determine the best mechanical options for meeting the mission's scientific objectives and goals. The mounted robotic arm will control the drill, the method chosen for collecting samples in tandem with the spectrometer. As a SPF, the drill is designed to take into account potentially getting stuck within the regolith by adjusting the drill pattern. In order to prevent stoppage, the drill moves in a space-creating pattern to allow for leeway once the drill is ready to extract from the site.

2.1.1.1. Mechanical Subsystem Requirements

The mechanical subsystem requirements define the mission constraints to which the vehicle design must comply, and the essential functionalities of the vehicle to accomplish the science goals. Mission-level constraints, which entail volume and mass constraints of the spacecraft, are defined by MEC-1 and MEC-2. Delineated to enable mission success is requirement MEC-3, which imposes the structural integrity of all mechanical components for the mission duration. Requirements MEC-4 and MEC-5 describe the required capabilities of the rover to accomplish science objectives, from site mobility to sample acquisition. The child requirements delineated from MEC-4 and MEC-5 further detail the rover's performance and capabilities needed to pursue the science objectives. Requirement MEC-5 solely outlines the functional capability of the rover chassis.

Figure 16 - Mechanical Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Mechanical							
MEC-1	The Endurance rover shall not exceed a total mass of 45 kg.	Provided by Mission Document.	Customer	TBD	Inspection	All	Met
MEC-2	The Endurance rover shall not exceed a stored configuration volume of 100 cm x 100 cm x 100 cm.	Provided by Mission Document.	Customer	TBD	Inspection	All	Met
MEC-3	All mechanical components shall maintain structural integrity throughout the duration of the mission.	Mechanical component degradation could impair all rover operations.	MR-1, MR-2	MEC-3.1	Demonstration	All	Met
MEC-3.1	The system shall maintain structural integrity within the temperature range of TBD-TBD degrees celsius.	Structure expands and contracts with the temperature fluctuations of the space environment.	MEC-3, MR-5	TBD	Test	TCS	Met
MEC-4	The rover shall have on-site mobility to access regions of interest.	The rover may need to traverse terrain in order to take scientific measurements.	MR-1, MR-2, LSO-2	MEC-4.1	Test	GNC	Met
MEC-4.1	The rover shall have a suspension system capable of navigating landing-site and nearby terrain.	Suspension enables the rover to traverse difficult terrain and protects the structural integrity of the rover.	MEC-4	MEC-4.1.1	TBD	All	Not Met
MEC-4.1.1	The Endurance rover shall be able to withstand a tilt of 45 degrees in any direction without tipping over.	The rover may traverse harsh terrain, requiring a balancing system to navigate safely.	MEC-4.1	TBD	Test	GNC	Not Met
MEC-4.2	The rover wheels shall be composed of material capable	The prolonged integrity of the rover wheels	MEC-3, MEC-4	TBD	Test	All	Not Met

	of wear of TBD (range/days).	ensures prolonged operational mobility.					
MEC-5	There shall be mechanical systems in place to deploy subassemblies that require mechanical motion.	Deployment may be required by instruments and solar arrays.	MR-1, MR-2, EPS-?	MEC-5.1	Test	Payload, EPS	Not Met
MEC-5.1	The rover shall have a means to position instruments for sample collection.	A means of sample collection enables the fulfillment of scientific objectives.	MEC-5	TBD	TBD	Payload	Not Met
MEC-6	The rover chassis shall support all system components, instruments, and maintain structural integrity.	Durable chassis composition ensures stability and reliability for carrying out operations.	MR-1, MR-2, MR-5, LSO-2	TBD	Test	All	Not Met

2.1.1.2.Mechanical Sub-Assembly Overview

The Endurance Rover incorporates the proven design and technology of previous rover missions all within the minimized volume and mass constraints of the mission concept. The Mechanical Subsystem of the Endurance Rover consists of the following subassemblies: vehicle chassis, wheels, suspension system, robotic arm, and drill collection device. These subassemblies are foundational in supporting the instruments and devices of other vehicle subsystems to fulfill mission objectives.

Similar in design to previous Mars spacecraft, the chassis of the Endurance Rover serves to carry and protect all the science instruments, electronics, and computer hardware systems, as well as provide structural integrity to reinforce the entire composition of the rover. Four materials commonly used in extreme-environment aerospace applications have been evaluated in the Chassis Material Trade Study for chassis composition. Among these materials are aluminum, steel, titanium, and composite materials. The criteria for evaluation are strength and durability, low-temperature tolerance, ease of manufacturing, mass, cost, and TRL. These criteria reflect the demands given the environmental factors of the mission objective and the customer constraints. Aluminum was selected to be the composition material of the chassis. Upon evaluation, aluminum possesses high strength characteristics not much lower than higher strength, heavier materials. Due to the high volume composition of the chassis, a greater emphasis was applied to the criteria for material mass, and aluminum is the most lightweight material. Aluminum outperforms other materials in low-temperature environments and is often used for cryogenic applications. Steel and titanium become brittle in far warmer temperatures than the mission landing site temperature, and low-temperature tolerance is a critical quality to ensure the structural integrity of the rover is not undermined. The TRL of the aluminum is ranked to 7 as it has been applied to previous Mars Rover chassis. Although aluminum is not the least costly material, its qualities ensure the best mission success compared to the other materials.

Further evaluation of several aluminum alloys was conducted in the Aluminum Alloys for Chassis Trade Study to determine the most suitable aluminum alloy for the rover chassis. The evaluated aluminum alloys, commonly utilized in aerospace and space mission endeavors, include 2014, 2024, 2219, 3003, 5052, 6061, 6063, 7050, and 7075. Aluminum alloys possess differing properties due to their differences in elemental composition. For example, the aluminum alloy of the 1XXX series has high corrosion resistance, but poor fatigue strength. The aluminum alloy of the 7XXX series has higher fatigue strength but poor corrosion resistance. Due to the wide range of material characteristics possessed by the different aluminum alloys, a trade study was deemed necessary to determine the most suitable alloy for the vehicle chassis. The criteria for evaluation include corrosion resistance, fatigue strength, ultimate tensile strength, specific strength, and TRL. Corrosion resistance was the highest weighted criterion as it is a critical factor in upholding structural integrity to ensure mission lifetime. Fatigue strength was another criterion necessary to determine how well each material would resist the various stresses and strains as the rover traverses rugged and uneven terrain. Ultimate tensile strength (UTS) was evaluated considering situations where the chassis may experience high forces, such as deceleration forces upon capsule landing or any unexpected impacts or loads. Instead of the criterion for mass, the alloys were evaluated on their specific strength (ratio of tensile strength to density) to determine which alloy offered appropriate strength for the least mass. Aluminum alloy 7075 was selected to be the most suitable material to constitute the chassis. Alloy 7075 possesses moderate corrosion resistance and fatigue strength, high UTS and specific strength, and the highest TRL of 7 due to its previous application on the Mars Exploration rovers.

The chassis subassembly was rated with a TRL of 4, as it is composed of an identical material to previous Mars spacecraft chassis, but is new in design and implementation.

The wheel of the Endurance Rover implements the latest designs and lessons learned from the Curiosity Rover mission. In the Wheel Type Trade Study, previous and experimental rover wheel designs were evaluated with the criteria for durability, traction, temperature tolerance, mass, cost, and TRL. Among the designs are the chevron treaded wheels of the Curiosity Rover, flat-line treaded wheels of the Perseverance Rover, and the experimental Shape Memory Alloy (SMA) tires in development by the NASA Glenn Research Center. A critical flaw of the chevron-threaded wheel of the Curiosity Rover is that the thinness of the wheel and the high traction design contributed to its significant degradation. The Perseverance Rover was designed with thicker wheels and straight-line treads to alleviate degradation. The SMA tires, although never implemented on a Mars mission, show promising potential with new shock-absorbing and elastic technology. Overall, the straight-line tread design and the SMA tires ranked highest in durability. Traction is an important factor in allowing the rover to traverse difficult locations and in ensuring full control over its position. The wheel designs have relatively similar performance in traction. The aluminum wheels of both the chevron and flat-line tread designs have satisfactory low-temperature tolerance, but the steel composition of the SMA tires does not perform as well. The masses of all the wheels are relatively low due to their hollow design, but the thicker wheels of the flat-line design have a slightly greater mass than the chevron-threaded wheels. The flat-line threaded wheels have the highest TRL due to their previous applications on multiple Mars rovers, particularly the Perseverance Rover. Ultimately, the flat-line design was selected to be implemented for its improved durability, satisfactory performance in traction and temperature tolerance, and high TRL.

To determine the material of the wheel, a trade study similar to the chassis material evaluation was conducted. The Wheel Material Trade Study examined aluminum, steel, titanium, and composite materials under the criteria of strength and durability, low-temperature tolerance, mass, cost, and TRL. The trade study resulted in similar scores, with aluminum scoring the highest. Another trade study with the same alloys and criteria as the Aluminum Alloys for Chassis Trade Study was conducted to determine the best-suited alloy for the wheel. A greater weight was placed for the corrosion resistance criteria as the wheels will be in constant contact with the Martian terrain. Alloy 7075 was once again rated highest among the alloys due to its anti-corrosion properties, relatively high strength, and a high TRL of 7.

The wheel subassembly is rated with a TRL of 6 since the wheel is identical in design and material composition to the Perseverance Mars Rover and only smaller in proportion.

The Endurance Rover will use the Rocker-Bogie suspension design. The Rocker-Bogie suspension system has been used by all Mars Rovers and has been proven effective in design. The Rocker Bogie enables the rover to remain stable and level when traversing over uneven terrain, can withstand an incline of 45° in all directions, and travel over obstacles as high as the wheel diameter.

Three suspension systems have been evaluated in a trade study with the criteria of mass, durability, adaptability, energy efficiency, and TRL. The Rocker-Bogie system ranked the highest significantly, and its capabilities are unmatched by any existing suspension system. The TRL for the Rocker-Bogie system has been rated 7 since its application has been universal in all previous Mars rovers and proven effective.

Three different sample-collecting devices were considered for evaluation in a trade study, with the criteria of efficiency, sampling capacity, complexity, durability, sample acquisition, and TRL. The device designs are the drill, scooper, and Rock Abrasion Tool (RAT). The drill was ultimately selected to accomplish the sample collection objective as its sample acquisition capability was the greatest among the other devices. Due to there being no drill of similar proportion or implementation, the TRL of the drill is rated to 4.

A device to position and manipulate the sample collection device is a crucial component of a rover. Two robotic arms were evaluated in a trade study to determine which design would be better suited to ensure a higher capacity for successful sample acquisitions. The criteria for the robotic arms are range of motion, carrying capacity, durability, and TRL. The first robotic arm design is the familiar, triple-jointed, shoulder-arm-wrist design, which offers 360° of rotation and range. The second design is the telescopic arm, which extends out perpendicular to the rover's body. Greater weight was placed on the criteria for range of motion since having full control of the drill offers a greater option for contact and extraction. The shoulder-arm-wrist robotic arm design was selected, with a TRL rating of 4 since the exact design for the Endurance rover has never been implemented.

Figure 17: Mechanical Sub Assembly Summary

Subassembly	Mass (kg)	Stowed Volume (cm)	Power Draw (W)	TRL
Chassis	4	58x52x38	N/A	4
Wheel (x6)	1 total	6x2x6	N/A	6
Suspension (x2)	2 total	62x7x26	17	7
Robotic Arm	2 total	1.8x12x1.8	40	4
Drill	0.825	1x3x1	15	4
Total	10	N/A	90	4

2.1.1.3. Mechanical Subsystem Recovery and Redundancy Plans

To address recovery attempts, the rover will have one chassis as it is not possible to have multiple so it will be a SPF. To combat this a relatively strong material with an excellent temperature tolerance and anti-corrosive properties was chosen so there should be a minimal chance of it breaking. In addition the rover will have a single suspension system which will be a SPF, but the suspension chosen has very high durability, adaptability, and has been used previously on Mars therefore the risk of it breaking is also very low. The rover’s will have multiple wheels so it will still be able to navigate even if one is missing. The rover also will be using a drill to collect samples which will be a SPF, but the drill will move slightly as it drills in order to minimize the chance of it getting stuck. If the drill ends up getting stuck even with it slightly moving the rover will start a process of trying to forcefully remove it by moving back and forth and try turning it on because once it is on it can create a larger hole and remove itself. The rover will be able to detect if a wheel has been damaged or is missing and automatically adjust movement so that wheel (or lack of wheel) is used minimally for traversal in order to prevent further damage.

There is an opportunity within the mechanical subsystem to implement redundancy. Based upon a performance analysis and lessons learned from previous NASA Mars missions, the six wheel configuration of the rover enacts redundancy within the system, allowing for greater balance and ability for the rover to recover if a wheel is damaged or lost. Considering duplicate motors within the subsystem to implement redundancy within mobility mechanisms can allow for essential operations to continue despite potential component failures.

2.1.1.4. Mechanical Subsystem Manufacturing and Procurement Plans

Mechanical Subsystem

Aluminum alloy Flat line wheels - 7075 Flat line tire

Relying on NASA JPL for manufacturing the wheels for a Mars rover is grounded in their specialized expertise and access to cutting-edge technologies, ensuring precision and adherence to the highest quality and performance standards. Leveraging insights from previous missions such as Curiosity and Perseverance, the design of the Endurance Rover's wheels integrates the latest advancements and lessons learned, enhancing its efficiency and durability for upcoming challenges. Extensive testing conducted at NASA's Jet Propulsion Laboratory has demonstrated that these wheels better withstand pressure from sharp rocks and offer improved grip, particularly on sandy terrain. After assembly and testing at JPL, parts are shipped to the Kennedy Space Center for additional assembly and testing, with approximately one month of travel time. The weight of the wheel, starting as a solid block of aluminum, depends on the thickness; for instance, a wheel with a thickness of 0.75mm weighs approximately 0.7 kg (1.5 lbs) per wheel.

Aluminum alloy 7075

The chosen contractor, Material Technology Solutions, offers unparalleled expertise in aerospace materials, specifically 7075 aluminum, which is critical to the business. Their expertise ensures that products meet the exacting standards set by the aerospace industry. With proven commitment to quality and compliance, we can rely on their products for reliability and quality performance. In addition, their advanced manufacturing capabilities, including CNC machining and precision casting facilities, enable them to manufacture with extreme accuracy, adding to their reputation in this industry.

Aluminum 7075 Alloy Chassis

The decision for in-house production of the aluminum chassis at NASA's Jet Propulsion Laboratory (JPL) stems from the consistent track record the lab has maintained over the years. Since the inception of Mars exploration missions, JPL has spearheaded the development of six successful robotically operated Mars rovers. These include Sojourner (1997), Spirit (2004–2010), Opportunity (2004–2018), Curiosity (2012–present), and Perseverance (2021–present), each contributing significantly to humanity's understanding of the Martian surface. By ensuring in-house production, JPL maintains control over the quality and reliability of crucial components like the aluminum chassis and previous rovers like perseverance, the chassis has weighed around 2,260 pounds / 1,025 kilograms so this is a number the team would like to consider

Rotary Precision Drill - Honeybee Robotics

As the team's supplier of precision drills, Honeybee Robotics Exploration Systems brings more than two decades of experience in space drilling technology developed in collaboration with NASA. Their expertise allows the rover to drill at depths ranging from millimeters to tens of kilometers. Furthermore, utilizing Honeybee Robotics Exploration Systems would be advantageous as they specialize in space drilling technologies, with their latest innovation being the "TRIDENT" drill. With plans to deploy "TRIDENT" on a mission "to the Moon in 2023," their expertise and dedication to advancing space exploration make them an ideal partner for the Mars rover mission.

Rocker-bogie suspension - JPL

JPL is an excellent supplier choice due to the past Rocker-Bogie suspension systems they have created. With their "expertise in precise steering, JPL ensures that rovers can turn in place, making them incredibly maneuverable" (nasa.gov). With such a track record of innovation, JPL stands out as a reliable supplier for the project. This system would take a few months to manufacture and test as it would need to be sent to different facilities to be tested.

2.1.1.5. Mechanical Subsystem Verification Plans

Figure 18 - Mechanical Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
MEC-1	Rover shall not exceed a total mass of 45kg	Test	This method provides quantitative data and ensures rigorous compliance with the requirement. It also allows for	This will conducted by weighing the rover with all components on

			the detection of any potential deviations from the specified mass limit	
MEC-2	Rover shall not exceed a total volume of 100 cm x 100cm x 100cm	inspection	This method was chosen because measuring the rover is the only way to detect if the maximum volume is exceeded	This will be conducted by measuring
MEC-3	Maintain structural integrity throughout the duration of mission	Test/analysis	This method was chosen to detect any potential weaknesses or failure points, enabling engineers to make necessary adjustments to improve the rover's design before deployment.	By subjecting the rover to various stressors, such as vibrations,and mechanical loads, engineers can directly observe how the structure behaves and ensure it remains robust throughout the mission.
MEC-3.1	System shall maintain structural integrity within temperature ranges of -40C to 50C	Test/analysis	This method was chosen to assess the system's ability to maintain structural integrity under temperature conditions, ensuring that its materials and components can withstand thermal stresses without compromising structural integrity.	This will be conducted by subjecting the system to controlled temperature environments ranging from -40°C to 50°C while closely monitoring its response for signs of deformation or failure.
MEC-4	On site access to all regions of the rover	demonstration	This method was chosen as it is a straightforward and tangible way to validate the accessibility aspect of the design, ensuring that all regions of the rover can be reached as necessary for maintenance, repairs, or other operational needs.	This will be conducted by physically showcasing access points
MEC-4.1	Rover shall have suspension system capable of navigating landing-site and nearby terrain	Test	This method was chosen as allows engineers to directly observe the rover's ability to navigate over uneven surfaces, slopes, rocks, and other obstacles that it may encounter during its mission	This will be conducted by selecting terrains representative of the mission area, such as rocky surfaces, slopes, and obstacles, and monitor the rover's performance, assessing its ability to traverse various terrains while maintaining stability and functionality.
MEC-4.1.1	Rover shall withstand a tilt of 45 degree in any	Test	This method was chosen to directly assess whether the	This will be conducted by physically tilting the rover

	direction without tipping		rover remains stable and does not tip over when subjected to the specified tilt angle	to these angles and observing its stability.
MEC-4.2	The rover wheels shall be composed of material capable of wear of …	analysis	This method was chosen to predict the wear properties of the material over time under various operating conditions without the need for extensive physical testing	This will be conducted by testing the capability of the rover wheels' materials, which may involve mathematical modeling, simulations, and potentially laboratory tests.
MEC-5	There shall be a mechanical system in place to deploy subassemblies that require mechanical motion	Demonstration	This method was chosen to directly observe the operation of the mechanical system and verify its capability to deploy the subassemblies without any issues.	This will be conducted by activating the mechanical system to deploy the subassemblies as required. And observations would be made to ensure that the deployment is smooth, accurate, and without any malfunctions.
MEC-5.1	The rover shall have a means to position for sample instruments	Test	This method was chosen as it lies in its ability to directly assess the functionality and performance of the rover's positioning system under real-world conditions.	This will be conducted by testing the rover's positioning system in a simulated mission environment, positioning sample instruments, and analyzing data to ensure accuracy and effectiveness.
MEC-6	Rover chassis shall support all system components instruments, and maintain structural integrity	Test	This method was chosen as it directly assesses the rover chassis's performance under real-world conditions. By subjecting the chassis to various loads and environmental factors, engineers can observe its ability to support all system components and instruments	This will be conducted by testing subjecting it to simulated loads, environmental conditions, and dynamic movements to ensure it can support all system components and instruments while maintaining structural integrity.

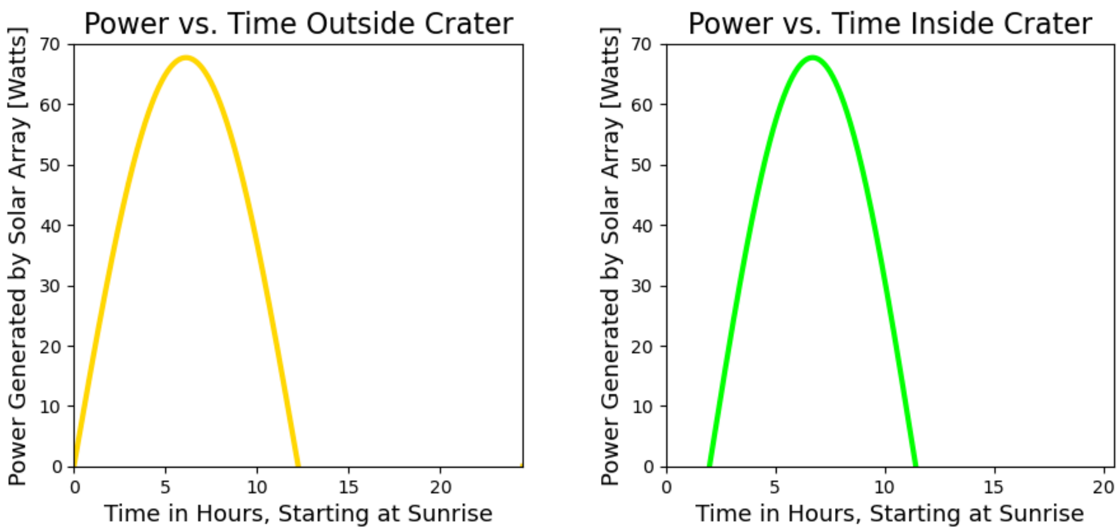
2.1.2. Power Subsystem Overview

The Electrical Power System is comprised of the solar array, battery pack and Power Distribution Unit (PDU) which interfaces with every subsystem with a main power bus. The UltraFlex-175 solar array generates power during the daylight hours, distributing power to all subsystems and charging the lithium-ion batteries. Once the sun goes down, power generation stops, and the charged batteries begin to discharge through the PDU, to the subsystems needing power. At night, power-demanding components like the arm and mass spectrometer will be used minimally in order to save power. The status and power capacity of the batteries will be monitored by the command and data handling computer. The computer will autonomously command the rover to go into a “low power mode” upon reaching 20% capacity, or component overheating, in which case power will be “cut off” to the arm, scientific instruments, and drivetrain (wheel motors). Only the thermal control system, communication systems, and GNC (for hazard detection) will remain operational.

In order to save power throughout the mission, operations will be carried out very slowly by the rover, driving a maximum of 100m/hr, and rotating the mechanical arm 5 degrees/second maximum at each joint. Constraining these speeds reduces the electrical demand of the motors significantly. Another power-saving constraint is that the rover will not drive and use the arm or scientific instruments at the same time. The powertrain driving the rover’s wheels will need between 30-90W to traverse the rough terrain, and the scientific instruments will require up to 70W at full power. Because these are the most costly operations to perform, the rover shall operate scientific instruments stationary at each of the science sites.

Two power vs. time plots are shown below, one for an average sol while operating outside the crater, and another for an average sol while operating within the crater described in the mission location summary. The rim of the crater will block sunlight from reaching the inside at low solar angles (~5 degrees), effectively shortening the period of daylight and effective charging each day. These plots were made using the maximum watts generated (calculated in the sub-assembly overview) as the peak value, and following a sine curve from sunrise to sunset, which is approximately half of a sol, or 12.25 hours.

Figure 19: Power Generation vs Time Plots



The initial function for power generation over time is peak_power × $sin(\frac{2\pi t}{25.5})$. A python script was used to plot this function over a 25.5 hour sol, and the scipy package was used to integrate the function, using the roots as the bounds of integration. The total watt-hours generated over one sol was calculated to be 528.2 Wh for outside the crater and 406.3 Wh for inside the crater.

2.1.2.1. Power Subsystem Requirements

The EPS requirements define what the subsystem should accomplish. There are constraint allocation, functional, and performance requirements that drive the trade studies and subsystem design decisions. EPS-1 and 2 come from mission-level constraints that were allocated to EPS. EPS-3 describes the overarching goal of the subsystem, and is the parent requirement to all other requirements. Under this are EPS-3.1, 3.2 and 3.3 which break down the overarching goal into power generation, power storage, and power distribution. From there, multiple child requirements follow to make more specific assertions within each EPS subassembly, and EPS-4 through 7 constrain the subsystem with respect to edge-cases and cohesion with other subsystems.

Figure 20 - Power Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?

Electrical Power System							
EPS-1	Any radioactive material used shall not exceed a cumulative mass of 5g.	Provided by Mission Document.	Customer	TBD	Inspection	All	Met
EPS-2	All hardware for the Electrical Power System shall not exceed a total mass of 12kg	This has been allocated from MR-6: "The spacecraft shall not exceed a total mass of 45 kg."	MEC-1	TBD	Inspection	All	Met
EPS-3	The Endurance Rover shall supply continuous power to subsystems as needed for the entire mission duration	All subsystems require electrical power to operate.	MR-1, MR-2	EPS-3.1, 3.2, 3.3, 3.4, 3.5	Demonstration	All	Met
EPS-3.1	The Electrical Power System shall generate sufficient power for all subsystems to perform as intended	Power generation is required as the rover will require more power than can reasonably be brought by primary batteries	EPS-3	TBD	Analysis	Power Generation	Met
EPS-3.2	The Electrical Power System shall store power while it is being generated	The power generation method may not be continuous due to day/night cycle and/or system anomalies, but subsystems may still require power.	EPS-3	TBD	Inspection	Power Storage	Met
EPS-3.3	The Electrical Power System shall safely distribute and control all of the power generated	Electrical faults could result in subsystem failure and potentially mission failure if vital components are overpowered, underpowered, or lose power entirely	EPS-3	EPS-3.3.1, 3.3.2, 3.3.3	Test	Power Distribution	Met
EPS-3.3.1	The Electrical Power System shall provide bus isolation between upstream and downstream loads	Isolation allows for faults and short circuits to occur without affecting the entire circuit.	EPS-3.3	TBD	Analysis	Power Distribution	Not Met
EPS-3.3.3	The Electrical Power System shall protect components from electromagnetic interference, transients, bus faults, and load faults.	EMI and other interferences and faults can cause system anomalies and/or failures	EPS-3.3	TBD	Analysis	Power Distribution	Not Met
EPS-3.4	The Electrical Power System shall provide enough power with margin for peak loads	There is always uncertainty and potential anomalies in the power consumption for each subsystem	EPS-3	TBD	Analysis	All	Met
EPS-3.5	The Electrical Power System shall interface properly with each system onboard	Each subsystem requires different amounts of power, current, and voltage over varying time intervals.	EPS-3	TBD	Test	All	Met
EPS-3.6	Electrical Power System components shall be kept within their respective safe operating temperature range	Electrical components tend to be less efficient, outside their normal operating temperature, and may fail if the temperature is too extreme	EPS-3	TBD	Test	All	Met
EPS-3.7	The Electrical Power System shall provide operating status (voltage, current, temperature, etc.)	The detailed status of the EPS is important to monitor and log for testing purposes and to enable root-cause analysis for observed anomalies	EPS-3	TBD	Test	All	Met

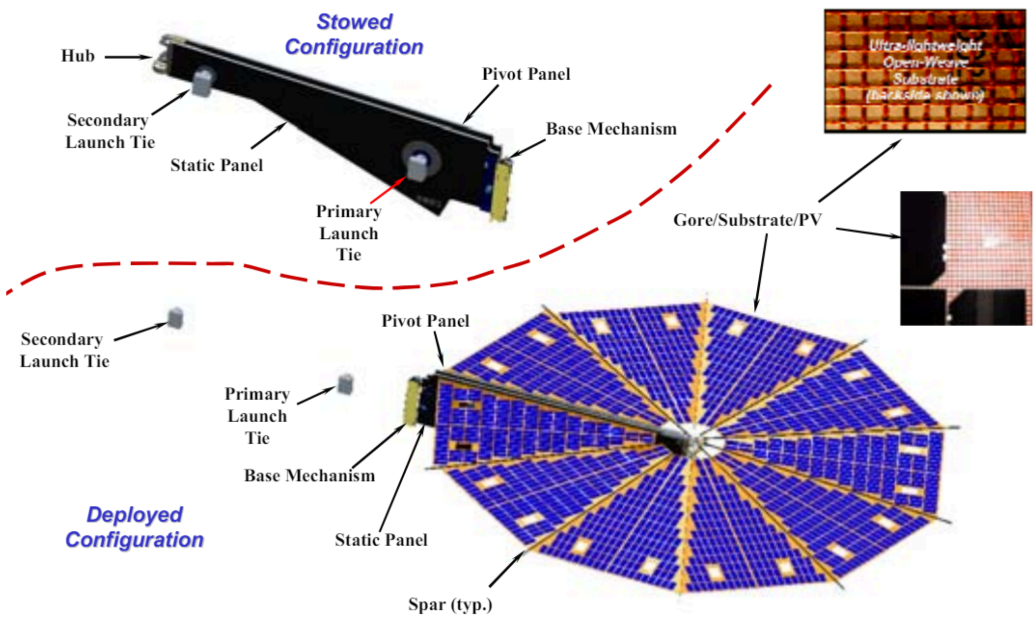
2.1.2.2. Power Sub-Assembly Overview

This overview outlines the preliminary design of the Electrical Power System (EPS), focusing on three main subassemblies: power generation, power storage, and power distribution. Each subassembly is essential for ensuring the rover's energy requirements are met efficiently and reliably throughout its mission on Mars.

The power generation subassembly is responsible for converting available energy sources into electrical power to sustain rover operations. Since power from a radioisotope thermoelectric generator is not feasible due to monetary and legal constraints, a solar array was the only logical option. The solar array contains solar cells on top of an array structure, which can come in a variety of forms. Through trade studies, Gallium Arsenide and Gallium Indium Phosphide cells showed the best efficiency, and it was found that both types of cells could be implemented with multi-junction (MJ) cells on top of a Germanium substrate. Another trade study on junction types showed that triple junction solar cells were given the best efficiency and specific power for the cost and TRL. This leads to an overall efficiency of 27- 32%. Although MJ cells are much more expensive than single-junction cells, the efficiency will be necessary for the rover being so far from the equator (decreasing solar angle), and MJ cells have been flight-proven by the Spirit and Opportunity rovers. The solar array chosen was the UltraFlex-175, a successor of the UltraFlex, which was successfully used on the Mars Phoenix mission. This solar panel conveniently combines all of the traits that were specified by trade studies: Thin, flexible array with multi-junction Ga/GaIP cells.

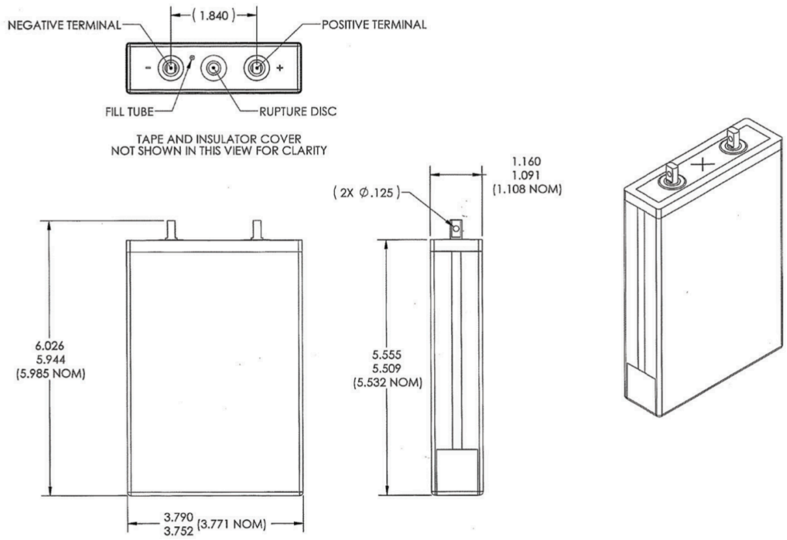
The specific power of the UltraFlex-175 is 175 W/kg. This means that, at 1 AU (Earth), with no atmosphere deflection or absorption, a 1kg UltraFlex-175 would generate 175W of electrical power if pointed directly at the sun during peak sunlight hours. Mars, with a distance of 1.52 AU, receives 43% of Earth's W/m^2 (175*0.43 = 75.25W/kg). Landing and operating at around 45 degrees north latitude will also cause the solar angle to be consistently lower and reach a maximum of ~45 degrees, rather than 90 (directly overhead) at the equator. This difference in solar angle is estimated to reduce solar energy hitting the rover’s array by another 10%, leaving the W/kg at 75.25*0.9 = 67.73W/kg. Over the course of one sol, 24hr 30 min, the sun will go from below the horizon, to a peak of ~45 degrees, and back to below the horizon. More power must be generated that is being consumed, so that some power may be used to charge the batteries for nighttime surface operations. If the average power consumed by the rover over one sol is 50W, then the power generated over the same period on average should be 20% more for margin, at 60W. If power generation is only happening over 50% of the sol (the sun is only out for half the sol), the array must generate 120W on average throughout that time so that the average over the entire sol is 60W.

Figure 21: UltraFlex-175 by ATK Space Systems



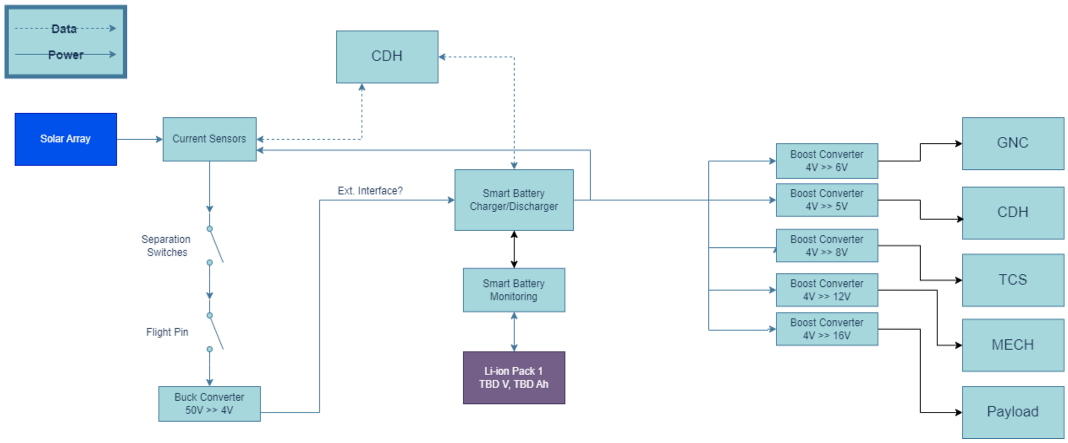
The power storage subassembly stores energy generated by the solar array during daylight hours for use during periods of low sunlight or nighttime operations. Lithium-ion batteries are utilized for their high energy density and reliability, and have been proven by many past Mars rover missions. The LP33081 30-Ah Space Cell by EaglePicher Technologies will work well for this application. The battery weighs roughly 1 kg, with a voltage range of 3.0-4.1V, and nominal capacity of 30 Ah. The battery also has extremely low operating and storage temperature capabilities at -20°C and -40°C respectively. Lastly the Cycle life was rated >2000, which is more than enough assuming the batteries are each charged and depleted once per sol. All these characteristics were highly valued in trade studies (see Appendix 1.2). Since each battery has ~ 90Wh (3V * 30 Ah = 90Wh), the rover will need three batteries (3*90Wh = 270Wh) to cover the 240Wh required overnight. To achieve this, the batteries will need to be connected in parallel, so that the total voltage capability remains the same, but the total capacity is the sum of each battery's capacity. Three batteries at ~1 kg each will have a total mass of about 3 kg. The dimensions of each battery is listed on the datasheet on EaglePicher's website: 15.2 x 9.58 x 2.81 cm (nominal). Stacking three of these on top of each other and accounting for a case around the stack leads to a volume of 6x3.7

Figure 22: LP33081 Dimensions (EaglePicher)



The Power Distribution Unit (PDU) distributes power to the batteries and all components in other subsystems. The PDU takes power directly from the solar array and uses a buck converter to decrease the voltage before feeding into the smart battery manager, which charges and discharges the Li-ion battery packs as the power is needed. Before connecting to components in other subsystems, a boost converter must be used to increase the voltage to the necessary spec for each subsystem. For example, the Hazcam and Navcams in GNC operate nominally with 6V, while the main CDH computer operates with 5V. Since the PDU has to be designed specifically for the other subsystems on Endurance, this cannot be taken from another mission or off the shelf from a vendor. However, circuit components (i.e. the boost and buck converters) within the PDU are chosen based on their use in other space missions. An experienced vendor (L3Harris) will be contracted to manufacture the PDU with the following layout specified. See the figure below for a block diagram of the PDU.

Figure 22.2: Power Distribution Unit Block Diagram



The TRL of the EPS is determined by the TRL of its subassemblies. Since the solar array technology is taken almost mostly from the successful Mars Phoenix mission, it may have a TRL of 5. The batteries will be very similar to the Li-ion batteries that were tried and tested in the spirit and opportunity rovers, and are bought off the shelf from EaglePicher, who has extensively tested them for space applications, so the TRL may also be 6. Lastly, the PDU will have to be designed specifically for the power requirements of Endurance's other subsystems, but it can be made with circuit components like buck and boost converters that have been tried and tested on past Mars missions, so the TRL may be 5. This puts the EPS at an overall TRL of around 5.

The table below shows a summary of the mass, stowed volume, and TRL of each EPS subassembly.

Figure 23: EPS Sub-assembly Summary

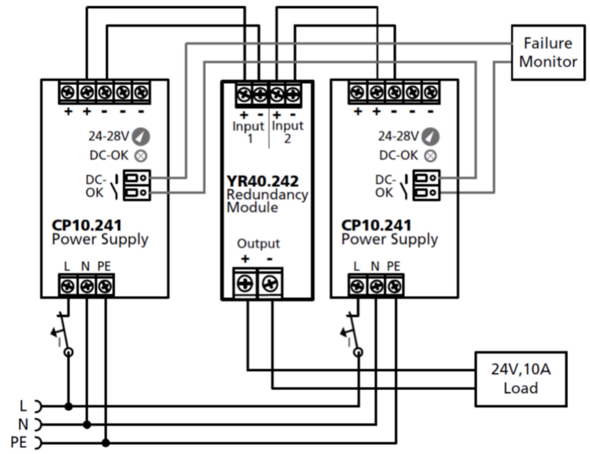
Subassembly	Mass (kg)	Stowed Volume (cm)	TRL
Battery pack	3.2	4x10x6	6
PDU	1	8x6x2	5
Solar Array	2	80x5x2	5
Total	6.2	n/a	5

2.1.2.3. Subsystem Recovery and Redundancy Plans

Battery Redundancy:

The power subsystem will have two battery packs and while both are operational there will be a large margin of power for peak power draws. If one of the batteries fails the other can compensate and be used though there will be a lower margin of power for peak power draws. Having an extra battery pack is important since without power the rover will be inoperational and the mission will not be able to continue.

Figure 24 - Example of Power Supply Redundancy



Battery Recovery:

If one of the batteries is damaged and not providing power anymore the rover will be able to detect that decrease and automatically increase the input of the other battery to subsidize. In addition, the rover will be able to manage power draw using the PDU so that it is not drawing excess power which is not being used for any function at that time. The PDU will be able to manage what subsystem is getting power at a certain time and if a certain subsystem requires extra power at a time it will be able to provide that.

Solar Array Redundancy:

Solar panels are expensive and very large, taking up a large percentage of the rover's allocated weight and space, therefore it is not possible to implement redundancy; they would be SPF's. This is okay since the solar panels have been used previously in space and are a reliable choice with minimal chance of destruction. If one solar panel in the array becomes damaged the rest will still be functional although a bit less effective, in this way the solar array already has redundancy built into it so no extra redundancy is necessary.

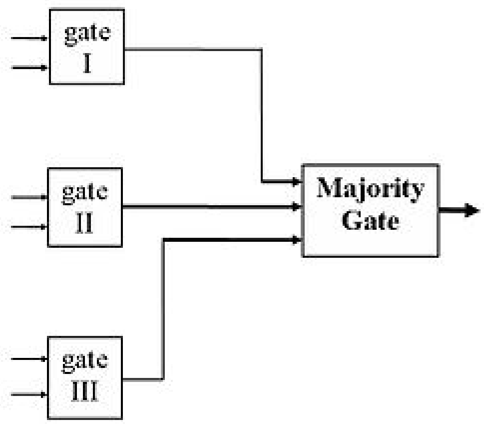
Solar Array Recovery:

If the solar panels become damaged and start charging the batteries slower the rover will be able to detect that and adjust and increase the standard charging time the rover takes. In addition, the rover will be able to determine what section of the solar array has been damaged by its positioning in relation to power charge.

Electric Circuits Redundancy:

Electric circuits used for moving power around the rover will be isolated in order to prevent damage of one section from affecting another. The electric circuits will also have redundancy built into them with multiple wires in a circuit and not just a straight connection using a single wire from the PDU to the subsystems' components.

Figure 25 - Example of Triple Modular Circuit



Electric Circuits Recovery:

If the electric circuits are broken there is no way to fix them while the rover is in space. However, since there will be multiple routes for electricity to get to each component, the EPS will be notified if a component is not receiving power and try rerouting the power.

2.1.2.4. Power Subsystem Manufacturing and Procurement Plans

Li-On Batteries

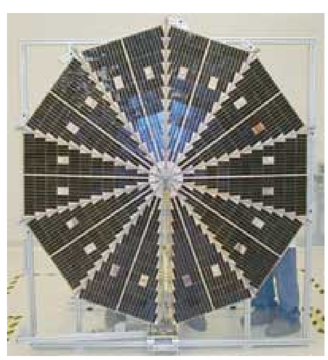
The supplier for Li-On batteries is EaglePitcher Technologies. They were selected since "off the shelf" is cheaper than getting custom batteries designed; however, they also provide custom batteries if asked. The batteries from Eagle Picher were used in multiple other successful Mars missions such as Spirit/Opportunity as well as Perseverance, and Eagle Picher supports missions throughout the entire lifecycle. They offer design flexibility, made-to-order solutions, and offer custom cells and batteries if requested. The batteries also meet all requirements of a high specific energy (>250 Wh/kg), long cycle life (>1000 Cycles @ >70% DOD), long calendar life (>5 Years), and low temperature operation (<−20°C). The Li-On batteries are very reliable with little to no passive discharge. They also have a high power-to-weight ratio, are rechargeable, and are very fast to activate. The lead time of the battery can be up to a year for all design and testing if the battery is customized and up to 20 weeks if a preset battery is chosen (epectec). The price of the battery can range from 5,000 to 20,000 depending on how much the battery is customized (lawnlove).

Figure 26 - EaglePitcher LP33081 30-Ah Space Cell

Solar Array - UltraFlex 175

The supplier is Northrop Grumman because the UltraFlex 175 is the only modern solar array already designed that fits all of the needs of the missions. This array was designed by ATK space but that company has been absorbed by Northrop Grumman. This solar array is capable of providing 7kW of power and a specific power of 175W/kg. The array is designed to have a large area electrically active and be sturdy enough to have a high structural frequency. This solar array also is built with storage in mind in order to have a minimal volume when stowed. The solar cells used on the array are triple junction and have a 28% efficiency. This design will be validated by the manufacturer with a 5.5m diameter solar array in air and a vacuum chamber. Other companies can make solar arrays in 6-9 months which would be considered short for this product. Realistically, it could take between 1-2 years for this complex solar array to be fully built and possibly another year for testing (sparkwing). The cost for just the array not including testing will be around $20,000 (solarreviews).

Figure 27 - UltraFlex 175



Power Distribution Unit (PDU)

The supplier is L3Harris. They made electrical power systems for Curiosity and Perseverance. L3Harris's PDUs have fault protected outputs. Their PDUs also can have two power inputs allowing connection to up to two batteries. The PDU also has an operating temperature of -54 to 71 celsius. The expected lead time could range from 4 to 28 weeks depending on if there are any customizations made to the PDU (raptorpwr). The cost can range from $700 to up to $2000 also based on customizations (eatonguard).

Figure 28 - Example of PDU System L3Harris can create

Additional Parts

There will also be some additional parts which are needed such as wires, resistors, transistors, logic gates, ect.

2.1.2.5.Power Subsystem Verification Plans

The following table goes over the verification method for each Power Subsystem requirement, the reason for choosing that method, and a plan for achieving that verification.

Figure 29 - Power Subsystem Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
EPS-1	Any radioactive material used shall not exceed a cumulative mass of 5g.	Inspection	This method was chosen because it is the only way to determine if there is radioactive mass exceeding 5g on the rover.	This will be done through an examination of the EPS to see if there is any radioactive material.
EPS-2	All hardware for the Electrical Power System shall not exceed a total mass of 12kg	Inspection	This method was chosen because weighing the Electrical Power System is the only way to determine if the total mass exceeds 12kg.	This will be done by weighing the EPS system.
EPS-3	The Endurance Rover shall supply continuous power to subsystems as needed for the entire mission duration	Demonstration	This method was chosen because only through demonstration can it be determined if the rover can supply power to its systems appropriately.	This will be done by running the EPS and seeing if all subsystems operate.

EPS-3.1	The Electrical Power System shall generate sufficient power for all subsystems to perform as intended	Analysis	This method was chosen as by analyzing the power generated can it be determined if the power is sufficient.	This will be done by running computer simulations and qualitative analysis of what is sufficient.
EPS-3.2	The Electrical Power System shall store power while it is being generated	Inspection	This method was chosen as inspecting the power storage system can be determined if it is functional.	This will be done through a review of the storage systems specs.
EPS-3.3	The Electrical Power System shall safely distribute and control all of the power generated	Test	This method was chosen as by testing it can be made clear that the electric power system is safe and controlled.	This will be done by testing the EPS using equipment to detect if there is any power being leaked.
EPS-3.3.1	The Electrical Power System shall provide bus isolation between upstream and downstream loads	Analysis	This method was chosen because the bus isolation is part of the design.	This will be done through analog modeling.
EPS-3.3.3	The Electrical Power System shall protect components from electromagnetic interference, transients, bus faults, and load faults.	Analysis	This method was chosen as running simulations would be most cost effective to show this without the chance of breaking components.	This will be done through computer simulations.
EPS-3.4	The Electrical Power System shall provide enough power with margin for peak loads	Analysis	This method was chosen as testing the EPS could worsen its effectiveness.	This will be done through computer simulations.
EPS-3.5	The Electrical Power System shall interface properly with each system onboard	Test	This method was chosen as before launch ensuring that every component is properly connected to EPS is crucial.	This will be done by testing each system on board individually and measuring if they are receiving power.
EPS-3.6	Electrical Power System components shall be kept within their respective safe operating temperature range	Test	This method was chosen as before launch ensuring every component is not exceeding temperature range will make sure no unexpected issues pop up when in operation.	This will be done by testing each component in the EPS using a temperature scanner and comparing the values with the safe range.
EPS-3.7	The Electrical Power System shall provide operating status	Test	This method was chosen since there are multiple factors to test to see if the	This will be done by testing the EPS using tools such as a voltage tester and

	(voltage, current, temperature, etc.)		EPS operating status is accurate.	temperature scanner to see if the status listed matches the tested values.

2.1.3. CDH Subsystem Overview

The CDH subsystem consists of two overarching subassemblies: Data Computing and Telecommunications. The role of the Data Computing subassembly is to act as Endurance's brain. This includes the onboard computers, which are responsible for processing data, executing commands, system management, and controlling the rover's various subsystems and instruments. The role of the Telecommunications subassembly is to handle all communication functions between the Mars rover and the MRO or directly with the DSN on Earth. This includes signal transmission where the rover sends data and telemetry back to Earth; signal reception where the rover receives commands and software updates from Earth; and communication links, which is how the rover maintains the communication links via the MRO or directly with Earth.

Interaction between telecommunications and data computing is underway constantly and helps carry out several mission critical functions. These two subassemblies facilitate the reception and execution of commands. Commands sent from mission control on Earth are received by the telecommunications subassembly, which then relays them to the data computing subassembly. The onboard computer processes these commands and carries out actions accordingly. Data handling and transmission is another crucial function of these two subassemblies. This is where health evaluation and data collected by the rover's instruments is processed by the data computing subassembly. This processed data is then packaged and relayed to the MRO every 112 minutes over the span of 6 minutes where connection can be made between the Mars orbiter and the Endurance Rover. Provided this tight window to transmit and receive data from the MRO, synchronization between telecommunications and data computing is key. This ensures commands are executed in a timely manner and data is sent during appropriate communication windows when links with the MRO are available. Lastly, these subassemblies work closely with one another to facilitate the execution of error handling and diagnostics. If the telecommunications subassembly detects issues in data transmission (signal loss or corruption), the data computing subassembly can be commanded to re-send data or perform diagnostic checks. Additionally, as outlined in the Concept of Operations EOL section, the data computing subassembly may even command the rover to perform pre-programmed routines to reestablish contact. This may include driving in circles until connection is made with Earth or backtracking to prior locations where connection was previously established.

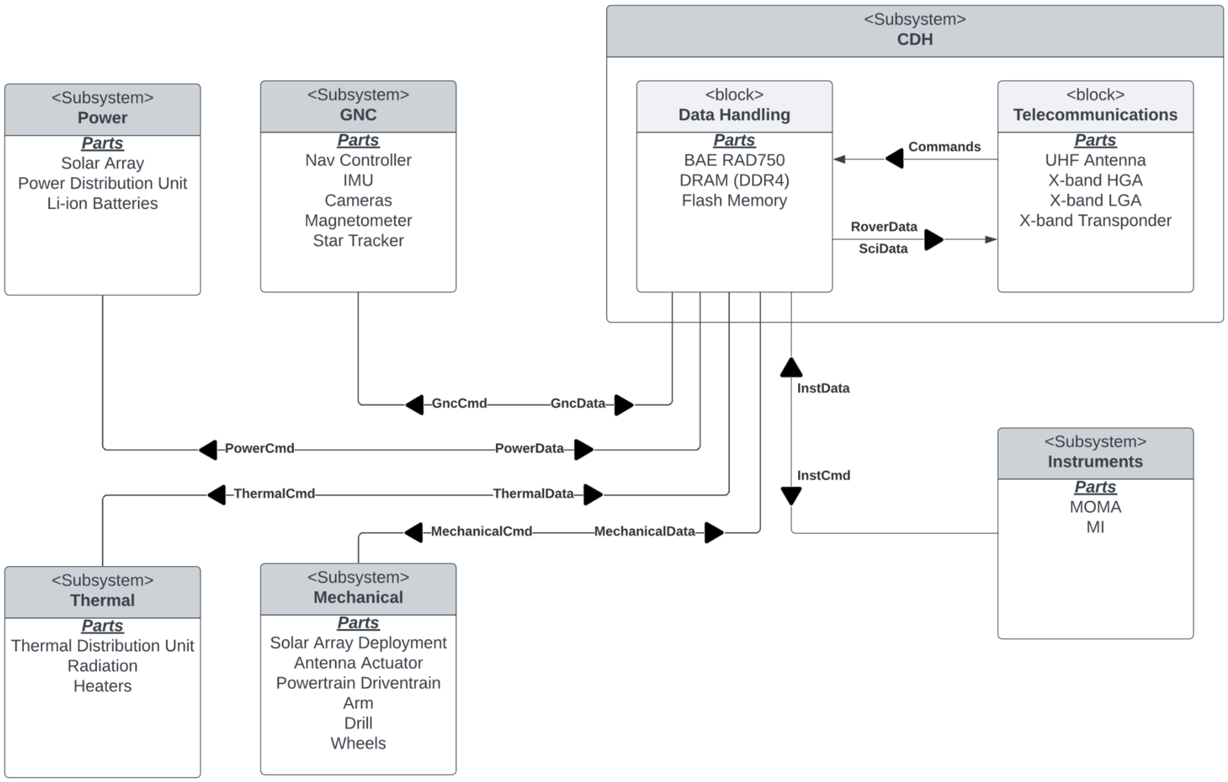
The accompanying table delineates the specifications of critical subcomponents within the telecommunications and data computing assemblies of the CDH subsystem. For telecommunications, this subassembly consists of the Ultra-High Frequency Antenna (UHFA), X-band High Gain Antenna (HGA), X-band Low Gain Antenna (LGA), and X-band Transponder. For data computing, this sub-assembly consists of the BAE RAD750 processor, flash memory, and DRAM. Each subcomponent is analyzed in terms of mass (kg), volume (cm^3), and maximum power draw (W).

Figure 30 - CDH Sub-Assembly Data Table

Sub-Component	Mass (kg)	Volume (cm^3)	Max Power Draw (W)
UHFA	1.5	3x3x12	5.0
HGA	2.0	5x5x10	8.0
LGA	1.0	3x3x5	3.0
Transponder	1.5	6x6x3	5.0
BAE RAD750	0.4	4x3x1	12.0
Flash Memory	0.2	5x5x1	1.0
DRAM	0.2	4x3x1	2.0
Total	**6.8**	**30x28x33**	**36.0**

The discussion of the CDH subsystem's subassembly functions components leads to the software architecture of the Endurance Rover. The Software Architecture Flowchart below provides a systematic overview of the data processing and command execution paths, highlighting the integration of the rover's CDH, GNC, Mechanical, Thermal, Power, and Payload subsystems. It is a critical element that ensures the effective data management and reliable command execution which are essential for the rover's operational success. The flowchart presented below offers an organized visual representation of these complex interactions within the Endurance Rover's systems.

Figure 31 - Software Architecture Flowchart



2.1.3.1. CDH Subsystem Requirements

The CDH subsystem requirements establish the mission constraints to which the vehicle design must adhere and delineate the essential functionalities needed to achieve the science goals. The top-level mission requirements, specifically CDH-1 and CDH-2, outline the telecommunication parameters for the Endurance Rover as provided by the stakeholders. CDH-1 details the rover's capability to send and receive communications, while CDH-2 focuses on the specifics of data transfer. These requirements specify that the rover must manage data transfers within a 6-minute window occurring every 112 minutes and stay within a 250 MB data cap every 24 hours. CDH-3 and CDH-5 primarily emphasize the health of the rover. CDH-3 accounts for the highly radioactive surface of Mars, where radiation doses are up to 700 times higher than on Earth (ESA, 2024); it is crucial to consider this to protect the integrity of the onboard electronics. Furthermore, CDH-5 states a straightforward yet essential requirement: the Endurance Rover must remain operational throughout the duration of the mission. This condition is vital to ensure the set objectives are met. Highlighted by CDH-3, the imperative need for an onboard computer is noted; without it, data cannot be processed, which is crucial for all functionality on the rover. Beyond these top-level requirements, they are further refined into more narrowly focused specifications, such as CDH-1.1 and CDH-2.1.1, derived from the top-level parameters described above.

For a comprehensive understanding of how these requirements interconnect and the verification methods employed to ensure they are met, please refer to the detailed table below.

Figure 32 - CDH Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
CDH Reqs							
CDH-1	The spacecraft shall send and receive communications to and from Earth via the MRO and DSN.	Provided by Mission Document.	Customer	CDH-1.1	Test	CDH	Met
CDH-2	The spacecraft shall adhere to the communication window and data volume allocated by the MRO.	Provided by Mission Document.	Customer	CDH-2.1, CDH-2.2	Test	CDH	Met
CDH-3	The rover shall utilize radiation-hardened components to meet defined Martian radiation exposure thresholds.	Protects the rover's electronic systems against the harmful Martian solar and cosmic radiation.	N/A	All	Inspection	CDH	Met
CDH-4	The rover shall have an onboard computer.	Provides the primary computational power needed for all rover functions.	N/A	CDH-4.1, CDH-4.2, CDH-4.3, CDH-4.4, CDH-4.5	Test	All	Met
CDH-5	The rover shall remain operational for the duration of the mission.	Guarantees the rover's sustained operation throughout the entire mission life.	N/A	All	Demonstration	All	Met
CDH-1.1	The rover shall implement an X-band transponder compatible with MRO communication protocols.	To ensure that the rover can communicate effectively with the MRO using the allocated frequency band.	CDH-1	CDH-1.1.1	Inspection	CDH	Met
CDH-1.1.1	The rover shall include X-band antennas to transmit data and receive commands.	Multiple antennas provide redundancy and ensure the rover can communicate with the MRO and Earth for the duration of the mission.	CDH-1.1	N/A	Test	CDH	Met
CDH-2.1	The rover shall include a communication scheduling system that adapts to the dynamic availability of the MRO.	Precise timing is required to utilize the communication window with the MRO effectively.	CDH-2	CDH-2.1.1	Test	CDH	Met
CDH-2.2	The rover shall compress data to a minimum of 2:1 ratio for transmission to MRO.	To maximize the data volume transmitted within the 250 MB daily limit.	CDH-2	N/A	Test	CDH	Met
CDH-2.1.1	The rover shall include an onboard clock synchronized with MRO time to facilitate timely communication.	Precise timing is required to utilize the communication window with the MRO effectively.	CDH-2.1	N/A	Test	CDH	Met
CDH-4.1	The onboard computer shall be capable of direct interfaces with all the rover components.	Enables the integration and coordination and coordination of all rover subsystems and instruments.	CDH-4	CDH-4.1.1	Test	All	Met
CDH-4.2	The onboard computer shall be capable of storing and processing incoming and outgoing data.	Allows the rover to manage and utilize the data it generates and receives.	CDH-4	CDH-4.2.1, CDH-4.2.2	Test	All	Met
CDH-4.3	The rover shall have a secondary computer for redundancy if the primary computer malfunctions.	Provides an operational backup to maintain functionality if the primary system fails.	CDH-4	N/A	Inspection	CDH	Met

CDH-4.4	The onboard computer will be equipped with a processor that provides the instructions and processing power the rover needs to work.	Supplies the necessary computational capability to process data and execute commands.	CDH-4	CDH-4.4.1	Test	All	Met
CDH-4.5	The onboard computer shall be equipped with volatile and non-volatile storage	Ensures data is retained correctly during power cycles and in the event of system interruptions.	CDH-4	CDH-4.5.1, CDH-4.5.2	Inspection	CDH	Met
CDH-4.1.1	The onboard computer shall be capable of conducting routine health evaluations.	Ensures the rover can perform self-checks to monitor its health status.	CDH-4.1	N/A	Test	All	Met
CDH-4.2.1	The computer shall be capable of using antennas to offload data to the MRO.	Allows for efficient data offloading to the MRO, utilizing the communication infrastructure.	CDH-4.2	N/A	Test	CDH	Met
CDH-4.2.2	The onboard computer shall be able to process data received from Earth.	Ensures the rover's onboard computer has sufficient processing capabilities to interpret and act on commands received from Earth.	CDH-4.2	N/A	Test	CDH	Met
CDH-4.4.1	The processor shall operate at a minimum of 100 MHz.	Specifies the processing speed required for the rover's computational tasks.	CDH-4.4	N/A	Inspection	CDH	Met
CDH-4.5.1	The onboard computer shall have a minimum 256 MG of volatile memory.	Defines the amount of volatile memory needed for the rover's operational processes.	CDH-4.5	N/A	Inspection	CDH	Met
CDH-4.5.2	The onboard computer shall have a minimum 2 GB of non-volatile storage.	Determines the required capacity for long-term data storage on the rover.	CDH-4.5	N/A	Inspection	CDH	Met

2.1.3.2. CDH Sub-Assembly Overview

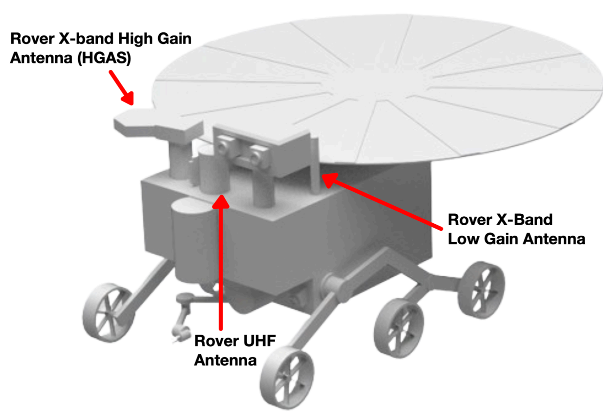
The Command and Data Handling (CDH) sub-system is a crucial component of the Endurance Rover, acting as the brain, orchestrating the rover's operations and ensuring its survival. It handles data management, from processing scientific discoveries to overseeing communications with Earth. Additionally, it executes commands from mission control, manages power supply and battery health, and oversees all subsystems and payloads to keep track of the rover's health and operational status. The CDH maintains precise timekeeping, navigates the rover through Martian terrain, executes strategic maneuvers, and autonomously monitors and addresses any anomalies. To enable these vital functionalities, the Command and Data Handling sub-system is broken down into three sub-assemblies: telecommunications, data computing, and software architecture, which in conjunction with one another ensure science objectives and success criteria are being fulfilled.

The telecommunication sub-assembly is comprised of an X-band Transponder and three antennas: an Ultra-High Frequency Antenna, an X-band High-Gain Antenna, and an X-band Low-Gain Antenna, which enable the rover to transmit data and receive instructions to and from Earth. The rover's primary method of communication will be facilitated through the UHF (Ultra-High Frequency) antenna, which will transmit and receive data through the MRO (Mars Reconnaissance Orbiter) every 112 minutes for a communication window of 6 minutes. Given the importance of communication to mission success, it is vital to implement redundancy so that the Endurance Rover can communicate at all times. Therefore, the high and low-gain antennas will provide backup options and flexibility in case they are needed.

The high-gain antenna can communicate directly with the DSN (Deep Space Network), capable of transmitting and receiving data to and from Earth at higher data rates compared to the low-gain antenna. This antenna is directional, indicating that it must point in a specific direction to properly transmit and receive data. To enable this, the high-gain antenna will be steerable, allowing the free flow of communications while being of low impedance to any operations the rover may be carrying out.

The low-gain antenna has a lower data rate in comparison to high-gain and will provide a reliable way of fulfilling the rover's basic communication needs. The low-gain antenna is capable of solely receiving data directly from the DSN, and in contrast to high-gain, the low-gain antenna is omnidirectional, allowing it to receive data regardless of its orientation. This allows low-gain antennas to excel at receiving basic commands, which are crucial to maintaining control of the rover and helping ensure mission success.

Figure 33 - UHF, HGA, & LGA Antenna on Endurance Rover

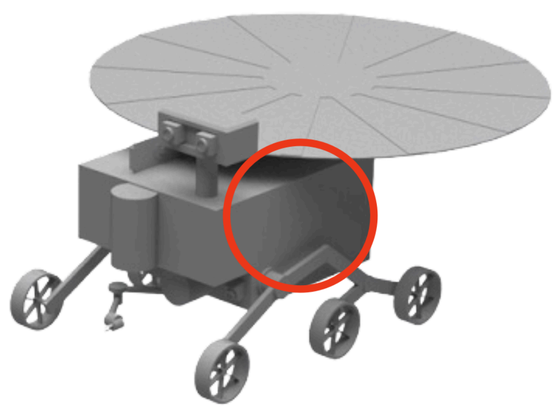


The X-band Transponder is a key component in the telecommunication system of the Mars rover, effectively working in tandem with the UHF, low-gain, and high-gain antennas. Its primary role is to facilitate two-way communication, acting as the rover's communication processor, managing both incoming and outgoing signals. The transponder processes and modulates signals by varying signal amplitude, frequency, or phase to prepare them for transmission through the appropriate antenna based on communication needs.

Through careful analysis and consideration, the CDH sub-team has evaluated the telecommunication sub-assembly TRL, based on the lowest sub-component TRL, to have a level of 6. This evaluation was primarily based on the premise that all the components mentioned for telecommunications have been previously used in past Mars missions, most notably, the 2020 Perseverance Rover Mission. However, given that the Endurance Rover will be operating with different components in a different location than previous rovers that have operated on the Martian surface, this justifies the decrease in TRL. Therefore, this categorizes the telecommunications sub-assembly as TRL 6, which states: “System/subsystem model or prototype demonstration in a relevant environment (ground or space).” Although this is not ideal, testing can be performed to bring the TRL up to a preferable level.

The data computing sub-assembly, a crucial component of the Endurance Rover, is powered by a BAE RAD750 processor and supported by DRAM and flash memory for volatile and non-volatile storage, respectively. To facilitate communication between the data computing sub-assembly and all other sub-systems, data is retrieved and commands are sent utilizing SpaceWire, a type of data bus. These sub-components collectively form the ‘brain’ of the rover, playing an essential role by ensuring efficient handling of all data and commands. This setup is vital for the rover’s performance, enabling it to process instructions, manage tasks, and store valuable information as required.

Figure 34 - Data Computing Location of Endurance Rover



The BAE RAD750 sub-component is a highly robust and reliable processor designed by BAE Systems, specifically for the harsh environments of space. The rover’s processor is responsible for all computational tasks, which include executing commands sent from Earth, processing data from the rover’s various scientific instruments, and managing day-to-day operations. Furthermore, the processor is also required to process real-time data, such as rover navigation and communication. The RAD750’s architecture is based on the PowerPC 750 and operates at speeds up to 200 MHz, making it more than sufficient to perform any computational tasks required by the Endurance Rover, while keeping power consumption minimal. One of the key features of the RAD750 lies in its tolerance to the harsh, Martian environment. This processor remains operational in temperatures ranging from -55ºC to +125ºC, which significantly outcompetes the tolerance of standard processors. Furthermore, the RAD750 has a radiation-hardened central processor, which enables it to withstand a total ionizing dose of 1 Mrad(Si). Taking into consideration the computing power, radiation resistance, and durability required for long-duration space missions that are offered by the RAD750, this processor will ensure the science objectives and success criteria are being fulfilled.

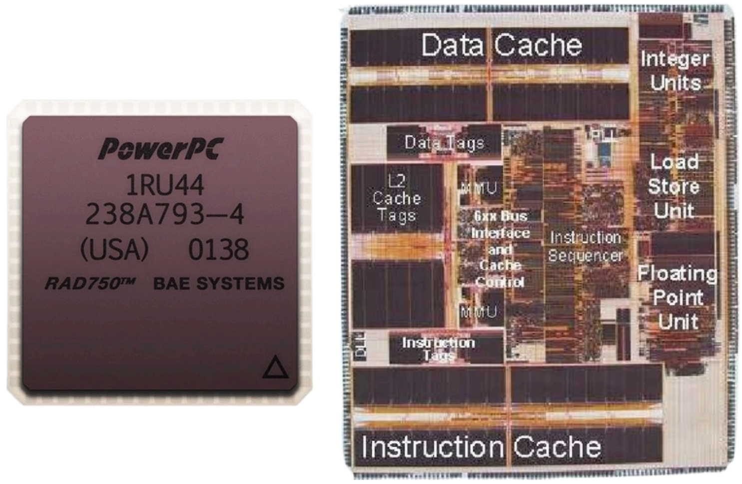
Despite the impressive specs of the BAE RAD750 processor, various other processors, including the Leon (GR740) and the Atemel (AT697F), were considered when determining a sub-component that was the best fit for the Endurance Rover. The decision was guided by six critical criteria: cost, Technology Readiness Level (TRL), speed, radiation tolerance, temperature resistance, and power efficiency. Given the mission's unique challenges, the CDH sub-team assigned the greatest significance to TRL and power efficiency, reflecting the mission's priorities.

TRL, accounting for 24% of the decision weight, was deemed paramount. The reliability of computer components is non-negotiable for mission success, necessitating a proven track record in similar environments. Power efficiency also received significant emphasis, particularly because of the anticipated limited sunlight in the rover's primary operational areas, impacting the availability of solar energy.

The BAE RAD750 emerged as the leading choice, largely due to its high TRL. Its current use in the Perseverance Rover attests to its reliability and suitability for Martian missions. While the Leon and Atmel processors have been utilized in various space missions, their lack of deployment on Mars marked a disadvantage in terms of TRL. Additionally, the RAD750's power efficiency set it apart, showcasing its ability to operate optimally with minimal energy consumption compared to its rivals, the Leon and Atmel processors. This blend of high TRL and superior power efficiency ultimately positioned the RAD750 as the ideal processor for the Endurance Rover, promising reliability and adaptability in the demanding Martian environment.

For further information on how this evaluation was conducted, please refer to the processor trade study table in the appendix. This is contained in the Appendix 1.3.1 Processor Trade Study section.

Figure 35 - BAE RAD750 Structure



The flash memory sub-component is a type of non-volatile storage and serves as a critical data repository aboard the Endurance Rover, ensuring that scientific discoveries and operational data are securely stored and ready for transmission to Earth. As previously mentioned, the MRO provides the rover with a 6-minute window every 112 minutes to send its data back to Earth. The rover’s flash memory plays a pivotal role during these brief windows, staging up to 250 MB of data for daily transmission via the MRO, and ensuring the data collected that is not offloaded will not be lost.

In determining the optimal form of non-volatile storage for the Endurance Rover, a trade study was conducted where two other forms of storage were evaluated: MRAM (Magnetoresistive Random-Access Memory) and FRAM (Ferroelectric RAM). Despite MRAM and FRAM surpassing Flash Memory in several key areas including power efficiency, cost-effectiveness, speed, temperature resilience, and radiation hardiness, the decisive factor was their Technology Readiness Level (TRL). The Command and Data Handling (CDH) sub-team prioritized TRL in its decision-making process, recognizing that the rover's reliability hinges on the performance of its computer system.

While MRAM and FRAM offer superior specifications in many respects, Flash Memory's extensive track record and NASA's comprehensive understanding of its behavior make it the safer choice. This depth of knowledge enables the CDH team to better predict and mitigate potential software failures. In contrast, the relatively limited flight heritage of MRAM and FRAM introduces a degree of unpredictability that could pose risks to mission success. Therefore, despite the appealing attributes of MRAM and FRAM, the team opted for Flash Memory, valuing proven reliability and predictability in this mission-critical component.

For further information on how this evaluation was conducted, please refer to the processor trade study table in the appendix. This is contained in the Appendix 1.3.3 Non-Volatile Storage Trade Study section.

The DRAM sub-component, and specifically its fourth-generation DDR4 type, is a form of volatile memory that the Endurance Rover uses for its immediate data processing tasks. This memory is essential for the rover's operations as it temporarily holds the data that the RAD750 needs to access quickly. This includes running calculations for navigation, processing sensor inputs, executing commands from Earth, and various other vital computations that are imperative for mission success. Given the limited time frame allocated to the Endurance Rover to offload large quantities of data, it is crucial that the rover processes and packages data efficiently with these windows. Therefore, given DDR4 DRAM's fast read and write speeds, this allows for the rover to make the most out of these 6-minute communication slots.

In the search for the superior volatile memory to power the Endurance Rover, a trade study was conducted where various forms of memory were evaluated: DRAM, Infineon SRAM, and SDRAM. The decision was guided by six criteria: cost, TRL, speed, radiation tolerance, temperature resistance, and power efficiency. Given the mission's unique challenges that place the rover at the poles of Mars where sunlight is limited and how the failure of these computer components could jeopardize mission success, TRL and Power Consumption were weighted the highest at 25%.

Although DRAM and Infineon SRAM came very close, with a margin of only 1.5%, the ultimate deciding factor became the variations in their speed. On the other hand, SDRAM barely contended with the other forms of memory. Based on this evaluation, the CDH sbu-team was able to deduce that DRAM (DDR4) is the optimal form of volatile memory to be used in the Endurance Rover.

For further information on how this evaluation was conducted, please refer to the processor trade study table in the appendix. This is contained in the Appendix 1.3.2 Volatile Memory Trade Study section.

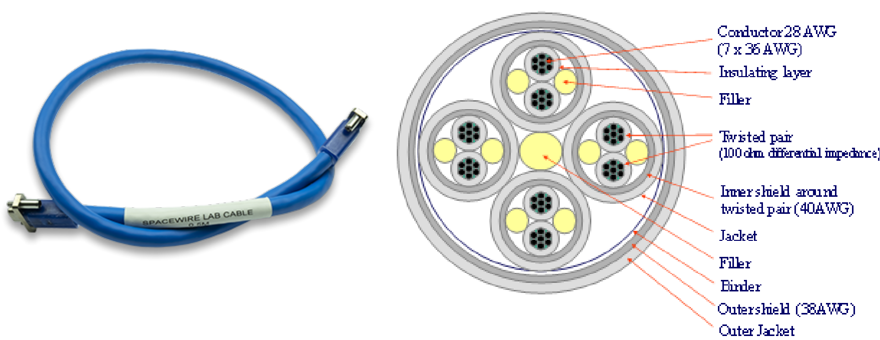
The SpaceWire data bus sub-component is essential for facilitating high-speed data transfers and command execution between the main computer and the rover's sub-systems, including Power, GNC, Thermal, Mechanical, and all scientific instruments. With an operating temperature ranging between -200ºC to +180ºC, a radiation resistance of up to 300 Mrad, and a data transfer rate of up to 400 Mb/s, SpaceWire offers durability and efficiency. This ensures seamless and secure data flow throughout the rover, enabling it to perform its tasks reliably.

In determining the superior data bus for the Endurance Rover, various promising data buses were evaluated, including SpaceWire, MIL-STD-1553, and 1553B. In this evaluation, the data bus options are assessed across several key criteria for the Mars rover operation: Power, where Sunlight is a scarce commodity at the poles; Cost, which is critical due to the strict budget cap; Speed, essential for the data transfer within limited time windows; Temperature, as the rover will face extreme thermal conditions; Radiation, considering Mars' high radiation levels that can impact electronics; and Technology Readiness Level (TRL), indicating the maturity of the technology.

SpaceWire stands out with its high transmission speed and superior tolerance to radiation, both of which are imperative for Mars' extreme conditions. MIL-STD-1553, commonly used in various spacecraft, shows reliable performance across the board. However, it does not lead in any specific category. When analyzing the total weighted scores, SpaceWire emerges as the preferred choice for the Endurance rover mission. Its advantages in critical areas such as data transfer speed and resistance to radiation make it the prime candidate for the demands of the Martian environment.

For further information on how this evaluation was conducted, please refer to the processor trade study table in the appendix. This is contained in the Appendix 1.3.4 Data Bus Trade Study section.

Figure 36 - SpaceWire Structure



Through careful analysis and consideration, the CDH sub-team has evaluated the data computing sub-assembly TRL, based on the lowest sub-component TRL, to have a level of 6. This evaluation was based upon various factors, and given the BAE RAD750, Flash Memory, and DRAM are all components used in past Mars missions, most notably, the 2020 Perseverance Rover Mission, this sub-assembly would receive a TRL of 9. However, given that the Endurance Rover will be operating with different components in a different location than previous rovers that have operated on the Martian surface, this justifies the decrease in TRL. Additionally, given that SpaceWire is being used in many high-profile scientific applications, including Gaia, ExoMars, BepiColombo, the James Webb Space Telescope, and other space-related missions but none on Mars, this categorizes the data computing sub-assembly as TRL 6. This technology readiness level states the following: “System/subsystem model or prototype demonstration in a relevant environment (ground or space).” Although this is not ideal, testing can be performed to bring the TRL up to a preferable level.

The software architecture sub-assembly directs every aspect of the rover’s activities. At its core, the software enables the rover to process and execute commands from Earth, manage and compress scientific data for transmission, and ensure optimal communication timing with the MRO for data relay back to Earth. The software is responsible for features such as autonomously monitoring the rover’s health, as well as diagnosing and addressing any issues to maintain operational integrity. Furthermore, the software controls the rover’s movements and operations, directing sub-systems such as power management, navigation, thermal regulation, and the operation of scientific instruments. This allows the rover to adapt to the ever-evolving Martian environment, conduct scientific research, and communicate findings efficiently back to Earth. Essentially, the software ensures the rover can independently perform its tasks, respond to new commands, and adapt as new challenges arise.

Given that the telecommunication and data computing sub-assemblies were both evaluated at a TRL level of 6, this places the entire CDH subsystem at a TRL level of 6. As stated in the previous sub-assembly TRL evaluations, this technology readiness level states the following: “System/subsystem model or prototype demonstration in a relevant environment (ground or space).” Although this is not ideal, testing can be performed to bring the TRL up to a preferable level, which will ensure a higher rate of mission success.

2.1.3.3. CDH Subsystem Recovery and Redundancy Plans

Antenna Redundancy/Recovery:

Redundancy: The CDH subsystem has three antennas, so in the event that one gets lost, the two remaining ones will be in a position to redeem that loss. It is this redundancy that is important in ensuring that communication with Earth is maintained all through the mission. The design also keeps changing to another antenna without breaking data links, thus increasing reliability.

Recovery: CDH design includes an antenna recalibration protocol, which enhances the assurance of the correct working of the antennas even when various unforeseen conditions, or if at all unexpected circumstances, occur. That is, routines and operational checks are established, and it proves that the alignment and operations are done automatically at preset periods.

Computer Component Redundancy/Recovery:

Redundancy: Built around a single processor with high radiation and heat tolerance, therefore reducing failure under space conditions. This firmware supports both the isolation and management of faults from those critical processing functions that can be efficiently isolated.

Recovery: In case of the processor failure in json exception, the CDH system can reboot to restore the mission operation functionality. The system also has a diagnostic software package that can identify and repair hardware and software errors by flagging them for human corrective action without interacting with the human.

Storage Redundancy/Recovery:

Redundancy: The data storage in CDH has volatile and non-volatile memory units for securing the data. The other kind of memory is there in the failure of one kind to store and secure data. This simply means such a dual memory approach would be ensuring that data is indeed not just backed up but also immediately available in any different formats. Further, the other memory which is non-volatile keeps data for the long run, therefore it offers stability and reliability of the system even during power failure and system booting up.

Recovery: allows rebooting of the memory systems to recover from failures without ever letting data integrity and availability be compromised. In such a case, automation is done to allow the error-checking routines to continually scan the integrity issues of the data, and when the system discovers a problem, it tries to put things together instantly. Critical errors of such type may be withstood by the system, which can also switch operations to a backup memory unit, and in the course of time, keep this unit available for thorough recovery without stopping or impairing continuous system operation.

2.1.3.4. CDH Subsystem Manufacturing and Procurement Plans

Antennae (UHF, XHG, & XLG)

L3Harris Technologies is a leader in developing sophisticated communication technologies for both aerospace and defense technology applications. Their vast and diverse history in space communications make them highly dependable, especially when considering that “for 20 years, every U.S. Mars rover and orbiting spacecraft mission has used L3Harris transceivers - including the Electra-Lite and Electra on both the current Perseverance lander and orbiting spacecraft respectively” (“Spacecraft

Communications," 2024). L3Harris's expertise in various frequencies, including UHF, XHG, and XLG, extensive and relevant experience in space applications, and strong track record make them an ideal contractor for the rover's antennae.

These antennas are off-the-shelf from L3Harris Technologies and will most likely require varying amounts of customization. Therefore, taking the company and possible delays into consideration, all antennas are estimated to have been manufactured and delivered within a 8 to 16 week timeframe. This takes into account factors such as processing, manufacturing, testing, and shipping phases.

Action Items:
Antenna Specifications: This antenna will be finalized only after deep discussions with L3Harris Technologies about the exact antenna to be used for all three (UHF, XHG, and XLG) types of required missions.

Schedule of Bi-monthly review meetings: Schedule of bi-monthly review meetings with L3Harris relative to the development phases of Antennae, processing, manufacturing, and testing.

Quality Assurance Check: A very detailed quality assurance process should be developed in a check on the functionality and reliability of the antenna under artificial space conditions.

Logistics Coordination: Delivery coordination of the antennas, at the very least, should be made timely for purposes of handling and meeting the delivery period as per the project program.

Computer Components (BAE RAD750, DRAM, & Flash Memory)

BAE Systems is renowned for its expertise in designing and developing advanced systems for civil and commercial agencies, with applications ranging from operations on Earth to missions in near space and deep space (BAE Systems, 2024). Selecting the primary computer components to be developed by BAE Systems was a strategic choice led by several key factors. Firstly, electronics developed by BAE Systems have been used extensively in space-related applications. BAE Systems (2012) reports that their RAD750 processor powers the Mars Reconnaissance Orbiter, and their radiation-hardened processors have been powering NASA rovers since 1997, used on the Spirit, Opportunity, and Perseverance rover. Picking a contractor with a comprehensive background is ideal, particularly since the rover's computer components are an integral part of the mission, making reliability a crucial factor. BAE Systems' technology is engineered specifically for harsh operating conditions, taking into consideration extreme temperatures and radiation. Therefore, this makes BAE Systems ideal, as their electronics are perfect for applications that take place in the harsh environments of Mars.

These computer components are off-the-shelf from BAE Systems and will most likely require varying amounts of customization. Therefore, taking the company and possible delays into consideration, all computer components are estimated to have been manufactured and delivered within a 12 to 18 month timeframe. This takes into account factors such as processing, manufacturing, testing, and shipping phases.

Action items:

Customization Requirement: This requires finalizing the customization requirements of RAD750 Processors, DRAM, and Flash Memory in close consultation with BAE Systems. The following components are supposed to be in compliance with special requirements to ensure they will work in a proper and reliable manner under the set harsh environmental conditions on Mars.

Integration Planning - Development, in coordination with BAE Systems, of a detailed plan of integration at the subsystems level, assuring that the computers' components delivered are fully compatible with the other rover's subsystems. The plan should include benchmarks testing, interface, and also performance testing under simulated Martian conditions.

Testing: Develop detailed testing protocols with BAE Systems to conduct long-duration tests on the computer components to ensure reliability and operational durability required for Mars-like surface radiation conditions. Certain areas of focus during this testing include long-duration testing of these computer components.

Monitoring of progress and reporting: Conduct routine progress meetings as per schedule with BAE Systems for development and manufacturing phases. Develop a timeline with milestones for manufacturing, process, testing, and delivery; provide for slippages where deemed probable.

Delivery and Logistics Management: Work with the other members of the logistics team and ensure proper planning and timely delivery of computer parts. The delivery should be planned, shipped, and handled so as to avoid damage, and synchronization should also be made with the assembly schedule of components.

SpaceWire

STAR-Dundee, recognized as a pioneer in SpaceWire technology, has a proven track record in numerous space missions. As an aerospace engineering company specializing in on-board data handling (Star-Dundee, 2019), STAR-Dundee's SpaceWire stands out for its high-speed data transfer, low power consumption, simplicity, cost-effectiveness, and architectural flexibility (Star-Dundee, 2019). These attributes are crucial for the Endurance Rover, especially in the face of stringent cost controls and the need to manage large data volumes efficiently under limited solar power. STAR-Dundee's technology has been implemented in major missions such as GAIA, ExoMars, the Lunar Reconnaissance Orbiter, and the James Webb Telescope, underscoring its reliability and performance in space exploration. Provided these factors, STAR-Dundee and its SpaceWire have been evaluated as being the ideal contractor.

SpaceWire is off-the-shelf from STAR-Dundee and will most likely require varying amounts of customization. Therefore, taking the company and possible delays into consideration, SpaceWire is estimated to have been manufactured and delivered within a 6 to 12 week timeframe. This takes into account factors such as processing, manufacturing, testing, and shipping phases.

Action Items:
Customization Consultation: Engage with STAR-Dundee to specify and finalize the customization necessities for SpaceWire to make certain it meets the information dealing with wishes of the Endurance Rover. Focus on optimizing the tool for high-speed data transfer and coffee electricity consumption below the environmental conditions predicted on Mars.

Interface Compatibility Testing: Develop a trying out plan with STAR-Dundee to ensure SpaceWire's compatibility with different rover systems. This ought to encompass rigorous checking out of the interface connections and facts switch abilities beneath simulated vicinity conditions.

Reliability and Performance Validation: Implement a sequence of reliability exams that mimic the operational environment of area missions. Leverage STAR-Dundee's enjoy fundamental missions to guide trying out protocols that determine the durability and overall performance of SpaceWire in coping with large volumes of data.

Progress Monitoring: Establish a smooth timeline for the tiers of processing, manufacturing, testing, and shipping of SpaceWire. Conduct everyday comparison meetings with STAR-Dundee to show progress toward this timeline and deal with any capacity delays directly.

Logistics Planning: Coordinate with logistics corporations to make sure that SpaceWire components are added within the expected 6 to twelve week time frame. Plan for constant and stable transportation to avoid any harm to the additives, aligning shipping schedules with the rover meeting timelines.

2.1.3.5.CDH System Verification Plans

Req #	Requirement Summary	Verification Method	Rationale for method	Preliminary Verification plan
CDH-1	Spacecraft shall send and receive communications via MRO and DSN.	Test	Customer requirements provided by mission document	Conduct testing with MRO communication protocols.
CDH-2	Spacecraft shall adhere to the communication window by the MRO.	Test	Customer requirement provided by Mission Document.	Verify communication scheduling and data volumes
CDH - 3	Rover shall utilize radiation-hardened components.	Inspection	Protects electronics against Martian radiation.	Inspect for radiation-hardened specifications.
CDH - 4	Rover shall have an onboard computer	Test	Provides primary Computational power for rover functions.	Test interfaces and processing capabilities
CDH - 5	Rover shall remain operational for mission duration.	Demonstration	Guarantees sustained operation throughout the mission.	Demonstrate operational longevity.
CDH - 1.1	Implement X - X-band transponder compatible with MRO protocols.	Inspection	Ensures effective communication with MRO using allocated	Inspect transponder and antenna compatibility.

			frequency band.	
CDH - 2.1	Include a communication scheduling system for MRO availability.	Test	Precise timing is required to utilize the communication window effectively.	Test scheduling system adaptability.
CDH - 2.2	Compress data for transmission to MRO.	Test	Maximizes data volume within the allocated limit.	Test data compression ratios.
CDH - 4.1	Onboard computer to interface with all rover components.	Test	Enables integration and coordination of all rover subsystems and instruments.	Test computer interfacing capabilities.
CDH - 4.2	Onboard computer to store and process data.	Test	Allows rover to manage and utilize the data it generates and receives.	Test data management and processing.
CDH - 4.3	Secondary computer redundancy	Inspection	Provides operational backup to maintain functionality if the primary system fails.	Inspect secondary computer operability.
Cdh 4.4	An onboard computer equipped with a processor.	Test	Supplies computational capability to process data and execute commands.	Test processor speed and efficiency.
CDH - 4.5	Onboard computers with volatile and	Inspection	Ensures data retention correctly during	Inspect memory and storage capacities.

	non-volatile storage		power cycles and system interruptions.	
CDH - 1.1.1	Rover to include X-Band antennas	Test	Provides redundancy and ensures communication for the mission duration.	Test for antenna functionality and redundancy.
CDH - 2.1.1	The onboard clock is synchronized with the MRO for timely communication.	Test	Precise timing is required to utilize the communication window effectively.	Test clock synchronization and accuracy.
CDH - 4.1.1	An onboard computer capable of conducting health evaluations.	Test	Ensures the rover can perform self-checks to monitor its health status	Test for routine health evaluation capabilities
CDH - 4.2.1	Computer to use antennas to offload data to MRO t	Test	Allows efficient data offloading to the MRO utilizing the communication infrastructure	Test data offloading efficiency and antenna usage.
CDH - 4.2.2	Onboard computer to process data received from Earth	Test	Ensures onboard computers can interpret and act on commands from Earth.	Test data processing from Earth-received commands.
CDH - 4.4.1	Processor to operate at a minimum of 100 MHz	Inspection	Specifies processing speed required for computational tasks	Inspect the processor for operational speed.

CDH - 4.5.1	Onboard computer with a minimum of 256 MB volatile memory.	Inspection	Defines the amount of memory needed for operational processes.	Inspect for memory capacity and performance.
CDEH - 4.5.2	Onboard computer with a minimum of 2GB non-volatile storage.	Inspection	Determines required capacity for long-term data storage.	Inspect for storage capacity and data retention.

2.1.4. Thermal Control Subsystem Overview

The thermal design for the rover's subsystems encompasses various methods and components aimed at ensuring efficient thermal management while maintaining reliability and optimization. Insulation methods like aerogel provide lightweight thermal resistance, while patch heaters offer reliable heating solutions. The integration of Variable Conductance Heat Pipes (VCHP) optimizes thermal control, and differential heat expansion heat exchangers aid in individual component temperature regulation. Passive structure radiators efficiently dissipate excess heat. Considering the mission's requirements and the rover's objectives, the thermal design will be set up to best optimize its performance. The thermal system of the subassembly is optimized to fit the requirements and science goals.

For example, the insulator aerogel is the lightest known solid material and has three times the density of air. Functioning better than foam and batt insulation. According to the thermal engineering handbook It achieves its insulating power by means of trapping gas and impeding convection. It turns out to be an excellent insulator, demonstrating its capacity to appropriately withstand the conduction of heat, thanks to its exceptionally high insulation qualities, lightweight construction, and thermal conductivity of roughly 0.017 W/m*K on Earth. Aerogel is an excellent insulation method for rovers, providing lightweight insulation with wonderful thermal resistance. For instance, according to NASA Mars exploration “The aerogel is encased in a low conductivity composite box structure which supports all Rover electronics. The WEB keeps all the components within their design operating range of -40C to +40C. Critical for dealing with temperature variations in the harsh situations of space exploration. Additionally, the TRL level on aerogel is 9 due to the fact that this insulator has been tested on past rover missions.

Furthermore, as far as heating methods, patch heaters emerge as a preferred option for the subsystem, in which an electrically resistant material is embedded in two Kapton-like flexible, electrically insulating layers. For example, according to the thermal engineering handbook patch heaters are versatile by design and can accommodate a single circuit or multiple circuits, the latter often used for redundancy purposes; redundancy is important because of the possibility of failure. Furthermore, according to EPEC engineering technologies “The heat is transferred to the surface that the [patch] heater is in contact with, providing a localized heating effect”. This system interacts with the components on the rover by keeping instrument panels in spacecraft and satellites from freezing in sub-zero temperatures”. It also helps keep the electronics up to temperature. The addition of patch heaters to the subsystem not only provides efficient heating but also meets the need for reliability, providing a reliable solution for temperature control in critical parts of the spacecraft. For example, according to NPH-Processes heaters, the operating temperature ranges from “60°F- 450°F and -50°C to 230°C”.

Moreover, to optimize thermal control within the rover system, a variable conductance heat pipe (VCHP) will be utilized. According to the NASA thermal engineering handbook,this layout carries a fuel reservoir related to the condenser, taking into consideration dynamic adjustments inside the active radiator based totally on the electronics container's cold-plate temperature. Furthermore As the cold-plate temperature rises, “the radiator area expands, making efficient thermal manipulation possible. The gas reservoir operates as an impermeable floating piston, compensating for multiplied vapor elevation in the evaporator with stress changes and reduces the control fuel volume, opening up a greater condenser place for warmth-pipe operation.” VCHP might also vary in reservoir control, with a few featuring wicks. In the heating process for this rover, a combination of VCHP and a resistive heater will address the limitations of each component, ensuring efficiency and effectiveness under various operating conditions. Patch heaters have a TRL of 5, as more testing needs to be performed to see how they will integrate with VCHP'S. Additionally, VCHP’S have a TRL of 5, as more testing is required to simulate the conditions representative of the rover's mission, including temperature extremes, radiation exposure, and vibration. Comprehensive testing will help assess and validate the reliability, durability, and efficiency of the VCHP'S.

The next subassembly is the heat switch, specifically the differential heat expansion heat exchanger, which plays an important role in spacecraft temperature control, controlling the temperature of individual components. The electronic box is supported in some way in the form of a spacecraft and it radiates as a heat sink to maintain the heat two components. When an additional heater is added, the switch can be turned off firmly, reducing the time required for adjustments. The design provides a better conductivity ratio, higher open switch resistance, and better thermal management, improving spacecraft thermal management. The TRL level of these heat switches is 5, as this system can get complex, especially when adding features like heaters. Furthermore, according to the NASA thermal engineering handbook “Passive structure radiators represent an efficient heat dissipation system for spacecraft” using existing structural components to radiate excess heat generated by onboard electronics In this design, the spacecraft’s aluminum wall plays a dual role as part of the structure and radiator. The simplicity of this method facilitates easy integration of the spacecraft, emphasizing efficiency.

The thermal subsystem design plays a crucial role in maintaining the functional integrity of spacecraft components across varying temperature conditions. Patch heaters are employed to enhance reliability by effectively heating critical components. This system utilizes a combination of variable heat pipes (VCHP) and thermal resistance to optimize heating, addressing the limitations of each component. Heat exchangers are integral to the design, facilitating temperature monitoring and increasing thermal conductivity ratios. The overarching aim of the thermal management system is to prioritize simplicity and efficiency in the rover's overall design. This approach integrates innovative solutions to achieve a balance between efficiency, reliability, and flexibility. With an overall Technology Readiness Level (TRL) of 7, the system demonstrates a high degree of maturity and readiness for implementation.

Figure 37 - Hot Heat Map

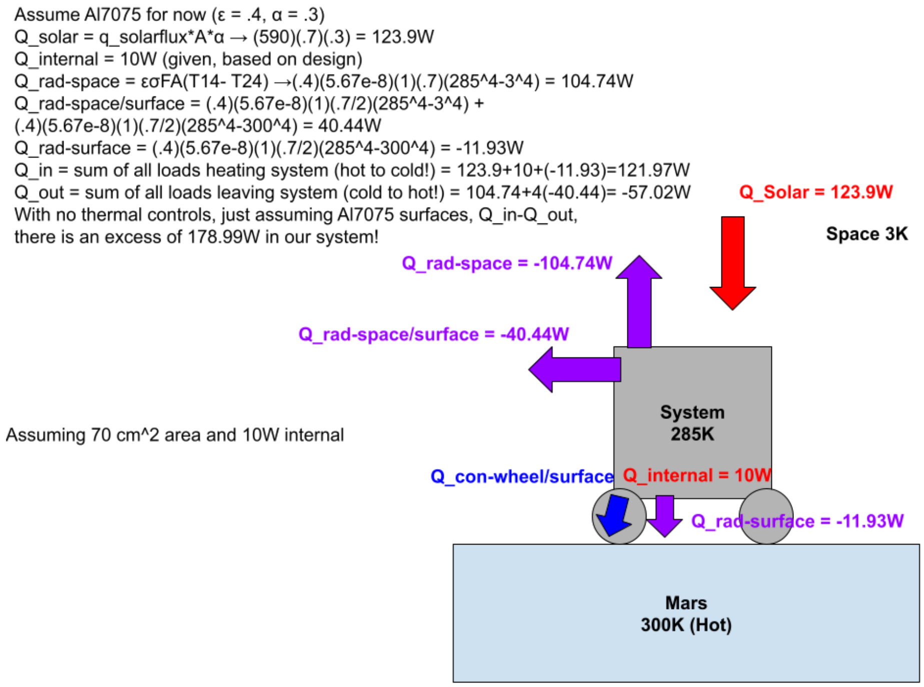
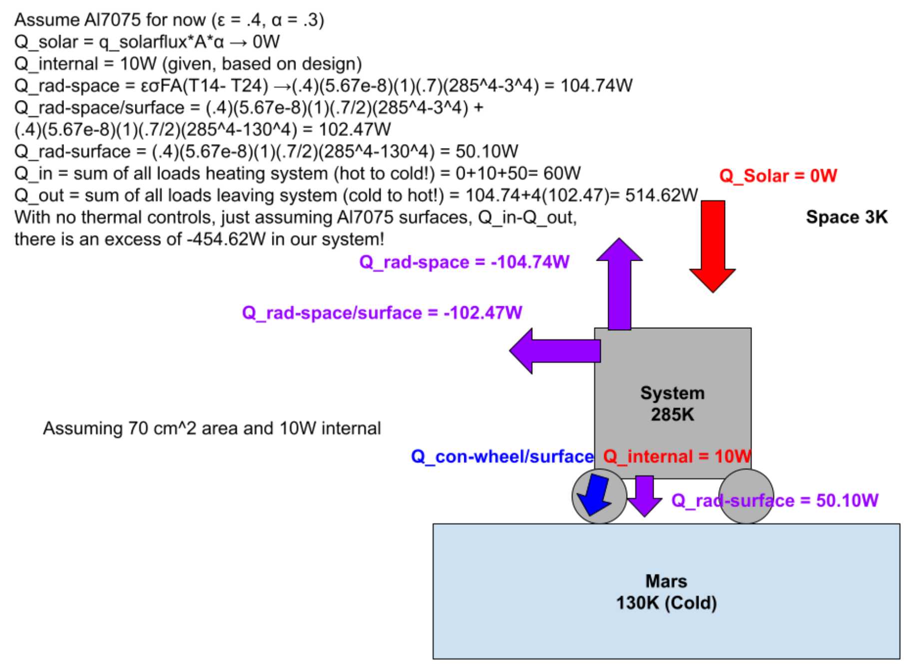


Figure 38 - Cold Heat Map



2.1.4.1. Thermal Control Subsystem Requirements

The Thermal requirements define what the subsystem should accomplish. There are functional and performance requirements that drive the trade studies and subsystem design decisions. TCS-1 and 2 come from the mission, requiring to last for 240 days. TCS-3 describes the overarching functionality of the subsystem, and is the parent requirement to multiple other requirements. Under this are TCS-3.1, 3.2 and 3.3, and 3.4 which break down the overarching functionality into heating, cooling, insulation, and temperature regulation.

Figure 39 - Thermal Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
Thermal Control System							
TCS-1	The spacecraft shall not exceed extreme temperatures -40C to 50C	The spacecraft has to be able to withstand the temperatures on Mars and internal components will start to degrade past these extremes.	MR-5	All TCS	Test	Thermal	Met
TCS-2	The spacecraft shall be resistant to UV radiation	The spacecraft has to avoid being destroyed by radiation and parts should be safe from degradation from UV	MR-5	TCS-2.1	Analysis	Thermal	Met
TCS-2.1	The spacecraft shall be coated appropriately to avoid having unnecessary heat escape and be resistant to radiation	The spacecraft should not waste energy heating itself due to leaks and coating should add resistance to UV radiation	TCS-3,TCS-2	TBD	Inspection	Thermal	Met
TCS-3	The spacecraft shall have an internal heating/cooling system	Components within the rover must be kept at their respective safe operating temperatures	TCS-1	TCS-3.1, 3.2, 3.3, 3.4	Inspection	Thermal	Met
TCS-3.1	The spacecraft shall be thoroughly insulated to keep internal components safe	The spacecraft should have a thermal resistance of at least 0.010 W/m*K	TCS-3	TBD	Analysis	Thermal	Met

TCS-3.2	The spacecraft shall have a device capable of regulating temperature	The spacecraft has to be able to regulate its own temperature and automatically switch between heating and cooling	TCS-3	TBD	Demonstration	Thermal	Met
TCS-3.3	The spacecraft shall have a heat rejection system	The spacecraft has to be able to cool itself at least by 20 degrees celsius	TCS-3	TBD	Test	Thermal	Met
TCS-3.4	The spacecraft shall have a heating system	The spacecraft should be able to heat itself by at least 20 degrees celsius	TCS-3	TBD	Test	Thermal	Met

2.1.4.2. Thermal Control Sub-Assembly Overview

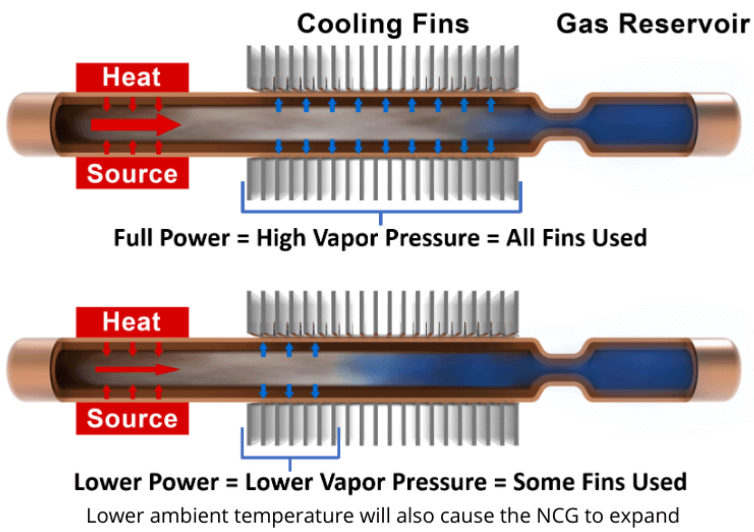
The Thermal Subsystem Heating Sub-Assembly will consist of a combination of heat pipes and resistive. This was decided in a trade study. The reasoning for the trade study is as follows:

A heat pipe is somewhat large, but it can vary depending on the amount. Resistive heaters are usually very light and flat. A combination would be in between because less of each would have to be used. Heat pipes are very reliable and depending on the type could be higher or lower. A resistive heater is somewhat reliable, but since they are simple they usually require additional redundancy. A combination would be most reliable and redundant because it implements both. A heat pipe and resistive heater are both around the same functionality and efficiency just varying in application. A combination would be most functional since it uses both. A heat pipe is more complex than a heater since it has more parts at factors when implementing, and a combination would be more complex since both have to be implemented appropriately.

The heat pipe used in the rover will be a variable conductive heat pipe. The variable conductive heat pipes will be placed in strategic locations of the rover which require the most flexibility in heating where a resistive heater won’t be able to adequately heat the area. For example, when an entire subsystem needs to be heated to a certain temperature range a heat pipe will be used. Variable Conductance Heat pipes work by using a gas reservoir and will have a different amount of pressure depending on the heat of the system. These heat pipes transfer heat without the need of a power source and are long lasting. This was also decided in a trade study. The reasoning for the trade study is as follows:

The weights/space just correlates to the size of the pipe. VCHPs have many different implementations and have been used in previous missions which is why it has a higher reliability/TRL. VCHP's also are very functional even if electricity is limited. VCHP's are somewhat complex though requiring them to be treated differently depending on the reservoir, but otherwise being simple.

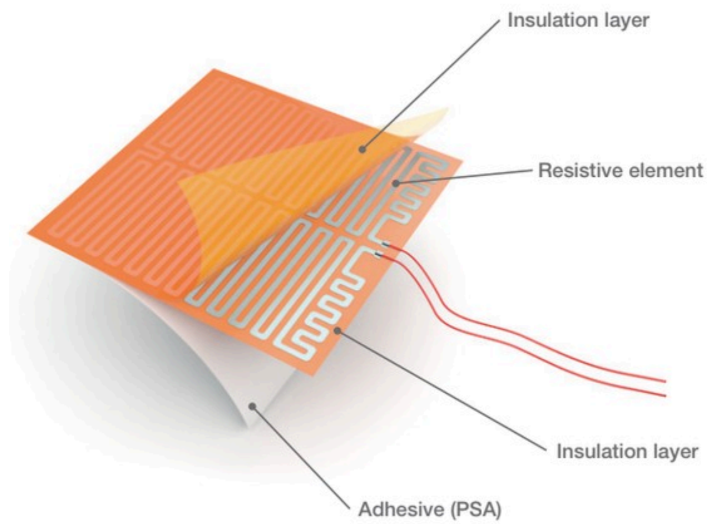
Figure 40 - VCHP Diagram



The resistive heater used in the rover will be a patch heater. Patch heaters will be used where hat pipes are not necessary. This would be in places which are smaller and don't require as much of a range. Patch heaters can only heat up one area and do not transfer heat and can be redundant or not in design. The patch heaters used on the rover will be redundant in design. These patch heaters require a power source to run unlike the heat pipes. This was also decided in a trade study. The reasoning for the trade study is as follows:

The weights/space just correlates to the size of the heater and its thickness. Patch Heaters and cartridge heaters are both pretty reliable, but patch heaters are more commonly used in rover missions and cartridges in thrusters. Patch heaters are somewhat functional, but not the most efficient, but since they are just an electrical-resistant element between insulation they are very simple.

Figure 41 - Patch Heater



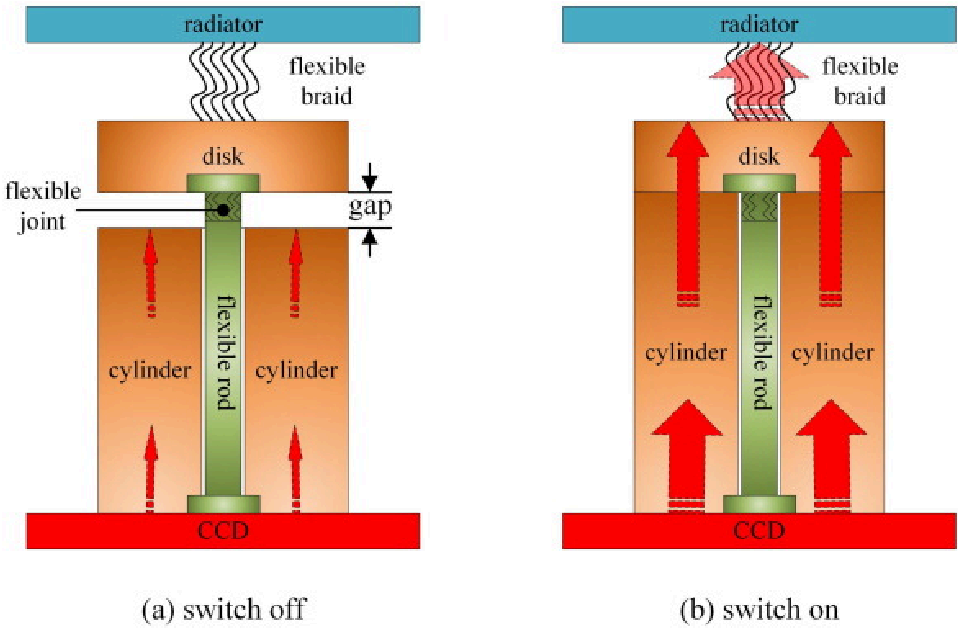
The Thermal Subsystem Cooling Sub-Assembly consists of a radiator. The radiator used in the rover will be a passive structure radiator. A passive structure radiator will be placed on the side of the rover and will be used to radiate away excess heat from the rover. The radiator requires a power source for it to work properly and can be filled with either water or coolant depending on the situation. The radiator will release some heat before taking in some more cool air to replace it. This was also decided in a trade study. The reasoning for the trade study is as follows:

The weights/space just correlates to the size of the radiator, passive structure radiator's are usually smaller than the others since they have to stay within the spacecraft. Passive Structure radiators are most reliable since they are directly connected to the spacecraft and are very functional since it is also part of the structure being dual purpose. Passive Structure radiators are a little more complex body-mounted radiators since they have to be designed to fit the spacecraft.

The Thermal Subsystem Cooling Sub-Assembly will include the heat switch. The heat switch used in the rover will be a thermal expansion heat switch. This heat switch will change whether heating or cooling is used depending on the temperature. The heat switch works by shrinking or expanding depending on the surrounding temperature. This heat switch is passive and does not require any monitoring, however it does require a power source to run. It also has to be connected to other thermal components to determine which should be activated at a certain time. This was also decided in a trade study. The reasoning for the trade study is as follows:

The weights/space just correlates to the size of the heat switch. Thermal Expansion Heat Switches are very reliable and functional as they offer a robust design and fast transition time. Thermal Expansion Heat Switches are a little complicated, but since it only relies on one part shrinking more than the other due to temperature changes it is mostly simple to implement.

Figure 42 - Differential Thermal Expansion Heat Switch Example



The Thermal Subsystem Insulation Sub-Assembly will consist of aerogel. This aerogel will be spread out the rover to help prevent outside temperatures from affecting the internal components as much. Aerogel prevents convection by trapping gas. This was also decided in a trade study. The reasoning for the trade study is as follows:
The weights/space just correlates to the weight of the insulation per gram with gas being lightest and being a bit heavier since it is usually made of fiberglass. Aerogel is mostly reliable, but it is extremely delicate and packing can be an issue. Aerogel is a very great insulator usually with a conductivity of 0.017W/m*K while on Earth (Thermal Control Handbook), but the gas void method is a little bit better at insulating. Aerogel is more complex to implement than foam and batt due to that packing issue but otherwise simple.

There was no trade study done for the thermal coating of the rover, however due to specific implementation still being determined spray paint will be considered as the thermal coating unless another alternative is needed due to its simplicity and low cost. The same can be said for the Kapton Tape being used as a heat protector for the rover as it is commonly used in Space missions, unless another alternative is required. The other thermal subsystem components should adequately heat and cool the system even without the use of a complex thermal coating.

The overall TRL of the Thermal Control Subsystem is 5 because the lowest TRL of any component is 5.

Figure 43 - Thermal Mass Volume Power Draw Table

Subsystem	Mass (kg)	Stowed Volume Container (cm)	Max Power Draw (W)
Heat Pipes	1.0	1x1x1	0
Patch Heaters	0.6	1x1x1	15
Radiator	2.2	6x6x6	25
Heat Switch	0.5	1x1x1	10
Aerogel	0.3	0.3x0.4x0.3	0
Coating	0.4	0.1x0.2x0.1	0
TOTAL	**5**	**WILL FIT IN 10x10x10cm**	**50**

2.1.4.3. Thermal Control Subsystem Recovery and Redundancy Plans

Figure 44 - Thermal Recovery and Redundancy

Thermal subsystem	Redundancy	Recovery
Heat patches	The thermal control system (TCS) incorporates redundancy for heat patch circuits, ensuring that if one part fails, the rest remain functional. Heat patches are strategically placed to heat specific parts of the rover as needed.	In the event of a failure, the TCS utilizes heat switches in conjunction with thermometers to detect temperatures and automatically adjust the system to prevent overheating or overcooling. This ensures that the rover remains within the appropriate temperature range, with heat patches serving as a backup heating mechanism if necessary.

Passive structure Radiator	The TCS includes a radiator as part of its cooling system, providing redundancy to ensure efficient cooling of the system. The radiator helps dissipate excess heat generated by the components.	If the radiator fails, the TCS can rely on other cooling mechanisms such as the heat pipe system and heat patches to compensate for the loss of cooling capacity. Additionally, heat switches regulate temperature to prevent overheating in the absence of radiator cooling.
VCHP	The TCS incorporates a heat pipe system for both cooling and heating, offering redundancy in heat transfer mechanisms. VCHPs efficiently transfer heat around the rover as needed.	If the heat pipe system malfunctions, the TCS can rely on alternative heating mechanisms such as patch heaters and radiator heating to maintain thermal stability. Similarly, if the VCHP fails, the TCS can utilize heat patches and radiator cooling to regulate temperatures.
Aerogel	While aerogel itself may not have inherent redundancy, its placement within the thermal insulation system can provide redundancy in thermal protection, ensuring consistent thermal performance.	In the event of a failure, the TCS can rely on other insulation materials or heating mechanisms like heat patches to maintain thermal stability. The redundancy provided by alternative insulation layers helps mitigate the impact of aerogel failure on overall thermal performance.
Heat switches	The thermal control system (TCS) incorporates redundancy for heat switch circuits, ensuring continuous operation even if one circuit fails. Heat switches are critical components that regulate heat flow within the rover, allowing for precise temperature control.	Heat switches play a vital role in the thermal management system, working alongside other components such as heat patches, radiators, and heat pipes. If a heat switch circuit fails, the redundant circuits continue to regulate heat flow, preventing temperature fluctuations that

	Recovery: In the event of a failure, heat switches work in conjunction with thermometers to detect temperature variations. Automated systems adjust the heat switch operation to prevent overheating or overcooling, maintaining the rover within the appropriate temperature range. Additionally, redundant circuits provide backup functionality, ensuring uninterrupted heat flow regulation even if one circuit malfunctions.	could impact rover performance. This integrated approach to redundancy and recovery ensures the robustness and reliability of the thermal control system, allowing the rover to operate effectively under varying environmental conditions.

2.1.4.4. Thermal Control Subsystem Manufacturing and Procurement Plans

High Heat Spray Paint

The supplier for paint is Rust-Oleum. This supplier was chosen because their spray paint can withstand very high and low temperatures as well as has rust and corrosion resistance. There are alternative suppliers for paint, but they are either way more expensive, have worse specs, come in less colors, or have longer lead times. Other suppliers were not chosen for at least one of those if not a combination of those reasons. The maximum temp it can resist is 1200 fahrenheit. The spray paint is applied using an aerosol application method and takes 120 minutes to dry to the touch. This paint also comes in a variety of colors which can be used on the spacecraft such as black, white, or silver. The lead time is the next-day when a commercial off the shelf is bought from Home-Depot or another retailer. The regular spray paint is $7 for 12oz and the ultra spray paint is $11.50 for 12oz.

Figure 45 - White High Heat Spray Paint and Black High Heat Ultra Spray Paint

Kapton Tape

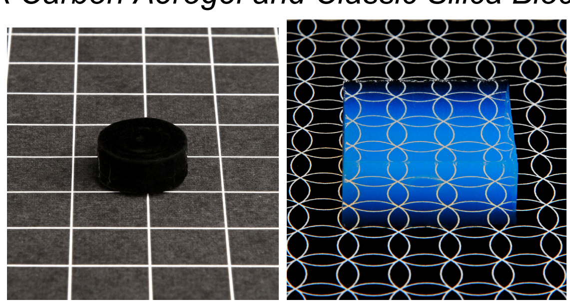
The supplier for kapton tape is DuPont. This supplier was chosen because they are the inventor of Kapton Tape. There are other alternatives which could be used as a substitute of Kapton Tape and which have similar specs; however, those tapes are not as commonly used on spacecraft and do not have as quick of a lead-time and lack some of the advantages. This tape can withstand very high and low temperatures and leaves no residue. The tape has a tensile strength of 30lbs/in and can be stretched up to 40% before breaking. The tape has a dielectric strength of 7,000 volts and can operate within -73 celsius to 260 celsius. This tape is also conformable to uneven surfaces and is resistant to tears and punctures. The lead time is the next-day when bought from kaptontape.com. The price for 1 Mil kapton tape is $29.50 for 1” by 36 yds.

Figure 46 - 1 Mil Kapton Tape

Aerogel

The supplier is Aerogel Technologies, LLC. This supplier was chosen because they are a leading aerogel manufacturer and have a license for NASA’s aerogel. There are other suppliers of Aerogel, but many of them are not located in the USA and are limited to the patents of this company. The lead time depends on availability, but next-day may be possible when buying from BuyAergoel.com. For carbon black aerogel sized at ~1cmx0.4cm the price ranges from $70 to $80. For a classic silica block sized at 2.5cmx2.5cmx1.0cm the price ranges from $45 to $60. The density for the carbon black aerogel is 0.2g/cc and around 0.095g/cm^3 for the classic silica block.

Figure 47 - Black Carbon Aerogel and Classic Silica Block Aerogel



Passive Structure Radiator

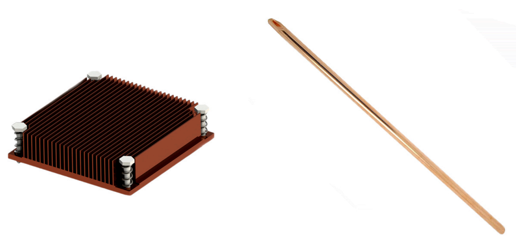
The supplier is Speedway Motors. This supplier was chosen because the radiators they make are able to lower the temperature by 10-20 Celsius and are lightweight. There are radiators available on the market, but many of them are heavier than this one and are not as universally applicable. Also since they are aluminum they are resistant to many hazards. Since the radiator is fused together with a metal joint it will conduct heat evenly and since the radiator uses a doublepass design there is a longer time in airflow. The lead time is 2-4 days when bought off Speedway Motors website. The price for a 22 inch wide radiator is $210, if we request a smaller one then it may be more expensive due to it being custom.

Figure 48 - 22 inch Radiator

VCHP

The supplier is WakeField Thermal. This supplier was chosen because their products can withstand a greater range of temperature than other manufacturers of similar products. Some manufacturers also do not produce heat sinks which means we would need a separate manufacturer for those. The lead time is 12 weeks to 14 weeks when bought online through Digikey. The price for a standard heat pipe sized 8x0.3x250MM ranges from $13 to $19. The heat pipes have a max temperature range of -40 celsius to 150 celsius. The price for a copper skived fin heat sink sized 90x90x10MM ranges from $21.45 to $28.62. The skived heatsink has a higher density in comparison to extruded ones and has an improved thermal performance.

Figure 49 - Copper Skived Heatsink and Standard Heat Pipe



Differential Thermal Expansion Heat Switches

The supplier is Honeywell. This supplier was chosen because they make space qualified heat switches. All switches are fully tested and have great reliability. There are other suppliers for heat switches but they are not as qualified or way more expensive. The lead time is 2 to 4 days when bought off newark. The price for one heat switch ranges from $20 to $40 depending on the specific kind.

Figure 50 - Example of Honeywell Thermal Switch

Patch Heater

The supplier is Minco. This supplier was chosen because it provides higher quality patch heaters than other brands. Their patch heaters also have NASA approval. The lead time is 7 weeks when bought off their website. The price for a 0.045oz FEP heater ranges from $30 to $770. The FEP heater has a min temp of -328 Fahrenheit and max of 392 fahrenheit. It also has a voltage range of 0.1 to 78. The maximum wattage is 39.5 with a maximum of 50w/in^2. The price for a 0.082oz WA heater ranges from $36 to $96. The WA heater has a min temp of -26 Fahrenheit and max of 212 Fahrenheit. It also has a voltage range of 0.1 to 39. The maximum wattage is 7.5 with a maximum of 20w/in^2.

Figure 51 - Minco Patch Heater

All Thermal Parts

Since all the thermal subsystem parts are commercial off the shelf the initial costs are not that high. However, there will be numerous tests run by the team since the manufacturers will not be doing special modifications. This assembly and testing will probably take multiple months (hopefully only three) and will be very costly. The benefit of this is that if we cannot afford to do the tests, at least we will have all components and a fully built rover

Additional Parts

There will also be some additional parts which are needed such as a coolant for the radiator, screws, wires, ect. in order to connect thermal to electrical or to attach a part to the rover.

2.1.4.5. Thermal Control Subsystem Verification Plans

Figure 52 - Thermal Verification Table

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
TSC-1	The spacecraft shall not exceed extreme temperatures -40C to 50C	Test	This method will be inspected by providing empirical evidence of the spacecraft's performance under real-world conditions, offering tangible assurance of its ability to withstand temperature fluctuations without exceeding the specified thresholds.	Testing the spacecraft's temperature tolerance would involve placing it in a thermal chamber capable of simulating temperatures from -40°C to 50°C. Internal temperatures would be monitored to ensure they remain within the specified range.
TSC-2	The spacecraft shall be resistant to UV radiation	Test	This method directly observes how the spacecraft's materials and components respond to UV exposure and verify their resistance.	This will be conducted by subjecting the spacecraft to simulated UV radiation in a controlled environment.
TSC-2.1	The spacecraft shall be coated appropriately to avoid having unnecessary heat escape and be resistant to radiation	Analysis	This method would analyze factors such as reflectivity, emissivity, and thermal conductivity of the coatings to ensure they effectively mitigate heat absorption.	This will be conducted by using software tools to model the spacecraft's thermal behavior with different coating materials.
TSC-3	The spacecraft shall have an internal heating/cooling system	Testing	This method would involve operating the internal heating/cooling system under various temperature conditions to ensure its functionality and effectiveness in regulating the spacecraft's internal temperature.	This will be conducted The spacecraft's internal heating/cooling system would be tested by activating it and monitoring its operation to ensure it maintains the desired temperature range within the spacecraft.

TSC-3.1	The spacecraft shall be thoroughly insulated to keep internal components safe	Inspection	This method would involve visually examining the spacecraft's insulation to ensure it covers all internal components adequately	Inspection of the spacecraft's insulation would be conducted by visually examining all internal components to ensure they are adequately covered.
TSC-3.2	The spacecraft shall have a device capable of regulating temperature	Test	This method would involve operating the temperature regulation device under various conditions to ensure its functionality in controlling the spacecraft's internal temperature.	This will be conducted by testing the spacecraft's temperature regulation device would involve activating it and monitoring its operation to ensure it effectively maintains the desired internal temperature range.
TSC-3.3	The spacecraft shall have a heat rejection system	Analysis	This method allows for a thorough evaluation of the spacecraft's heat rejection capabilities without the need for costly and time-consuming physical testing.	This will be conducted by analyzing the spacecraft's heat rejection system and would involve creating a detailed thermal model, running simulations to assess heat distribution and rejection, and evaluating the results to ensure compliance with requirements.
TSC-3.4	The spacecraft shall have a heating system	Test	This method allows engineers to directly observe how well the heating system maintains the desired temperature range within the spacecraft.	This will be conductedTesting the spacecraft's heating system would involve activating it and monitoring its operation to ensure it effectively maintains the desired internal temperature range.

2.1.5. GNC Subsystem Overview

The Guidance, Navigation, and Control (GNC) subsystem of the rover is responsible for guiding, navigating, and controlling the rover's movements on Mars. It ensures the rover's ability to autonomously move, make real-time decisions, and successfully achieve mission objectives. The GNC system is divided into six subassemblies: sensing data, mobility, autonomy, navigation, integration, and computer hardware, each identified under the requirements table as GNC-5, GNC-6, GNC-7, GNC-8, GNC-9, and GNC-10. These components collectively play a crucial role in the rover's overall functionality and mission success.

The sensing sub-assembly of the GNC system is responsible for capturing, processing, and interpreting visual information from the rover's surroundings. The sensing data of the rover involves input such as the navigation cameras, the hazard-avoidance cameras, and their corresponding sensors. As illustrated in the Navcam and Hazcam trade studies, the rover will follow a hereditary design from the Enhanced Engineering Camera task (EECAM) employed in the 2020 Perseverance

Rover. The Mars 2020 EECAMs enhance MER/MSL designs with their compact bodies, stereo pairs, and advanced lenses, featuring a CMOSIS CMV20000 for superior resolution and color imaging. With navcams boasting over twice the resolution and Hazcams over three times, coupled with improved anti-blooming capabilities, the EECAM design was the most sensible choice. The rover is equipped with two navigation cameras, two front hazard-avoidance cameras, and two rear hazard-avoidance cameras, each requiring a 20-megapixel color CMOS sensor, MER ECAM IMG software module, and a custom-built Linux version for the EDLCAM DSU. (Maki et al. 2016) This subassembly has demonstrated a Technology Readiness Level (TLR) of 7, as exemplified on the 2020 Perseverance rover.

The Actuation and Mobility Subassembly enables the ability to move and manipulate the rover in order to move through Martian terrain. This subassembly combines multiple parts to allow for controlled movement. The GNC system has submitted three actuator proposals, but the exact system has not yet been determined. At this point, the mechanical system is managing the wheels in accordance with the MEC-4 requirement. Brushless DC Hub Motors stand out among the suggested solutions due to their excellent volume efficiency. By integrating into wheel hubs, they produce a small design that ensures effective power transmission with low losses and lessens the need for additional parts, improving weight efficiency. Brushless DC Gearmotors combine a DC motor with a gearbox, efficiently transmitting power to the wheels, contributing to weight efficiency through power efficiency and adjustable motor speed. Electric Linear Actuators convert rotary to linear motion, simplifying the rover's design with high-efficiency and lightweight features, enhancing weight efficiency. These considerations will lead to foreseeable trade studies to make a final decision. Regardless of the actuator chosen, it should fall within a TRL of 6 at the least.

Determining and maintaining the rover's position and orientation with respect to its surroundings is a critical function of the Navigation subassembly of the GNC system. It combines several sensors and algorithms to ensure accurate and reliable Martian surface navigation. As illustrated by the Navigation system trade study, an integrated design of either a SINS/VNS and SINS/CNS subsystem model is established. The first configuration outlines a navigation system involving inertial data and visual odometry. The second configuration also involves inertial data but is accompanied by the celestial navigation method based on large field-of-view star sensors. (Zhao et al. 2019) It is yet to be announced until the specifications of each system are compiled and more trade studies are conducted to see which one is preferable. Both configurations have reached a TRL of at least 5.

One of the most important parts of the rover's GNC subsystem is the Integration & Calibration subassembly, which coordinates the proper operation of several sensors and systems. Its main responsibilities include gathering sensor data, optimizing instrument calibration, and guaranteeing the GNC system's overall accuracy and dependability. Some examples of subcomponents include sensor integration, instrument calibration, reference frame consistency, calibration operations, and defect detection. This subassembly is mainly made up of software components, such as sensor fusion algorithms and software updates, as well as redundant hardware when required. The TRL for this subassembly is at least 6.

The Computer Hardware subassembly within the Guidance, Navigation, and Control (GNC) subsystem of a Mars rover is a critical component responsible for processing sensor data, executing control algorithms, and managing the overall decision-making process for autonomous navigation and operation. In terms of the GNC subsystem, this section mostly focuses on enabling the communication of data between the GNC's software and environmental input to the CDH subsystem components. It will outline the application programming interfaces between both subsystem components. The TRL of this subassembly is at least 6.

2.1.5.1. GNC Subsystem Requirements

Figure 53 - GNC Subsystem Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?
GNC-1	The GNC subsystem shall not exceed a mass of 2.25kg	Less than 5% of total rover mass.	MEC - 1	TBD	Inspection	TBD	Met
GNC-2	The GNC subsystem shall not exceed a stored configuration volume of 36^3cm.	Less than 5% of total rover volume.	MEC - 2	TBD	Inspection	All	Met
GNC-3	The total GNC subsystem cost shall not exceed $15M	Less than 5% of total rover cost.	MR - 4	TBD	Inspection	All	Met
GNC-4	Ensure the rover can autonomously navigate, guide, and control movements on Mars.	Enables thorough investigation of Mars.	MR-1	TBD	Inspection	All	Met
GNC-5	The rover shall gather real-time and accurate data on terrain and obstacles throughout the mission.	Enables the rover to autonomously navigate and operate on mars terrain.	MR-1, MR-2	GNC-5.1, GNC-5.2	Test	All	Met
GNC-5.1	The sensing sub-components shall be able to perform in low-light conditions	Enables the rover to navigate during nighttime.	GNC-5	TBD	Test	All	Met
GNC-5.2	Any external equipment shall be environmentally robust.	Ensures the sensing equipment's survivability during extreme weather conditions.	GNC-5	TBD	Test	All	Met
GNC-6	Provide precise and reliable control of the rover's movement.	Ensure rover's ability to execute navigation commands.	MEC-4, MEC-5	GNC-6.1	Test	MEC	Met

GNC-6.1	The actuator system must be compatible with the mechanical system handling the wheels	Enables mobility of the rover.	GNC-6	TBD	Test	All	Met
GNC-7	Incorporate software with the capability to autonomously process sensor data and execute navigation commands.	Rover can operate independently and within unforeseen circumstances.	CDH-4	TBD	Test	CDH	Met
GNC-8	The rover shall determine its orientation by referencing internal or external phenomena.	Ensures rover's ability to move and operate effectively on the martian surface.	MR-1	GNC-8.1	Test	All	Met
GNC-8.1	The algorithm must integrate inertial data and visual odometry with a margin of error not exceeding [TBD].	Ensures the navigation system's performance.	GNC-8	TBD	Test	All	Met
GNC-9	Must seamlessly integrate GNC components and implement calibration procedures.	Ensures sustained accuracy and reliability of GNC over the rover's operational life.	MR-1	GNC-9.1	Test	CDH	Met
GNC-9.1	Ensure technological compatibility between subassemblies.	Enables integration of components.	GNC-9	TBD	Test	All	Met
GNC-10	Must be able to communicate with the command & data handling system	Enables use of GNC software.	CDH-5	TBD	Test	CDH	Met

2.1.5.2. GNC Sub-Assembly Overview

The following section will outline the parts and processes in detail for every GNC sub-assembly.

Sensing Sub-Assembly

The sensing sub-assembly plays a vital role in capturing, processing, and interpreting visual information from Endurance's surroundings. This data is crucial for navigation and hazard avoidance during the rover's operations on Mars' surface. The sensing data includes input from navigation cameras and hazard-avoidance cameras, each equipped with 20-megapixel color CMOS sensors, software modules, and custom-built Linux versions for the EDLCAM DSU. (PDS Geosciences Node)

The design of the navigation and hazard-avoidance cameras, inherited from the Enhanced Engineering Camera task (EECAM) used in the 2020 Perseverance Rover, features compact bodies, stereo pairs, and advanced lenses. The cameras are attached via a titanium bracket that is mounted on the outside of the rover body. The CMOS sensors used in these cameras offer superior resolution and color imaging compared to traditional CCD sensors. Additionally, CMOS sensors consume less power and are more cost-effective to manufacture, making them ideal for space missions like a Mars operation. (Abarca et al., 2019) The flight software, based on the MER ECAM IMG software module, controls camera operations, command handling, and post-processing of camera images. This software ensures seamless integration with the rover's systems and enables efficient data management and transmission.

The EDLCAM DSU runs a custom-built version of Linux optimized for data throughput from the USB cameras to the rover's non-volatile storage. It operates in two modes: command mode and Entry, Descent, and Landing (EDL) mode. During EDL, the system autonomously collects data from the cameras, while in command mode, it awaits commands from the rover's flight software. The core data processing and compression engine is powered by FFMPEG, with additional functionality available via open-source software projects.

Overall, the sensing sub-assembly integrates state-of-the-art technology, demonstrated by its Technology Readiness Level (TRL) of 6, as evidenced by its successful deployment on the 2020 Perseverance rover. This sophisticated system enables the rover to navigate autonomously, avoid hazards, and collect valuable data during its mission on Mars.

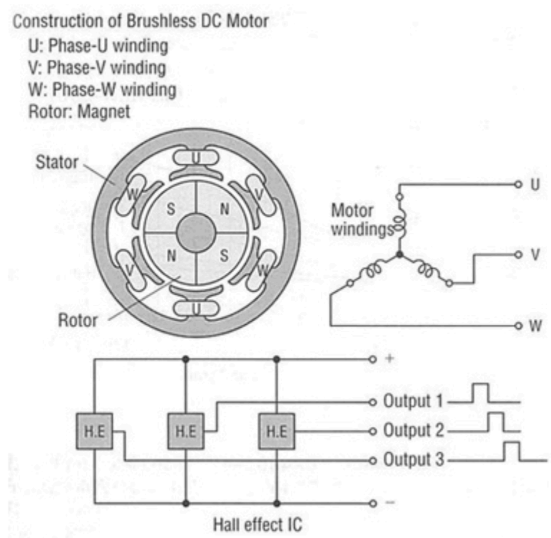
The Actuation and Mobility Subassembly

The Actuation and Mobility Subassembly of the Endurance rover enables its movement and manipulation across the Martian terrain. This subassembly utilizes Brushless DC Gearmotors, which combine a DC motor with a gearbox, efficiently transmitting power to the wheels. These gearmotors contribute to weight efficiency through power efficiency and adjustable motor speed, while also eliminating the need for maintenance typically associated with brushed DC motors.

The brushless DC motors in the gearmotors feature a highly magnetic permanent magnet in the rotor and utilize a three-phase coil configuration in the stator. Feedback signals from hall effect ICs integrated into the stator allow for continuous adjustment of motor speed based on desired settings. These motors can be easily controlled through electronic-input systems, eliminating the need for power relays and reducing setup time. (BLDC motor)

The gearbox, connected to the output shaft of the brushless DC motor, transfers power to the rover's wheel assembly through a drivetrain mechanism. The front and rear wheels feature additional steering motors. This wheel and steering motor configuration enables precise control over the rover's movement, including turning in place and executing arcing turns, enhancing its maneuverability on the Martian surface. The TRL for this subassembly is at least 6.

Figure 32 - Brushless DC Motor Diagram



Navigation Subassembly

The Navigation system of Endurance is crucial for determining and maintaining its position and orientation in relation to the Martian environment. To enable long-term autonomous roving and scientific operations, high-precision autonomous navigation is essential. Endurance utilizes an innovative scheme of strap-down inertial navigation system/celestial navigation system (SINS/CNS) deep integration, which leverages a large field of view (FOV) star sensor to continually correct misalignment angles and gyro drifts of the SINS. This provides a high-precision mathematical reference, allowing the star sensor to derive the local position vector based on SINS data. The deep integration of SINS/CNS maximizes navigation information from each subsystem, correcting errors in the inertial measurement unit (IMU) and navigation parameters in SINS, and significantly improving navigation accuracy. (Yang et al., 2022) The tightly coupled rotational SINS/CNS integrated navigation method further enhances accuracy by using rotational SINS error equations and starlight vector measurements. This integrated system ensures continuous and autonomous navigation by utilizing accelerometers and gyros in SINS, while CNS employs a large FOV star sensor to determine vehicle attitude and position based on a constructed high-precision mathematical horizon reference (MHR) determination method. Overall, this innovative SINS/CNS deep integration scheme improves navigational accuracy and reliability, meeting the requirements of long-time and high-accuracy autonomous navigation for the Endurance rover on Mars. The TRL for this subassembly is at least 5. (He a et al., 2014)

Integration & Calibration Subassembly

One of the most important parts of the rover's GNC subsystem is the Integration & Calibration subassembly, which coordinates the proper operation of several sensors and systems. Its main responsibilities include gathering sensor data, optimizing instrument calibration, and guaranteeing the GNC system's overall accuracy and dependability. Some subcomponents include sensor integration, instrument calibration, reference frame consistency, calibration operations, and defect detection. This subassembly is mainly made up of software components, such as sensor fusion algorithms and software updates, as well as redundant hardware. The TRL for this subassembly is at least 6.

Computer Hardware subassembly

The Computer Hardware subassembly within the Guidance, Navigation, and Control (GNC) subsystem of a Mars rover is a critical component responsible for processing sensor data, executing control algorithms, and managing the overall decision-making process for autonomous navigation and operation. In terms of the GNC subsystem, this section mostly focuses on enabling the communication of data between the GNC’s software and environmental input to the CDH subsystem components. It will outline the programming interfaces between both subsystem components.

The sensor interface module facilitates the connection and communication between the various sensors (IMU, GPS receiver, cameras, Lidar/Radar) and the GNC computer hardware. They include high speed A/D converters (10 MSPS to 125 MSPS), sensor drivers, and interface protocols. Signal Processing Units are responsible for processing raw sensor data, performing filtering, fusion, and other signal processing tasks to extract relevant information for navigation and control algorithms. FPGAs are used as the main processing units in the Endurance rover for applications such as radar transceiver, navigation systems, motor controllers and computer vision applications. Endurance utilizes an FPGA technology (Xilinx Virtex-5) as one of the main processing units. This unit is first responsible for rover entry, descent and landing on Mars and then it is programmed for computer vision tasks by NASA engineers from Earth.

The computer hardware subassembly contains a specialized navigation processor to execute navigation algorithms, including Kalman filters, SLAM (Simultaneous Localization and Mapping), and other path planning algorithms. It handles tasks related to position estimation, trajectory planning, and obstacle avoidance. Kalman filters are used to help correlate multiple objects with their respective tracks, anticipate an object's future location, and adjust for noise in the object's observed location. The SLAM technique enables a rover to estimate its current position and orientation as well as to construct a consistent map of its surrounding environments. Enhanced AutoNav (ENav), the baseline surface navigation software for the Endurance rover, sorts a list of candidate paths for the rover to traverse, then uses the Approximate Clearance Evaluation (ACE) algorithm to evaluate whether the most highly ranked paths are safe.

A real-time operating system (RTOS) is an operating system (OS) for real-time computing applications that processes data and events that have critically defined time constraints. The RTOS provides deterministic scheduling, priority-based task management, and low-latency communication mechanisms necessary for responsive control loop execution. The endurance rover's RTOS is called Real-Time Executive for Multiprocessor Systems, or RTEMS. This open-source operating system has many features that make it ideal for the Endurance mission's target domain: embedded systems that must respond fast and leverage the specially engineered, radiation-hardened CPUs. At the moment, RTEMS supports about 200 BSPs and 18 different processor architectures. (Rtems real time operating system) Overall, the TRL for this subassembly is 6 and the TRL for the GNC subsystem is 5.

2.1.5.3. GNC Subsystem Recovery and Redundancy Plans

Guidance, Navigation, and Control (GNC)

Redundancy:

The GNC will use inertial sensors and gyroscopes to guide the rover and navigate the Martian terrain. If one inertial sensor or gyroscope fails, the other can be used to compensate. In addition to these sensors, the rover will have a hazard camera and a navigation camera. Although these cameras serve different purposes, if one breaks, the other can be used for the other’s purpose.

Recovery:

The GNC system will implement recovery for its inertial sensors and gyroscopes through the use of a recalibration system, which will activate after a specific time frame to ensure the sensors are working properly. The GNC system will also be able to reboot the cameras if they stop functioning properly to hopefully fix any software issues.

2.1.5.4. GNC Subsystem Manufacturing and Procurement Plans

Navcam Design - Sodern

Surely the Navcam was designed by Sodern, and its choice was probably made under the influence of that fact and the specialization of Sodern in imaging technology for space, which is proved by the participation of this company in ESA's JUICE mission. The cameras are built for the harsh environment of space, which would be a vacuum, radiation, and extremely low temperature. Every product component and cycle of testing in the procurement cycle contains a uniquely detailed design for its robustness. Though the costs would be variable, given that projects are mostly designed to order, Sodern has carried out similar missions before and could provide cost-effective solutions, mainly based on designs and components already in hand.

Hazcam Design - JPL (Jet Propulsion Laboratory)

A design experience with JPL has contributed to Hazcam, given the participation of the institution in many successful programs for the development of rugged equipment for Mars rovers. Hence, the design of Hazcams is to work during the mission life of the rover. This has called for them to withstand the surrounding environmental challenges, including dust storms, intense colds, and radiation. Such a process, based upon leveraging the experience, technologies, and know-how of similar projects from the past, can really be managed in a way to contain costs while ensuring that the developed product is indeed very durable and functional.

Real-time Operating Systems - Wind River (VxWorks)

The choice of Wind River VxWorks as the Real-Time Operating System is put together with the priority of a well-established system, which has to be known for reliability and resiliency in the system essential for confronting the software challenge in space missions. The integration with VxWorks reflects the complexity of the system because of an enormous amount of software engineering over months. The licensing acquisition cost and its customization towards VxWorks directly point out the contribution value in raising the robustness and the reliability level of the software in critical mission scenarios.

Navigation Systems - Terrain Relative Navigation

As exemplified by the successful landing of the Perseverance rover on Mars, which used the Terrain Relative Navigation system from NASA, their precision in extraterrestrial navigation and landing is apt for this mission. This is through integration with different vehicles, whereby engineers take days and even long hours before such tests are deemed safe and time-consuming to ensure accuracy and reliability. The choice of using the system will be made based on proven effectiveness from past missions that justify investments for its adaptation and developments to new mission parameters.

Actuator Systems - Moog Inc.

Moog Inc. has been selected for highly durable actuator systems, both in extreme conditions and in performance. Such harsh space environments normally have high radiation levels and micrometeorite exposure but are not limited to other harsh elements. The actuators are specially designed, in a joint and concentrated effort by Moog, to withstand such harsh space environments. They are meant to deal well with temperature extremes and launch stresses. The procurement and integration phase is expected to leverage Moog's established solutions, which could, in turn, be procured at a cheaper cost than new in-house development, along with performance reliability and cost efficiency for the mission.

2.1.5.5. GNC Subsystem Verification Plans

The Product Verification Process ensures that Endurance meets its specified requirements and specifications, establishing a baseline for configuration control.

Verification testing confirms conformity to requirements using instrumentation and measurements. This plan provides an outline on the assurance that requirements of GNC-1 through GNC-10 are verified to meet the goals of the mission.

Physical parameter requirements such as GNC-1 and GNC-2 will be verified through a visual inspection and a review of the Mission Task documentation and the Mechanical subsystem requirements.

Mobility & Navigation:
The GNC-4 requirement will be verified through a field test to ensure Endurance's capability to navigate, guide, and control movement on Mars. A mission simulation will be conducted on the Desert Research and Technology Studies (Desert RATS), located in Arizona. Deserts can provide valuable data into the rover's performance in Martian terrains and temperatures. During the same field test, the capability for Endurance to determine its orientation by referencing internal or external phenomena can be verified.

Computer Hardware & Software:

The incorporation of software with the capability to autonomously process sensor data and execute navigation commands is stated by GNC-7 and will be verified by running a variety of computational tasks, unit testing, and functional tests.

Figure 54 - GNC Verification Table

Req #	Requirement Summary	Verification Method	Rationale for Method	Preliminary Verification Plan
GNC-1	The GNC subsystem shall not exceed a mass of 2.25kg	Inspection	Inspection of the total system mass is the only way to verify it is within limits.	Summation of all GNC component masses
GNC-2	The GNC subsystem shall not exceed volume of 36^3cm	Inspection	Visual inspection is the only possible way to confirm this requirement.	Visual Inspection
GNC-4	Rover can autonomously navigate, guide, and control movements on Mars.	Test	Analog test will expose any faults in the requirement due to exposure to a Mars-like environment.	Conduct mission simulation on the Desert Research and Technology Studies (Desert RATS)

GNC-5	Rover shall gather real-time and accurate data on terrain and obstacles throughout the mission.	Test	Analog test will expose any faults in the requirement due to exposure to a Mars-like environment.	Conduct mission simulation on the Desert Research and Technology Studies (Desert RATS)
GNC-5-1	sensing sub-components shall be able to perform in low-light conditions	Test	Analog test will expose any faults in the requirement due to exposure to a Mars-like environment.	Conduct mission simulation on the Desert Research and Technology Studies (Desert RATS)
GNC-5-2	Any external equipment shall be environmentally robust.	Test	Analog test will expose any faults in the requirement due to exposure to a Mars-like environment.	Conduct mission simulation on the Desert Research and Technology Studies (Desert RATS)
GNC-7	Incorporate software with the capability to autonomously process sensor data and execute navigation commands	Test	Simulation tests will expose any faults in the requirement to meet computational demands.	Computational tasks, unit testing, and functional tests
GNC-10	Must be able to communicate with the command & data handling system	Test	Simulation tests will expose any faults in the requirement to meet computational demands.	Computational tasks, unit testing, and functional tests

2.1.6. Payload Subsystem Overview

The first instrument, Mars Organic Molecule Analyser Mass Spectrometer (MOMA-MS), is specifically designed to analyze volatile and refractory organic material in martian surface and subsurface sediments. It volatizes a variety of organic compounds that have been extracted by a drill and then analyzes them by mass spectroscopy (MS). Volatilization can be achieved by heating the sample before the mass spectroscopy phase, and pulsing preserves weak molecular bonds, allowing detection of organic compounds in low concentrations in the sample. The MOMA-MS is capable of furthering its function to detect some thermally released inorganic molecules (e.g., $SO2$, $CO2$) or laser-desorbed fragments of inorganic minerals (e.g., carbonates, iron oxide or silicate fragments). To be able to analyze the data collected by the payload, the samples are dispensed into a refillable container before they are dispensed into the oven.

One technique of MOMA-MS, Laser Desorption Mass Spectrometry (LDMS), may be used to determine the presence and chemical makeup of nonvolatile compounds in the sample. This could aid the objective to determine the mineral composition of the regolith as many minerals are nonvolatile including carbonates. The Endurance mission will specifically investigate the regolith found near subsurface ice deposits that may affect the properties of the minerals and studying this phenomenon may produce scientific value. Next, the samples will be dispensed from the refillable container to the oven where heating releases the volatile organic compounds from the minerals. These volatile compounds are separated by mass, ionized, and their mass-to-charge ratios are determined. The properties of organic molecules are not only dependent on its molecular formula, but also on its structure. Many compounds have the same mass-to-charge ratio making them difficult to distinguish, but the MOMA is able to differentiate these compounds. MOMA's advanced techniques allow detection of biosignatures like lipids (although, not the focus of the objectives). The MOMA’s comprehensive approach combining different methods like laser desorption and chemical derivatization enables it to play a crucial role in analyzing the organic and inorganic composition of Martian sediments and detecting amino acids and other biomarkers.

The Microscopic Imager (MI) serves as the second instrument capable of providing high resolution close up imaging contributing to the objective of determining the characteristics of subsurface ice deposits, erosion, volcanic activity, and sedimentary layers on the Martian surface. The MI is designed to capture images with a resolution for 30 microns per pixel across a 31 x 31 mm field of view. It leverages a 1024 x 1024 CDD (Charge-Coupled Device) image sensor and obtains images using only solar illumination of the surface it is targeting. The MI is equipped with a retractable dust cover to protect its optics from the harsh Martian environment. This dust cover includes a tinted orange Kapton window that enhances its ability to capture color information by restricting the spectral bandpass to 500 - 700 nm. The imager also utilizes a Schott BG-40 (light blue) filter that creates a spectral response similar to that of a human eye. In order to correct for potential image distortions and bad pixels, it is able to perform simple onboard image processing tasks allowing for a higher standard of input. High quality data from the MI will help put data from the MOMA in context revealing special insights into volcanic processes and geological interpretations otherwise unattainable.

The MI underwent extensive calibration and testing of components, camera assembly, optics, sensors, electronics, and the integrated system before its launch. Optical barrel assemblies were tested for spectral transmission by the vendor Kaiser Electro-Optics. MI filters were measured for spectral transmission at JPL, and dust cover windows went through spectral transmission testing at Johnson Space Center. Temperature sensors were calibrated by the vendor Rosemount Aerospace. CCD cameras were tested for linearity, dark current, flat field effects, and spectral quantum efficiency, with results used to select flight CCDs per MER project guidelines. The MI cameras were assembled, tested, and calibrated in customized JPL laboratories in two separate conditions, one for ambient and one for thermal/vacuum conditions. Video offsets were determined for low-temperature optimization. Most MI calibration spanned operational temperature extremes of 218K to 278K. From July to September 2002, over 18GB of test image data was collected and sent to USGS for analysis.

The MI exhibits flight heritage dating back to the Spirit and Opportunity Mars Exploration Rovers. The MI launched and landed successfully on Mars as part of the rover payload and operated in the Mars environment for over 15 years. It acquired over 5,923 full-frame images from Spirit alone used for scientific analysis and has exceeded its expected lifetime requirements. Through years of reliable imagery from Spirit and Opportunity, rigorous increment testing, calibration, integration, launch, Mars operations, and imaging, the Microscopic Imager has shown itself to be at TRL 7. The components of the MOMA exhibit flight heritage dating back to the Vikings Project, but the new innovations including LDMS have yet to be tested on Mars. MOMA has undergone extensive laboratory testing, but there will be more testing of the payload before launch, assessing its capabilities that cater to the objectives. NASA Goddard is working on the development of the mass spectrometer for MOMA, while laboratories in other countries are developing the other components. MOMA has undergone reviews that cleared the path for the flight instrument to be delivered to the mission. The MOMA-MS was transported from Goddard to Thales Alenia Space in Turin, Italy and was integrated into the rover's payload as part of upcoming missions. MOMA's TRL is estimated to be 5, but it has the potential to climb up to 6 and demonstrate relatively high flight readiness prior to the mission with environment and integration testing. The overall TRL of the payload is 5 due to the novelty of the MOMA.

Other spacecraft subsystems support the payload in its operations. The mechanical subsystem helps with the proper alignment and structural integrity of the instruments. The power subsystem ensures that the instruments receive the power for its data collection and analysis. The CDH subsystem stores the data from the payload and transmits it back to Earth as well as facilitates communication between the payload and mission control. The thermal subsystem helps maintain the temperature of the instruments, and keep it in its ideal operating range. The GNC subsystem utilizes sensors to determine the best orientation of the spacecraft for optimal performance of the payload.

Figure 55 - MOMA-MS Overview Table

MOMA-MS

Mass:	Volume:	Power draw:
9.3kg	20 × 20 × 25 cm	65W

Figure 56 - MI Overview Table

MI (Microscopic Imager)

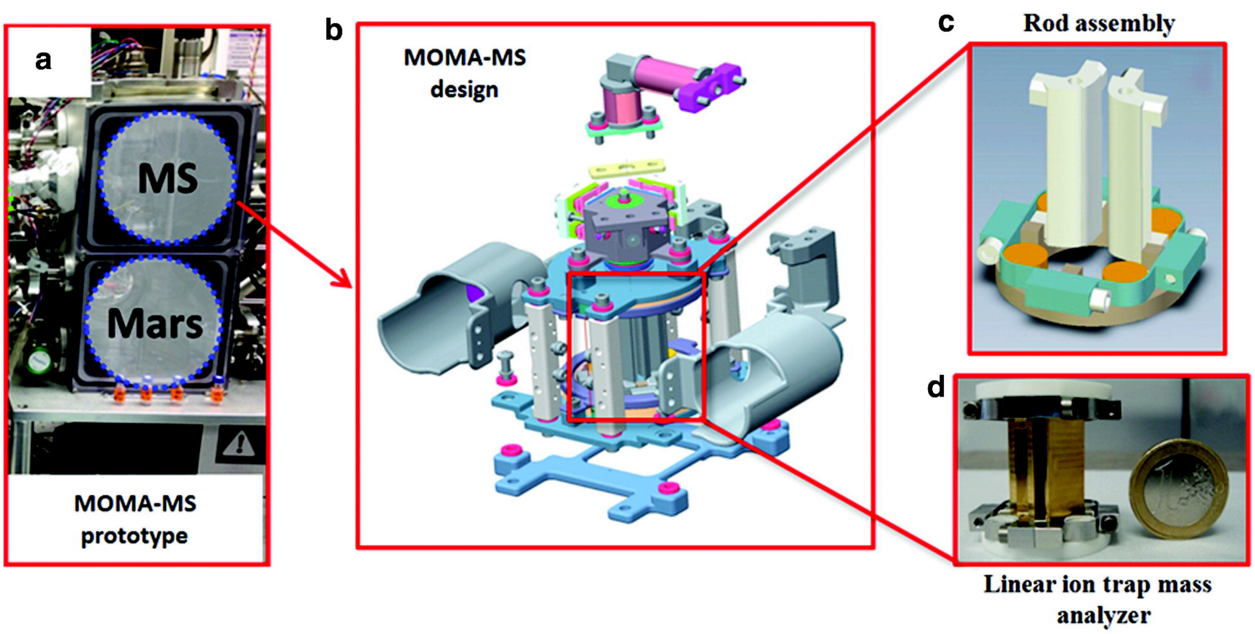
Mass:	Volume:	Power draw:
0.21kg	4.85 x 5.08 x 4.09 cm	3.0-4.8W

The mass, volume, and power of the MOMA-MS and the MI are shown in the figures above. Although the physical attributes of the MOMA-MS are slightly above the ideal allocation of constraints for the payload subsystem, the trade study (Mission Compatibility) weighs the relevancy to scientific objectives as significantly more important than its physical attributes. The rover is capable of supporting both instruments on the payload.

The depth of the Martian regolith is one of the determining factors in constructing the mechanism for sample collection in the pursuit of potential life on Mars. Samples retrieved from the surface regolith provide the most diverse and immediate access to materials that may have been affected by long-term geological processes. However, due to its thin atmosphere and absence of a magnetic field, Mars's surface is exposed to cosmic radiation that may lead to contamination and affect sample integrity. Minerals and organic compounds may degrade and its composition and spectroscopic signatures could be altered. Radiation may also exhibit detrimental effects to the health of the instruments and other components of the rover. The rover has limited physical capacities that may not support the power and mass consumption that heavy drilling requires.

The MI and MOMA-MS are not specifically designed to penetrate deep into the regolith. Considering the specific scope of the objectives the Endurance mission plans to accomplish, there were not many tailor made instruments that suited its specific scientific objectives. The Mini-Tes and PIXL were excellent instruments for their low weight and flight heritage, however they did not align with the objectives as well as the MOMA did. The figure demonstrated that the MOMA's durability and integration is the lowest among all the instruments. Despite the MOMA not being a flight tested instrument, its capabilities and strong alignment with the science objectives outweigh its low rating. High-resolution images can reveal key geological features and characteristics of life that would otherwise be indiscernible. Mass is very significant because of the rover's limited capacity for carrying instruments. A lighter camera would allow for room for other instruments including a more sophisticated spectrometer to aid in achieving the science objectives. Durability ensures the camera can withstand the harsh Martian environment, including extreme temperatures and dust storms. Integration with Spectrometer is necessary for combining visual data with analysis, enhancing the mission's scientific return.

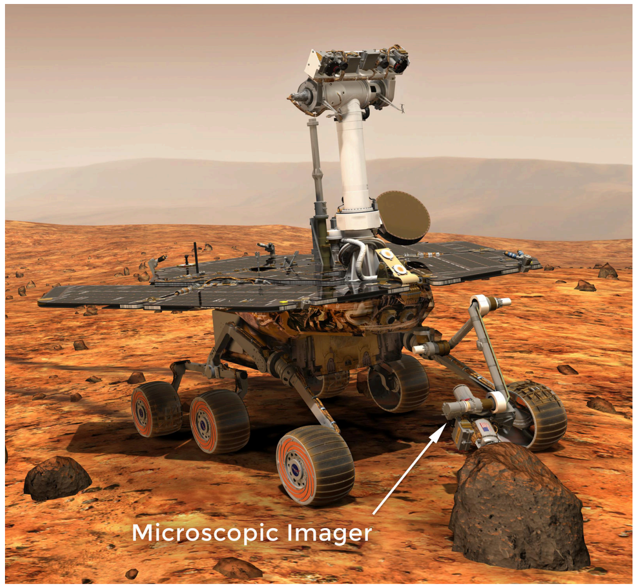
Figure 57 - MOMA-MS Model



(Li et al.)
Shown in the figure above is the laboratory setup of the MOMA-MS. The bottom chamber houses the samples under simulated martian conditions. MOMA-MS is based on a Linear ion trap (LIT) mass analyzer, and its miniaturization and ability to withstand higher pressure allows it to exhibit a greater dynamic range, sensitivity, and mass resolution. A transfer tube transports ions into the mass spectrometer, which is held at vacuum pressures. The aperture valve is opened to facilitate gas entering its system,

resulting in an increase in pressure. Laser pulses are fired on the sample, descorbing and ionizing the species. The valve closes, and the detector on the MOMA-MS scans and detects the ions.

Figure 58 - Microscopic Imager on Rover



(mars.nasa.gov)

On the Spirit and Opportunity Rovers, the Microscopic Imager was orientated on the robotic arm and its compact design optimizes its precision when capturing images. It produces close-up views of surface materials, and analyzes specific targets.

2.1.6.1. Science Instrumentation Requirements

The construction of the lower-level instrument requirements was systematically structured to guarantee alignment with the overarching mission goals, science objectives, and operational constraints of the rover. A comprehensive analysis of the payload's performance and environmental adaptability was used and factors such as mass, power consumption, volume, and operational temperature range were considered to optimize instrument functionality while adhering to physical and technical limitations. Verification methods including inspection, testing, and analysis were utilized ensuring that each instrument is capable of performing its designated tasks effectively

Figure 59 - Science Instrumentation Requirements

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem	Req met?

PLD-1	The science objectives shall be achievable with no more than two science instruments.	Provided by Mission document	Customer	All	Inspection	PLD	Met
PLD-2	Instruments shall not exceed physical constraints	Adhere to rover constraints	N/A	PLD-2.1, PLD-2.2, PLD-2.3, PLD-2.4	Inspection	MEC, PLD	Not Met
PLD-2.1	Instrument shall not exceed 13.5 kg	Should not exceed 30% mass constraint	MEC-1	TBD	Inspection	MEC, PLD	Met
PLD-2.2	Power consumption requirement for instruments must not exceed 70W	Power is a limited resource	N/A	TBD	Test	EPS, PLD	Not Met
PLD-2.3	The instruments shall not exceed a total volume of 20cm x 20cm x 25cm	Adhere to space constraints	EPS-2	TBD	Inspection	MEC, PLD	Not Met
PLD-2.4	Instruments shall be able to operate within temperature range of -40°C to +20°C	Must be able to withstand Martian environment	N/A	TBD	Test	TCS, PLD	Not Met
PLD-3	Instruments shall support scientific objectives and goals of mission	Mission needs to find insightful information	N/A	PLD-3, PLD-3.1, PLD-3.2, PLD-3.3, PLD-3.4, PLD-3.5, PLD-3.6, PLD-3.7, PLD-3.7.1	Analysis	All	Not Met
PLD-3.1	Mass spectrometer shall be sensitive enough to detect carbon organics	Conforms to the bio-markers objective	PLD-3	TBD	Test	PLD	Met
PLD-3.2	Mass spectrometer shall be able to detect appropriate mass fractions	Conforms to the isotopic fraction objectives	PLD-3	TBD	Test	PLD	Met
PLD-3.3	Instruments shall be able to perform in situ analysis	Sample return may not always be possible	PLD-3	TBD	Test	PLD	Met
PLD-3.4	Instruments shall be able to analyze data without affecting sample integrity	Minimize errors during data analysis	PLD-3	TBD	Analysis	PLD	Met
PLD-3.5	Camera shall provide high resolution multi-spectral imaging capabilities	Gather research data and support characterizati on of	PLD-3	TBD	Test	PLD	Met

		resources					
PLD-3.6	Camera shall operate efficiently under Martian conditions	To maintain operational integrity and data quality under Mars' conditions	PLD-3	TBD	Inspection	PLD	Met
PLD-3.7	Camera shall not surpass missions total data bandwidth allocation	Minimize data loss	PLD-3	TBD	Test	PLD	Not Met
PLD-3.7.1	Camera shall utilize compression without significant loss to meet data return requirements	Optimize amount of images with scientific value	PLD-3	TBD	Test	PLD	Not Met

2.1.6.2.Payload Subsystem Recovery and Redundancy Plans

Redundancy:

Since the rover is limited to two science tools it is not possible to achieve significant redundancy if the scientific instruments have a wide range of use. Each instrument will be an SPF. These tools are very critical to the mission so though having a backup of each tool is not possible the rover will maneuver these tools slowly and delicately which will help to reduce the odds of them getting damaged. One of these science tools is a camera, so even though it is not exactly the same one of the cameras used in the GNC system can be used to somewhat replace its function. Advanced diagnostic and algorithms will also be implemented to help compensate for potential instrument failures.

Recovery:

The Payload system will much like the other systems have a recalibration system to ensure the science tools are working at their highest capabilities. Since one of the science tools is a camera, there will be a reboot process in place in order to fix any errors which occur. A fail-safe mode would also be implemented that would activate if sensors detected anomalies in environmental conditions that exceed safe operating parameters. In this mode, the instruments would shift to a minimal operational state, preserving critical functionality while reducing the risk of damage.

2.1.6.3.Payload Subsystem Manufacturing and Procurement Plan

Microscopic Imager (MI)

The Jet Propulsion Laboratory (JPL) has been at the forefront of Mars exploration missions, including the creation of the original Microscopic Imager used in the Mars Exploration Rovers Spirit and Opportunity. Opportunity is known for outlasting its planned 90 day mission by nearly 15 years, making it the longest-lasting extraterrestrial robotic mission. The MI played a crucial role in these missions.

JPL is chosen for the development of the Microscopic Imager (MI). Its involvement in the creation of the original Microscopic Imager and its deep expertise and experience in Mars exploration makes it an ideal supplier for the imager. Despite the fact JPL has not disclosed specific lead times for past projects, the lead time estimate is 12-18 months reflecting the development and extensive testing phases required to adapt the MI for the new mission, along with the potential production capacity and constraints of the laboratory. The opportunity to lean on in-house resources and expertise when they are available and capable of fulfilling mission requirements is not to be taken for granted.

Mars Organic Molecule Analyzer Mass Spectrometer (MOMA-MS)

The MOMA mass spectrometer subsystem and main electronics were built and tested at NASA's Goddard Space Flight Center, making GSFC the ideal supplier for this mission. Their expertise in developing and testing high quality instruments time and time again aligns perfectly with the mission's objectives. The MOMA-MS is a critical component for the mission, as it will search for organic compounds in the collected soil samples, potentially revealing the presence of life on Mars. The selection of GSFC ensures that the MOMA-MS will be developed with the highest standards of reliability and performance, crucial for the success of the mission

Given the complexity and precision required for the MOMA mass spectrometer, the development process is expected to take around 18-24 months. This timeline includes the design, production, and testing phases. The extensive experience of the Goddard Space Flight Center in similar projects ensures the reliability and performance of the MOMA-MS in the mission conditions, justifying its selection.

2.1.6.4.Payload Subsystem Verification Plans

The Payload Verification Plans ensure that Endurance’s scientific instruments meet the standards necessary for Mars exploration. Many of the verification plans focus on measurements to follow the physical constraints outlined in the Mission document. The integration plans require more in-depth testing and software training to ensure that the instruments work properly.

Physical parameter requirements such as PLD-1 and PLD-2 will be verified through a visual inspection and their respective power, physical, and temperature constraints in the Mission document.

Mass Spectrometer/MI:

The PLD-3 requirements will be verified through various and specific environments to test the performance of the instrument's functionality. Additional adjustments and notes will be made from the analysis of individual instrument testings and integration testings. Specifically PLD-3.1 and PLD-3.2 will be verified with the findings in PLD-3.5 and PLD-3.6 to directly address the limitations of each instrument. Consequently, the cross referencing and analysis of both findings will determine further actions to guarantee that the instruments will not only meet their individual requirements but also satisfy the Endurance science mission objectives.

Figure 60 - Payload Verification Table

Req #	Requirement Summary	Verification method	Rationale	Preliminary Verification Plan
Payload				
PLD-1	The science objectives shall be achievable with no more than two science instruments.	Inspection	Provided by Mission document	This will be verified by confirming and rooting instrument choice.
PLD-2	Instruments shall not exceed physical constraints	Inspection	Adhere to rover constraints	This will be conducted by weighing and measuring the instruments.
PLD-2.1	Instrument shall not exceed 13.5 kg	Inspection	Should not exceed 30% mass constraint	This will be measured by weighing the instruments.
PLD-2.2	Power consumption requirement for instruments must not exceed 70W	Test	Power is a limited resource	This will be tested by individually testing the power draw and consumption of each instrument in expected scenarios.
PLD-2.3	The instruments shall not exceed a total volume of 20cm x 20cm x 25cm	Inspection	Adhere to space constraints	This will be verified by measuring the instruments.
PLD-2.4	Instruments shall be able to operate within temperature range of -40°C to +20°C	Test	Must be able to withstand Martian environment	This will be tested by monitoring instrument performance in various temperature controlled environments to measure expected performance.
PLD-3	Instruments shall support scientific objectives and goals of mission	Analysis	Mission needs to find insightful information	Ensure that the expected data and analysis from instruments prove to satisfy the scientific goals sufficiently.

PLD-3.1	Mass spectrometer shall be sensitive enough to detect carbon organics	Test	Conforms to the bio-markers objective	The MOMA mass spectrometer shall be tested in expected scenarios with various samples to ensure instrument sensitivity.
PLD-3.2	Mass spectrometer shall be able to detect appropriate mass fractions	Test	Conforms to the isotopic fraction objectives	The MOMA mass spectrometer shall be tested with multiple mass carbon mass fractions to ensure accuracy and sensitivity.
PLD-3.3	Instruments shall be able to perform in situ analysis	Test	Sample return may not always be possible	The instruments will be tested individually and in tandem in controlled testing environments. Analysis and adjustments will also be made on the data retrieved.
PLD-3.4	Instruments shall be able to analyze data without affect sample integrity	Test	Minimize errors during data analysis	Ensure the instruments have no capability of affecting sample integrity by monitoring instrument behavior in various scenarios.
PLD-3.5	Camera shall provide high resolution multi-spectral imaging capabilities	Test	Gather research data and support characterization of resources	This will be tested by testing the camera's specs while analyzing imaging capabilities during data transfer.
PLD-3.6	Camera shall operate efficiently under Martian conditions	Test	To maintain operational integrity and data quality under Mars' conditions	This will be confirmed through controlled temperature testing environments and scenario training.
PLD-3.7	Camera shall not surpass missions total data bandwidth allocation	Test	Minimize data loss	This will be conducted by testing the camera's performance with the CDH infrastructure and parameters.
PLD-3.7.1	Camera shall utilize compression without significant loss to meet data return requirements	Test	Optimize amount of images with scientific value	The camera will be tested using verified samples and adjusting camera software to optimize camera compression usage.

2.2. Interface Control

The N^2 chart shows how the subsystems generally interact and the block diagram characterizes that interaction in more detail. Both the Electrical Power System and Thermal Control System interact with every other system (including each other). External solar panels generate power for the EPS which then delivers the power to each subassembly through a power distribution unit. TCS interacts with everything either through patch heaters or heat pipes to route heat to external radiators. The Powertrain can be thought of as the mechanical hub. It is powered by EPS and turns that electrical energy into mechanical energy, then distributes that through other mechanical components like the wheel motors and other actuators. The CDH subsystem houses the central computer and communication devices. All internal and external communications go through the computer which can log data and autonomously send commands to any subsystem based on health checks and direct commands from mission control. The guidance and navigation system, similar to mechanical, has hardware spread throughout the rover, with cameras and sensors attached to the exterior and navigation controller hardware inside the chassis with the CDH “brain” of the rover. Finally, the scientific instruments are attached to the arm and chassis of the rover so that the mass spectrometer can easily receive samples and the microscopic imager can take images of the samples and any interesting features of the rover's surroundings.

Figure 61 - N^2 Chart

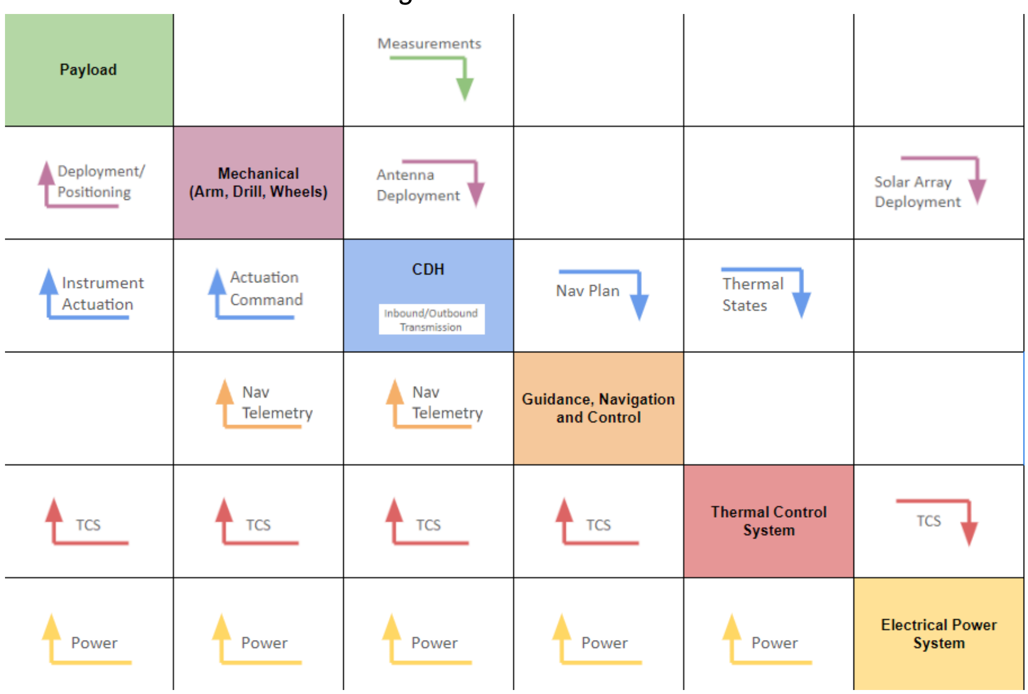
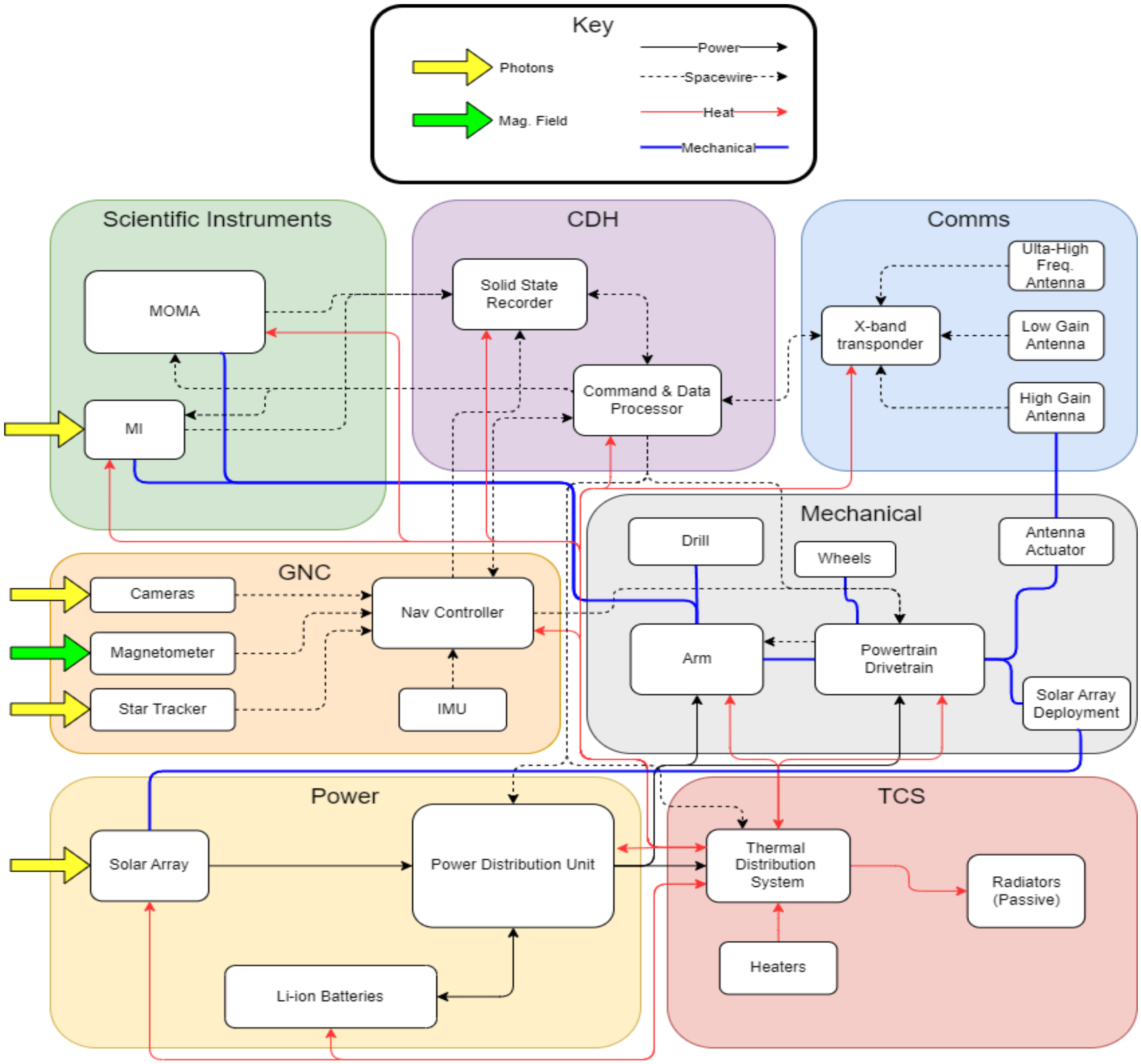


Figure 62 - Block Diagram



3. Science Mission Plan

3.1. Science Objectives

One of the team's objectives is to detect certain sediment isotopic fractionation to determine the possibilities of strong potential biosignatures on Mars. This objective was strategically chosen given that identifying regions rich in isotopic fractionation on Mars would provide potential indications of previous biological activity, guiding future landing sites and subsequently enhancing the impact of subsequent missions. The MOMA is robustly equipped to analyze the isotopic composition of organic molecules and fulfill this objective. This leads to the next objective, which is to determine the mineral composition of Martian regolith found near subsurface ice deposits. By identifying carbon-containing minerals in the thicker areas of the Martian regolith, a buffer against cosmic radiation, it is less likely that minerals and other materials will degrade or be chemically altered. The mineralogical composition of Martian regolith provides insights into past water activity and potential habitable conditions as certain minerals could indicate similar past conditions on Mars if found near ice deposits. The third objective is to determine the characteristics of subsurface ice deposits, erosion, and volcanic activity on Mars. Understanding these features more will provide significant clues about Mars' climatic history and potential habitability. The MI and MOMA are tailored to capture a wide range of data from chemical compositions to physical characteristics of the Martian surface ensuring that these objectives exceed their potential.

3.2. Experimental Logic, Approach, and Method of Investigation

The MOMA-MS and MI will work in concert to achieve the mission's scientific goals and objectives. The MOMA-MS will provide detailed chemical analysis of the sample by detecting organic compounds and isotopic fractionations to identify potential biosignatures. The MI will aid in this analysis by capturing high-resolution images of Mars's surface. Scientists will be able to combine the data collected of chemical features and geological features to holistically curate accurate scientific reports.

Following successful landing, the Endurance rover will run radiometric calibration on the MI and inject a liquid calibration mixture into the MOMA-MS before deploying the instruments. The specific calibration techniques are detailed in "3.4 Testing and Calibration Measurements", later in the Science Mission plan.

The drill on the mechanical subsystem will collect samples by penetrating the Martian surface or regolith. Once the drill reaches the desired depth, it will extract a sample of the material, crush the sample into a powder-like consistency, and transport it to the payload subsystem for scientific analysis. Then, the MOMA-MS will fire a single laser pulse at the sample at moderate laser power densities (MW to GW/cm2), and the physisorbed bonds of molecules are broken. This allows for the analysis of the chemical composition of the sample. LDMS analysis is triggered, and collects several hundred mass spectra from the laser pulses (Goesmann et al. 2017).

The MOMA-MS can perform measurements directly on ice samples, but this isn't the most accurate way to analyze biosignatures. Instead, it will warm up the ice sample until the water ice sublimates and residues of biosignatures, salts and minerals remain.

The MI will capture multiple images of the ice from different angles and camera settings are adjusted for optimal precision.

It remains critical that the MOMA-MS and MI are frequently monitored to ensure its accuracy and precision, and maximizing the amount of scientific value Endurance will bring back. Data collected by the payload is transferred to the CDH subsystem for storage and future analysis.

3.3. Payload Success Criteria

The payload success criteria are characterized by accurate detection of biosignatures and valuable insights for future missions on Mars. Instruments on the payload must deliver data that yields scientific value, or confirmation of an understudied assumption from previous missions. There must be some indication of the level of habitability that exists on Mars. The possibility of finding life on Mars does not determine payload success, but instead, the criteria's backbone is whether the information gathered by Endurance can benefit the scientific community. There is great interest in studying Mars because it has water in the form of ice at the polar caps, and astrobiologists believe that life could develop due to this phenomenon. It is also possible these water sources can be used for manned missions to Mars.

The MOMA-MS must be able to distinguish between abiotic and biotic sources of biosignatures. The instrument is more sensitive than other mass spectrometers utilized on past missions, and thus, it is expected to yield more accurate data. Since the MOMA-MS has yet to be tested on a mission, another criteria of payload success is whether the MOMA-MS performs better than other instruments and may be integrated in future missions.

The MI must be able to capture detailed images that allow scientists to study the characters of geological features. The MI has been integrated into the payload of past missions, but often accompanied by other imagers. Endurance will evaluate the performance of the MI by itself and test how feasible it is to use a single compact imager to collect data.

3.4. Testing and Calibration Measurements

All instruments onboard the payload will be tested during Phase D of the mission to optimize the performance of the MOMA-MS and MI. Once the Endurance rover has reached its desired landing location, calibration methods and tests will be conducted for proper instrumentation.

For conducting in-situ calibration of the MOMA-MS, the experiments will be based on control variables, including temperature and the chemical composition of the sample. Controlling the temperature helps maintain the integrity of the sample. A liquid calibration mixture will be used for injection into the MOMA oven and will consist of 5 µL of phenylethanol, 1-butanol, methyl-acetate, hexane, benzene, toluene, dodecane, heptanol, pentanol, fluoronaphthalene, and DMF diluted in 100 µL of pure methanol (Goesmann et al. 2017). A greater range of organic compounds can be detected and analyzed by using that calibration mixture, allowing for more reliable scientific data from Martian samples. During the calibration process, the mass spectrometer records the mass-to-charge ratios generated as volatile organic compounds pass through and undergo ionization and fragmentation.The abundance of each ion is quantified and this data will help scientists calibrate the mass spectrometer to accurately detect organize compounds in future samples.

For conducting in-situ calibration of the MI, the experiments will be based on control variables such as temperature, illumination, and the landing site. The MI will be radiometrically calibrated which involves multiple factors such as dark current, offset/bias, flat field sensitivity variations, and conversion to radiance or I/F correction. The optimum video offset will be determined by analyzing dark current in zero-exposure images and avoiding clipping the signal to zero DN (St). This ensures that the signal, even at extreme temperatures, remains above the minimum detectable level. The rover will execute simple image processing to correct for flat field variations, and its software system will adjust to the images captured by the MI. During the mission, the MI will primarily capture images of soil, surface material, and sedimentary layers, and the sensitivity variation of pixels will be accounted for due to that calibration method. Selecting the appropriate calibration target specific to the landing site that matches the geological characters of Endurance's path will reduce errors in calibration and enhance the accuracy of scientific data collected by the MI. Calibration targets will take into consideration known radiance values. To determine whether the MI is providing accurate data, regular quality assurance checks will be implemented. There will be extensive pre-flight laboratory testing of the MI, and in-flight monitoring by science and engineering teams to pinpoint abnormalities. Calibration procedures will be adjusted if unexpected environmental conditions are encountered and if data discrepancies between the MOMA-MS and MI pose problems.

3.5. Precision and Accuracy of Instrumentation

The Microscopic Imager (MI) on the Athena instrument is a high-resolution imaging system designed to study Martian soils up close. It features a field of view of 1024×1024 pixels and works the same way with a simple, fixed focus design at f/15, providing ±3 mm depth for 30μm/pixel sampling. With a focal length of 20 mm and a working area of 63 mm, it offers a field of view of 31×31 mm. The spectral bandpass of MI ranges from 400 to 680 nm, with a modulation transfer function of at least 0.35 at 30 lp/mm. Radiometric calibration has a relative accuracy of ≤5% and an absolute accuracy of ≤20%, with measurements taken every 10 nm of spectral bandpass. The MI signal-to-noise ratio is at least 100 within its estimated operating temperature range of -55 to +5º C. However, it does not have an onboard radiometer calibration objective for in-flight calibration. The MI can acquire images using solar or overhead illumination, and can be transported between successive frames to control for stereo and mosaics. The device also uses optical sensors to create well-focused images on every frame. The MI's performance is enhanced by its ability to use solar or overhead lighting, and its contact mechanism helps bring precise locations closer to target areas, especially in smooth surfaces, for better images. In addition, MI's retractable dust cover, an orange tinted Kapton window that limits the spectral bandpass to 500 - 700 nm, ensures protection from Martian environmental conditions at k 'have access to color information.

The Mars Organic Molecule Analyzer - Mass Spectrometer (MOMA-MS) subsystem is equipped with specific performance requirements according to its pyrolysis gas chromatography mass spectrometry (Pyr/GCMS) and laser desorption mass spectrometry (LDMS) modes. In Pyr/GCMS mode, MOMA-MS targets volatile organic compounds such as alkanes, amines, alcohols, and carboxylic acids, with a mass range capability of 50–500 U. It achieves a range of detection of £nmol analyte (SNR > 10) and a resolution (FWHM) of £1u. Meanwhile, in LDMS mode, the focus shifts to non-persistent organic substances such as macromolecular carbon and proteins, along with inorganic species, extending its mass range to a detection limit of £pmol mm^-2 analyte (SNR ‡3). which extends from 50-1000 u and a resolution (FWHM) of £2u. Both modes maintain a single scan dynamic range of ‡100 over their respective mass ranges, ensuring broad analytical capability. MOMA-MS operates within a challenging environmental range, with an operating pressure of 4 to 8 Torr of the Martian atmosphere and an operating temperature of -40°C to +20°C. It can withstand non-operating temperatures from -50°C to +60°C and withstand temperatures up to +145°C. These stringent requirements ensure that the MOMA-MS subsystem can effectively analyze Martian samples, providing important insights into the presence and nature of organic compounds on the Red Planet.

3.6. Expected Data & Analysis

The Mars Organic Molecule Analyzer - Mass Spectrometer (MOMA-MS) onboard the rover focuses on examining solid crushed samples exclusively, without atmospheric analyses. MOMA utilizes two main modes: Laser Desorption Mass Spectrometry (LDMS) and Pyrolysis Gas Chromatography Mass Spectrometry (Pyr/GCMS). LDMS is the initial mode applied to a sample, targeting nonvolatile compounds on the outer surface of sample grains. LDMS provides insight into the sample's potential organic content, aiding in decisions regarding further analysis. Depending on the LDMS results, Pyr/GCMS analysis may be conducted on subsequent subsamples to explore specific compounds further. MOMA's analytical capabilities are applied to different aliquots of a given crushed drill core, guided by tactical science decisions. The LDMS data acquired autonomously during sample runs comprise several hundred mass spectra, providing insight into the organic content. After data collection, the MOMA science team reviews the data for features of interest and decides on potential next steps, such as detailed LDMS investigations or further analysis by Pyr/GCMS. MOMA's LDMS mode offers a rapid and nondestructive method to analyze the organic content of crushed samples before detailed Pyr/GCMS analysis. In addition to MI decision making, the LDMS or Pyr/GCMS analysis will be conducted when necessary to detect strong biosignatures within the Martian subsurface. LDMS data interpretation involves identifying organic signals amidst inorganic peaks, aided by information from other instruments on the rover. The geological context provided by instruments from the MI influences MOMA's analysis strategy. In case of detecting indigenous Martian organic molecules, the overall geological context becomes crucial in determining their origin which can be ascertained by the MI instrument.

Figure 63 - LDMS Coronene Sample

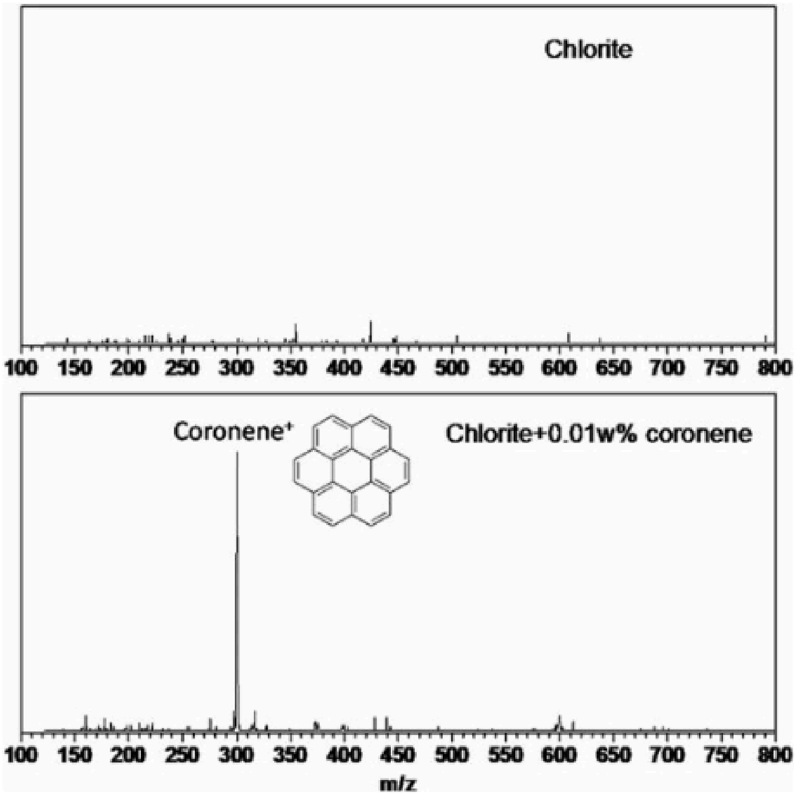


FIG. 11. Positive ion LDMS spectrum of chlorite alone (top) and chlorite doped 0.01 w% with example PAH coronene. In this example case, the Coronene molecular ion is readily detectable above the very low background contributed by the mineral analog. LDMS, laser desorption mass spectrometry.

Vago, “The Mars Organic Molecule Analyzer (MOMA) Instrument: Characterization of Organic Material in Martian Sediments.”

Figure 64 - LDMS Organics Table

TABLE 3. LIST OF GC COLUMNS SELECTED FOR MARS ORGANIC MOLECULE ANALYZER GC AND THEIR MAIN CHARACTERISTICS

Name (supplier)	*Stationary phase*	*Dimensions L/ID/d_f (m/mm/μm)*	*Compounds targeted*
MXT Q BOND (Restek)	Divinylbenzene	25/0.25/8	Inorganic volatile molecules C1-C5 organic molecules
MXT CLP (Restek)	Not available from the supplier	25/0.25/0.25	C4-C25 organic molecules
MXT 5 (Restek)	95% dimethylsiloxane 5% diphenylsiloxane	25/0.25/0.25	C4-C25 organic molecules
CP Chirasil Dex CB (Agilent)	enantioselective, B-cyclodextrin bonded to dimethylpolysiloxane	25/0.25/0.25	Organic enantiomers

Vago, “The Mars Organic Molecule Analyzer (MOMA) Instrument: Characterization of Organic Material in Martian Sediments.”

The Mars Exploration Rover Spirit's Microscopic Imager (MI) data has unveiled significant insights into the characteristics of Martian soil. Surface and subsurface soils exhibit disparities, with surface materials displaying more pronounced evidence of eolian influences, particularly in sorting. Subsurface soils, on the other hand, bear resemblance to crushed sediment analogs, indicating a process of impact comminution followed by eolian reworking. Eolian processes emerge as the primary driver shaping the distribution of soil grain sizes and shapes along Spirit's traverse. Additionally, the presence of dust at the surface, initially expected to be <4-μm air fall dust particles, was confirmed by MI observations to manifest as sand-sized aggregates with irregular shapes and filamentary textures, displaying low density and fragility. These dust aggregates are notably easier for wind mobilization compared to ordinary sand grains which directly aids research and data analysis for possible isotopic fractionation. Following a strong wind event that cleared much of the transient dust mantle from Spirit's landing site, MI images of rocks and soils revealed more detailed information. Furthermore, various soil classes and subclasses, delineated based on MI and Alpha Particle X-ray Spectrometer (APXS) data, showcased distinct characteristics in terms of grain size, shape, and composition, which benefits the MOMA mass spectrometer integration for this particular scenario. Notably, MI observations also captured changes in soil distribution, with alterations in the abundance of fine sand grain within the Martian surface. Overall, the MI data has proven invaluable in unraveling the complex dynamics of Martian soil properties, shedding light on processes such as impact comminution, eolian reworking, and dust mobilization on the Martian surface.

Figure 65 - Gallant Knight Sample

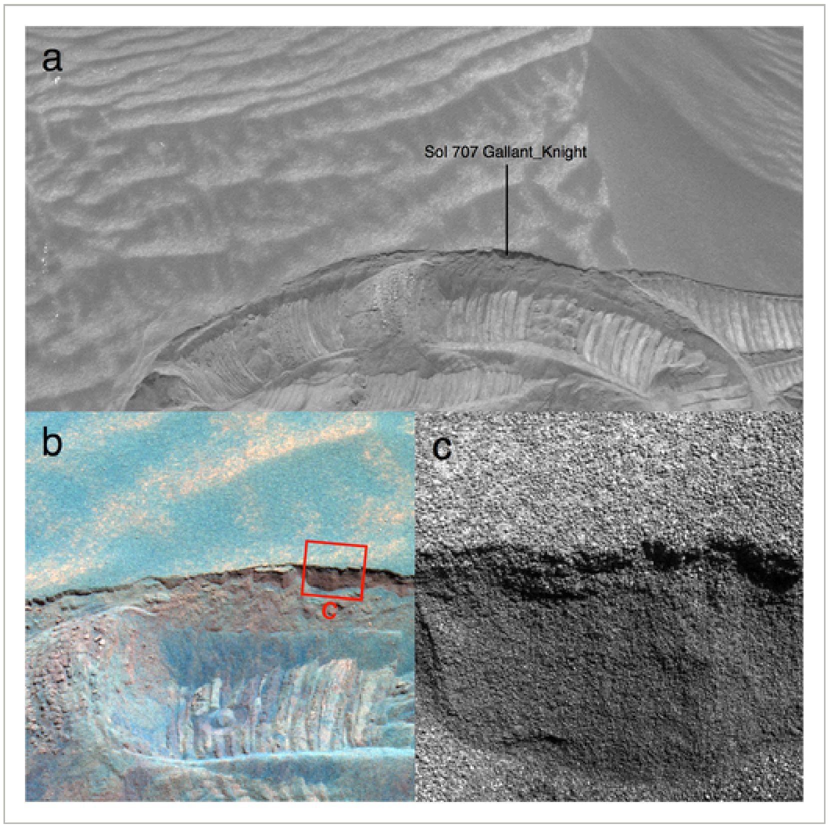


Figure 32 Open in figure viewer | PowerPoint

(a) Sol 706 Navcam view of wheel scuff bisecting crest of large ripple of dark, mafic sand at El Dorado feature. (b) Sol 711 Pancam enhanced-color view (L257) showing "roadcut" exposure created by wheel scuff. Color differences between surface and interior materials correlate with grain size observed by the Microscopic Imager. (c) Merge of radiometrically calibrated Microscopic Imager images (3 × 3 cm) of El Dorado target *Gallant_Knight* acquired on Sol 707 with illumination from upper right, revealing well-sorted 200- to 300-um grains at the surface and within the lightly cohesive 1-mm-thick surface crust that give way at greater depths to less sorted material with a higher fraction of finer, poorly resolved grains.

K. E. Herkenhoff et al., "Overview of Spirit Microscopic Imager Results," *Journal of Geophysical Research. Planets* 124, no. 2 (February 1, 2019): 528–84, https://doi.org/10.1029/2018je005774.

Figure 66 - MI Troy Feature Sample

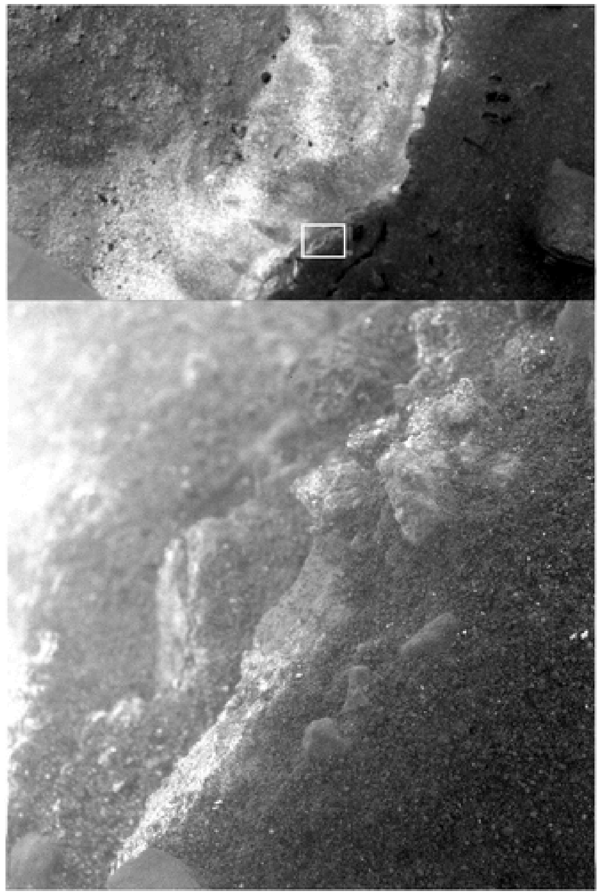


Figure 33 Open in figure viewer | PowerPoint

(top) Sol 1933 Pancam blue (R7) image 2P297975925ESFB1E5P2382R7M1 of the Troy feature, showing footprint of the Microscopic Imager image below in white. (bottom) Focal merge of Microscopic Imager images of Olive Tree 1 acquired on Sol 1927 when target was shadowed except at left edge. Area shown is 3 × 3-cm square.

K. E. Herkenhoff et al., "Overview of Spirit Microscopic Imager Results," *Journal of Geophysical Research. Planets* 124, no. 2 (February 1, 2019): 528–84, https://doi.org/10.1029/2018je005774.

Figure 67 - MI Cliffhanger Feature Sample

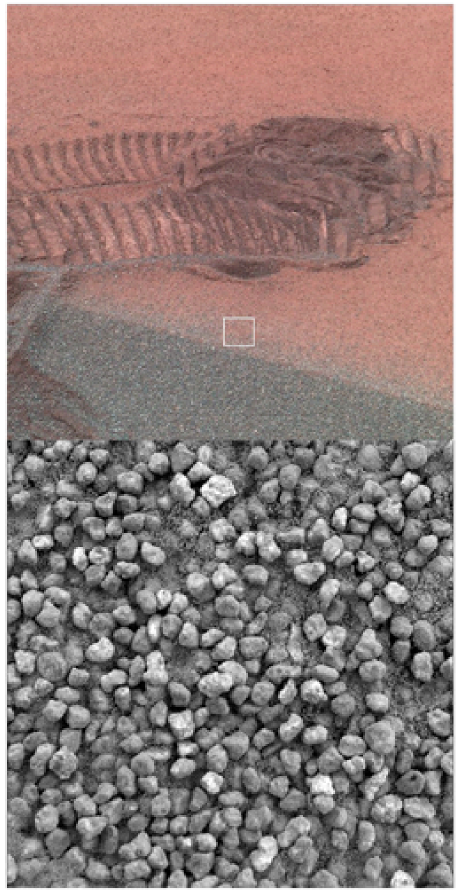


Figure 34

Open in figure viewer | PowerPoint

(top) Sol 612 enhanced-color Pancam image 2P180695038RSDAEMDP2589L2MZ of the *Cliffhanger* feature, showing approximate location of Microscopic Imager image below in white. (bottom) Radiometrically calibrated Microscopic Imager image 2M180252684IFFAEM9P2977M2F1 of the HangTwo target, taken on Sol 607 when target was fully shadowed. Note coarse sand grains on the surface and finer-grained material below.

Herkenhoff et al., "Overview of Spirit Microscopic Imager Results."

4. Mission Risk Management

4.1. Safety and Hazard Overview

Methods for identifying Risk

- Method 1:

  One method for identifying risks is based on mission and system requirements. Failure to meet a major requirement is also a potential risk and therefore should be listed as one.

- Method 2:

  The other method for identifying risks is based on potential hazards such as failure to protect the planet or weather causing damage to certain parts.

Criteria for Analyzing Risk

- Criteria 1: Likelihood/Occurrence

  The first criteria the risks will be analyzed on will be their likelihood to occur. This means that the more likely the risk is to occur the more dangerous the risk is.

- Criteria 2: Consequence/Severity

  The second criteria the risks will be analyzed on will be their consequences if they were to occur. This means that the higher the impact on the mission if the risk were to occur the more dangerous that risk is.

- Criteria 3: Detection

  The third criteria the risks will be analyzed on will be on how difficult they are to be detected if they were to occur. This means the harder it is to detect the risk the more dangerous it is as it is more difficult to mitigate.

Why it's important

It is important to have methods for identifying risk because if a large risk is not identified and instead overlooked it could lead to many issues to the rover or even mission failure. In addition, if there is not a set criteria for analyzing risk it will be difficult to determine what risks are most important to prevent and to focus the team's attention on and which risks will not have major repercussions and can be left alone. For example, staying within budget is a lot more important than preventing dust from collecting on solar panels as it will definitely lead to mission cancellation and the dust only might lead to some minor issues. After identifying and analyzing risk the team should continue to plan, track, and control the risks in order to mitigate and lower the risk as much as possible

Planetary Protection Concerns

The main planetary protection concern is to keep the mission site as close to the way it was found as possible. There should be no contamination from the rover to the mission and site and all materials found in the site should be at the same spot when the mission is completed. Failure to protect the planet could lead to future missions being affected and even compromised.

4.1.1. Risk Analysis

General Risks

- Risk 1: Rover mass exceeds 45kg (ID: 3)

The rover has to stay under a 45 kg mass constraint in order to be deemed suitable for launch because it is a secondary payload aboard a primary vehicle. Since there is a finite amount of space reserved for the rover it can't be exceeded by any amount or the mission will be canceled. To reduce the risk of going over the allotted mass, it was a factor considered in the trade studies for certain parts. In addition, when determining manufacturers the weight of the part was also considered.

- Risk 2: Rover volume exceeds Length 100cm x Width 100cm x Height 100cm stored (ID: 4)

The rover has to stay under volume constraint in order to be deemed suitable for launch because it is a secondary payload aboard a primary vehicle. Since there is a finite amount of space reserved for the rover it can't be exceeded by any amount or the mission will be canceled. To reduce the risk of going over the allotted volume when determining manufacturers and specific parts the size of it was considered. In addition, each subsystem provided a volume estimate and the combination of all estimates is less than the constraint.

- Risk 3: Rover exceeds maximum of two science instruments(ID: 5)

The rover has to stay under a science instrumentation constraint with the science objectives being achievable with no more than two science instruments. If there are additional science instruments without approval from the Change Control Board the mission is subject to cancellation. To prevent going over the limit the science instruments were chosen based on how effectively they would be at accomplishing the mission objectives. In addition, before the science objectives were chosen, how many instruments it would take to accomplish them was considered as well as if the same instrument could be repurposed for another objective.

- Risk 4: Rover exceeds 5g of radioactive material or contains a Radioisotope Thermoelectric Generator (ID: 6)

The rover is not allowed to contain a RTG as it is prohibited in an effort of planetary protection. In addition, having over 5g of radioactive material is prohibited as it could infect the planet's environment ruining future missions. In order to prevent the risks the rover will not contain any radioactive material at all. In addition, to substitute needing a RTG an alternative power source which does not require radioactive material was chosen.

Budget

- Risk 1: Mission cost exceeds $250 million cost cap (ID: 1)

Given that there is not an unlimited budget, there is a possibility of overspending. The mission cost does not exceed the budget, and staying within the budget is essential to ensuring that the mission is allowed to operate. If the proposed budget exceeds the cost cap, NASA could shut down the operation before physical development begins. To reduce the risk of going over budget, materials will be bought in bulk when possible to keep cost as low as possible. In addition, only basic testing will be officially included in the budget, and extra extensive testing will only occur if additional funds are available.

- Risk 2: Additional budget cuts or Unknown Costs (ID: 21)

The development team does not fund this mission and, therefore, is subject to budget cuts by NASA. In addition, not all costs can be estimated, and if there is a huge unknown cost, it could greatly affect development. To combat this, mission success parameters can be scaled back to factor in any significant changes. Personnel can also be reduced if additional budget cuts or unanticipated costs occur. If these changes are not made in a timely manner, NASA could scrap the entire mission or the mission will fail to be ready for launch.

Schedule

- Risk 1: Mission length exceeds December 31st, 2028 launch date (ID: 2)

The mission has a set launch date, which the spacecraft must be fully ready for, or it will miss launch and be declared a failure. This could occur for various reasons, such as hiring taking longer than anticipated, facilities not being ready on time, or a team lagging behind and does not complete their part of development on time (Construx 2020). The development will start with the current team to combat hiring taking longer than anticipated, even if only some have been hired. In addition, to combat facilities not being ready no time development will occur in a temporary location while the facilities are being prepared or people will be allowed to work from home on other tasks. Lastly, to combat a team lagging, staff on another team can be relocated to assist or additional personnel can be hired. If these changes are not made when they occur the mission is likely to miss launch and be a failure.

- Risk 2: Design Issues require complete overhaul (ID: 22)

The mission design has not been built or tested and if there are major issues which cannot be addressed the design will have to be completely changed or the mission will be scrapped as it will not be able to continue. To combat this issue when designing the spacecraft risk and efficiency are being in high consideration. In addition, a manufacturer may end up not being able to deliver the required part in time in which case there will have to be a substitution to a different part or manufacturer. If a part which is essential has an issue it could lead to huge ramifications so manufacturing and procurement should be discussed with the manufacturers long before physical development is scheduled to begin. That way any changes can be made before it is too late.

Planetary Protection

- Risk 1: Contamination to Mars' environment through Earth bacteria (ID: 23)

Ensuring that Mars' environment is kept the same as it was before the mission is crucial to keeping studies accurate. If the spacecraft is not properly handled and disinfected then life not native to Mars' can be unintentionally transported to Mars. To prevent this from occurring there will be strict sanitation requirements when handling the spacecraft. In addition, the spacecraft will be kept in a controlled environment where outside bacteria and dirt cannot get onto the spacecraft. If Mars' environment is contaminated it could lead to inaccurate results and huge impacts down the line.

- Risk 2: Contamination to Mars' environment through mismanagement of samples (ID: 24)

Like previously stated on (ID: 23) keeping Mars' environment unaffected by the mission is crucial. If the samples are dropped in places where they do not naturally occur it could lead to a change in the ecology on Mars. To keep this from happening samples will be kept in a consistent location and/or returned to where they were taken from when analysis has been finished. If contamination does occur then it could cause inaccurate readings down the line and make Mars harder to study.

Electric Power System (EPS)

- Risk 1: Short-circuiting due to wiring problems (ID: 9)

The EPS is critical to the operation of the spacecraft, and powers all other subsystems. To reduce the risk of short-circuiting, the design includes wiring grade wiring and connectors, which increase resistance to physical and thermal stresses Each component is individually tested before assembly. In addition, the system design includes automatic circuit isolation features that detect and isolate faults, so it does not impact the overall power system. Regular in-class diagnostics will monitor the flow of electricity and the integrity of the EPS, to enable the detection of an immediate problem.

- Risk 2: Dust accumulation on solar panels (ID: 10)

The spacecraft will operate in dusty environments, posing a significant risk to the efficiency of solar panels. To combat this, engineers developed two methods. First, the solar panels are covered with a soft electromagnetic layer that repels dust particles. Second, the panel mount integrates an industrial vibration system, which can be activated periodically to shake off accumulated dust If operating parameters are changed to increase power production, they will be monitored the efficiency of this system by monitoring power.

- Risk 3: EPS fails to generate enough energy for movement (ID: 8)

The EPS is responsible for generating energy for the entire rover. If the EPS cannot generate substantial power in order for the rover to move the science objectives will not be accomplishable. In order to prevent this, a backup-battery will be implemented to help ensure the rover can generate the required power even if there is a failure with the original. Also, the rover will have a regular time to charge its batteries so that it does not end up running out of power in a hazardous location.

Command and Data Handling (CDH) System

- Risk 1: Radiation damage to computer components (ID: 11)

The sensitivity of CDH systems to radiation is a well-known challenge. The spacecraft uses both passive and active charging methods to protect sensitive electrical equipment. Passive shields have objects that absorb or deflect them, while active shields use magnetic fields to deflect energetic particles away from critical objects Besides, spacecraft software incorporates error detection and correction algorithms to ensure data integrity despite harsh space conditions. Although some components are damaged by radiation.

- Risk 2: Weather causing network failure (ID: 12)

Significant Mitigation: Martian weather, including dust storms and temperature fluctuations, can disrupt communications systems. The antennas are designed with automatic heating to prevent ice formation and are made of materials that reduce the attachment of dust. The spacecraft's communication system includes that if the initial transmission fails, data is automatically retransmitted, ensuring that no data is lost. Regularly ordered maintenance from Earth will change the antenna orientation and operating frequency to reduce the effects of climate change on signal strength.

Mechanical Subsystem

- Risk 1: Tipping Over on Rugged Terrain (ID: 13)

Adaptive suspension systems are designed to stabilize even on uneven terrain Simulation software, developed with data from previous Mars missions, allows engineers to predict and design potential tipping scenarios, and adjust the rover's course accordingly There are sensors which detect tripping hazards in real-time and trigger automatic correction tips.

- Risk 2: Getting stuck in sand or Ice (ID: 14)

    To avoid getting stuck, the rover's wheels are designed with a self-washing mechanism that prevents sand or snow from sticking, preventing slippage The rover is also dynamically adjustable in wheel speed and direction and to get out of soft soil or snow. In more extreme cases, the rover can use onboard tools, such as a robotic arm, to instantly change its environment, providing optimal maneuvering conditions.

Thermal

- Risk 1: Effect of dust on temperature control (ID: 15)

The spacecraft's thermal system is designed to be highly flexible, with protective variables that respond to changes in solar absorption. Active heaters can compensate for solar heat loss due to dust cover, ensuring room temperatures remain within operating limits These systems are continuously monitored, with dependent changes in real-time information as needed.

- Risk 2: Radiator freezing (ID: 16)

    The temperature controls include radiators designed to work well in the cold Martian environments. The use of non-refrigerant, combined with a new loop design that prevents condensation, reduces the risk of condensation The electric refrigeration system is installed effectively to ensure that water remains at freezing temperatures, with ongoing monitoring of system health to identify any abnormalities.

- Risk 3: Rover fails to maintain safe temperature range (ID: 7)

    The thermal system is responsible for keeping the entire rover at a suitable temperature. If the thermal system fails to do this many of the parts would be subject to severe damage and could stop functioning. In order to prevent this many different thermal controls are to be implemented including a radiator, aerogel, heat pipes, and heaters with redundancy between components.

Guidance, Navigation, and Control (GNC)

- Risk 1: Sensor calibration and degradation (ID: 17)

    The reliability of the GNC system is paramount to mission success. To reduce sensor degradation, the spacecraft is equipped with multiple sensors of each type, allowing cross-reference and calibration checks Automated onboard software algorithms adjust sensor excursions over time to ensure the trip is the same. Regular calibration advisories are planned throughout the mission to ensure sensor accuracy to known celestial or Martian landmarks.

- Risk 2: Inaccurate Navigation (ID: 18)

To combat potential navigation errors, the spacecraft uses a multisensor fusion technique, combining information from visual and passive satellite navigation systems for overall accuracy Navigation has been performed the software is designed with fault tolerance in mind, capable of detecting and ignoring faulty entries. Simulations and experiments on Earth using Mars-like environments have developed carefully designed transportation systems to ensure optimal performance.

Payload

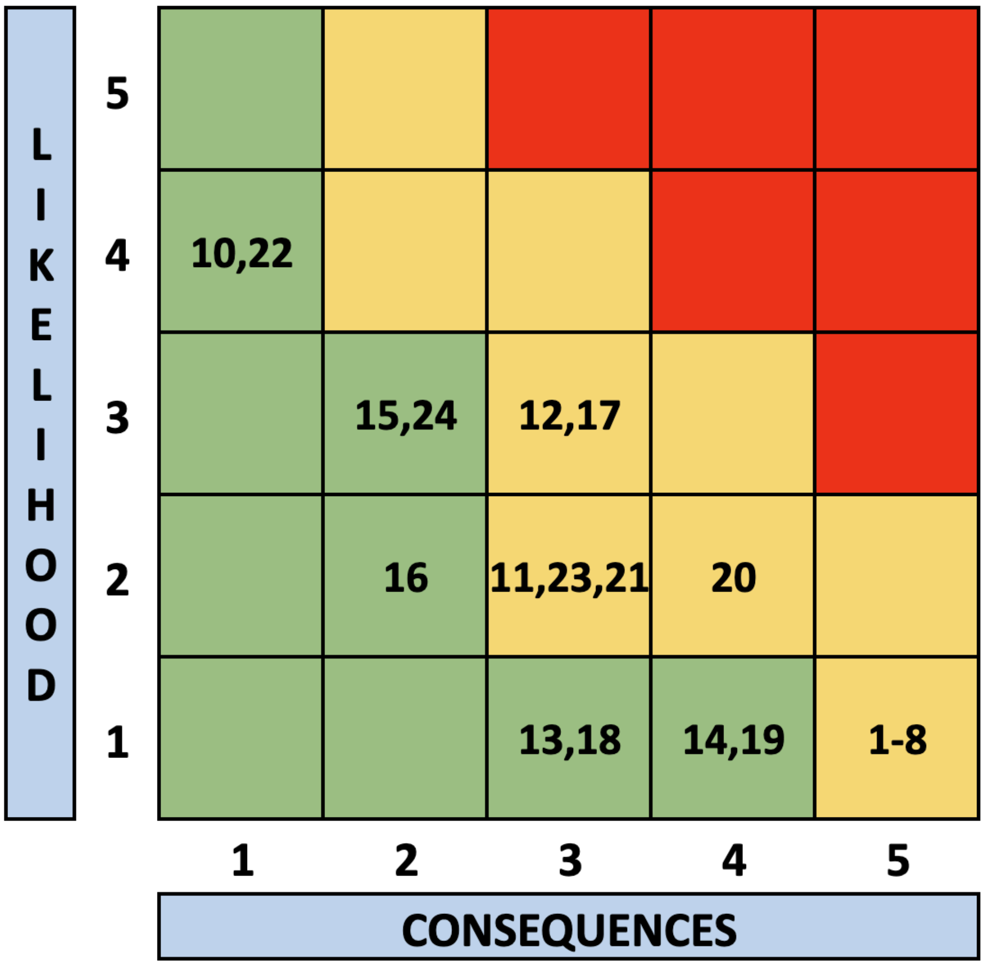
- Risk 1: Equipment malfunctions due to environmental interactions (ID: 19)

The development of scientific instruments, especially drills, include features such as auto-retraction and options to reduce adhesion to the Martian soil or ice, prevent the instrument from becoming stuck Regular diagnostic tests assess instrument health, and enable maintenance or modification of operational parameters to avoid failure.

- Risk 2: Sample contamination (ID: 20)

To prevent contamination of the sample storage, the payload bay is isolated from the rest of the spacecraft's system, with access only allowed during sample collection or analysis and for contamination control procedures for all phases of the mission from assembly to deployment. The use of sterilized instruments and solvents ensures the integrity of the scientific data, allowing for a more accurate examination of Martian objects.

Figure 68 - Risk Matrix



4.1.2. Failure Mode and Effect Analysis (FMEA)

A detailed Failure Mode and Effect Analysis (FMEA) was conducted, focusing on the most critical risks identified in the Risk Analysis. By analyzing these risks and tracing down its potential effects on other subsystems, the team will be able to propose more effective mitigation strategies and ensure the success of the Endurance mission. CDH, Payload, and Mechanical subsystems are included although all subsystems were thoroughly evaluated.

The Command and Data Handling (CDH) subsystem manages vital data and communication mechanisms. Its failure modes: power loss, communication lapse, and network failure, pose threats to the mission's success. Power is essential for CDH and all subsystems onboard the spacecraft. In 2018, the Opportunity rover entered a hibernation-like mode following a massive dust storm that covered over 41 million square kilometers. With no sunlight to generate power, the rover preserved the little energy it had remaining by sleeping (“The Mars Exploration Rovers Update Special Report: Opportunity…” n.d.). Communication was severely hindered, and although dust storms of this extremity are rare, it may be mission-ending. Therefore, the Endurance rover must be prepared for intense dust accumulation. Designs on the rover will be put into place to protect its health and prolong the duration of the mission. These designs include thermal regulation systems to manage temperature fluctuations, the application of soft electromagnetic layering on solar panels, and the integration of an industrial vibration system to protect the rover from dust accumulation. If the level of dust accumulation and resulting power loss exceeds the rover's system capability, low-energy mode must be stimulated. The rover will be programmed to enter low-energy mode under certain criteria, but if it fails to initiate this function, mission control will command the rover to enter low-energy mode. Communication between mission control and the spacecraft occurs during specific windows and important commands may be missed if there is a communication lapse. Miscalculation in timing of communication even by 10 minutes may cost the rover a full day of exploration (Wilford 1997) . If the spacecraft clock is turned off by environmental hazards or software/hardware malfunctions, any subsystem and function that relies on timing, is off put. The rover won't know when its communication windows are. To ensure optimal command execution and data transmission, real-time monitoring and the rover's predicated location and movement must be constantly taken into consideration when determining next steps. A simple troubleshooting may fix the communication lapse. The FMEA identified network failure to have the most severe consequences. The Mars Global Surveyor (MGS) spacecraft was ultimately lost due to a High Gain Antenna (HGA) positioning command written to the wrong memory address within the spacecraft's computer system five months prior. The mission terminated following the error (“Llis,” n.d.). To prevent network failure from occurring on Endurance, the team will optimize signal tracking from the spacecraft and reduce attachment of dust to prolong the efficiency of antennas. Due to unforeseen events, it is critical that mission control is able to send commands and communicate with Endurance at any time.

The payload subsystem of the Endurance rover exhibits a significant role in accomplishing the mission's scientific objectives. It comprises two instruments that will analyze the Martian samples, detect potential signs of past or present life, and characterize the Martian environment. Failure modes include sample contamination, instrument malfunction, and operating outside of an ideal temperature range, and these failures will ultimately affect the success of the mission and effectiveness of scientific data collection. Sample contamination can have a domino effect on solar panels, thermal systems, mechanical components, and antennas in addition to affecting the integrity of the data collected. Sample contamination from cosmic radiation and dust will affect the samples collected by the payload. Protective measures such as sterilizing instruments and isolating the payload subsystem from the rest of the spacecraft system's will mitigate the risk of the cascading contamination effect. While the rover is on Mars, sample collection techniques cannot be altered, but the location of data collection can be altered. Instrument malfunction may be caused by communication errors, calibration errors, and sensor failures. Instrument malfunction can lead to power strain, communication disruption, mechanical stress, and thermal regulation issues if the issue isn't promptly addressed. Extensive testing and calibration before launch must be conducted to ensure the maintenance of the instruments. If one of the instruments fails, the rover must be able to increase its reliance on the functional instrument. This may involve descoping scientific instruments since one instrument is unable to accomplish all three science objectives. Both instruments are affected by temperature extremities and the MOMA-MS may not be sensitive enough to detect biosignatures, and the MI may produce less quality images if it is operating outside of its ideal temperature range. The rover operating outside of its optimal temperature range, in general, introduces complexities in all subsystems. Active heaters and radiators will help regulate the temperature of the instruments and the spacecraft.

The mechanical subsystem of the Endurance rover is substantial for its mobility and stability on Mars. Failure modes - structural damage, structural fatigue, and wheel damage - within the mechanical subsystem and their impact on mission performance are assessed. Crossing rugged terrain is inevitable, and the impact may force scientific instruments out of optimal position and disrupt its ability to collect data. Communication would be affected and the overall health of the rover would deteriorate. Endurance will integrate adaptive suspension systems to stabilize the rover on uneven terrain and the rover's course will be closely monitored. Extreme weather and the long duration of the mission will cause structural fatigue, which is also inevitable. Mechanical components such as the chassis will be stressed and this may hinder mission operations. To minimize the effects of structural fatigue, the rover has employed highly durable materials that will be able to withstand harsh environmental conditions. Regularly monitoring will be done to assess weaknesses in the rover's state to mitigate the impact of wear and tear. The rover may enter low-energy mode to rest and resume normal mission operations after. If the physical state of the rover is insufficient to follow the mission's original scope, scientific objectives may be descaled to match the capabilities of the rover and the route can be altered. Wheels are central for mobility and over time, the wheels will undergo tears from fatigue. Endurance will have structurally sufficient wheels to roll over rocks, but when multiple wheels are pushing against the same rock, the stress on the wheel increases. If the wheels reach their point of use, the robotic arm may be used as the central component for maneuvering. Wheel damage can slow progress and limit the paths the mission can traverse, but it may not limit the capabilities of the rover (Lakdawalla, 2014).

Figure 69 - FMEA Table

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
CDH	Power loss	Loss of communication, shut down of critical subsystems, data loss, impact mission operations, rover could enter hibernation mode	8	Dust accumulation	2	Thermal regulation, cover solar panels with soft electromagnetic layering and integrate industrial vibration system	2	32	Manually stimulate low-energy mode from mission control
	Communication lapse	May miss mission communication windows and important commands, delays to timeline, disrupt navigation systems, data loss	5	Miscalculation in timing of communication, mission clock failure	4	Close real-time monitoring, recalculations of communication timing	3	60	Pinpoint precise source of error and recalcuate communication window, or wait for rover signal
	Network failure	Missed commands for: solar panel orientation, change in rover's movements, payload instructions, thermal and mechanical operations, can terminate mission if communication cannot be reestablished	10	Command error or mislocation, extreme weather	1	Multiple antennas on Earth and on rover to track signal from spacecraft, automatic heating of antennas, reduce attachment of dust	4	40	Regulary ordered maintenance from Earth, thorough flight software configuraton manament process
Payload	Sample contamination	Inaccurate data analysis, contamination buildup on solar pannels, thermal systems, mechanical components, and antennas	5	Cosmic radiation, dust	7	Using sterilized instruments and isolating payload from spacecraft's system	3	105	Modify location of data collection
	Instrument malfunction	Affect success of overall mission goals, disrupt operations of other subsystems	8	Communication errors, calibration errors, sensor failures	2	Extensive testing and calibration before launch	4	64	Maximizing reliance on functional instrument
	Operating outside ideal temperature range	Reduced instrument sensitivity, decrease efficiency of other subsystems	7	Extreme weather, faults in thermal system	4	Active heaters, radiators	3	84	Descope mission objectives
Mechanical	Structural damage	May force the scientific instruments out of position for chemical composition of regolith, may tilt or damage rover, disrupt data processing and communication	6	Rugged terrain, landing impact, collisions	7	Adaptive suspension systems	4	168	Real-time monitoring and corrections, descope mission objectives to fit rover's physical state
	Structural fatigue	Stress on mechanical components, alter insulation mechanics, slowing down rover and hindering mission potential	4	Extreme weather	10	Regular maintenance and designing rover to withstand harsh environments	5	200	Temporarily enter low-energy mode, change route
	Wheel damage	Require more power consumption, disrupt antannae orientation, introduce errors in navigation	5	Tears from fatigue, multiple wheels pushing against same pointy rock, immobile pointy rocks	8	Select landing site where rover doesn't need to rove out of eclipse to find good targets, maximize sandy terrain, design rover to sense wheel currents, self-washing wheels	7	280	Perform shorter drives, driving backwards, use robotic arm to manuever

4.1.3. Personnel Hazards and Mitigations

The manufacturing, integration, and testing phase of constructing the Endurance Rover at The Endurance Exploration Laboratory (EEL) poses several personnel hazards that need to be addressed for the safety of team members. These hazards include exposure to toxic chemicals, physical hazards, biological hazards, and machine shop hazards. This following section will detail each hazard and its associated mitigations.

Chemical Hazards

Exposure to toxic chemicals such as Carbon Tetrachloride (CCl4), 1,1-Dichloroethene (1,1-DCE), 1,2-Dichloroethane (1,2-DCA), Tetrachloroethene (PCE), Trichloroethene (TCE), Perchlorate, Hexavalent Chromium, Trivalent Chromium, and 1,4-Dioxane can lead to severe health issues including respiratory problems, organ damage, and carcinogenic effects.

Figure 70 - Chemical Hazards Analysis

Chemical	Relevant Location(s)	Associated Risk
Carbon Tetrachloride (CCl_4)	Machine shops, cleaning stations, solvent storage areas.	Accidental spills or leaks during handling or storage.
1,1-Dichloroethene (1,1-DCE)	Plastic manufacturing areas, solvent handling areas.	Exposure during plastic fabrication or solvent use.
1,2-Dichloroethane (1,2-DCA)	Chemical synthesis labs, degreasing stations.	Inhalation or skin contact during handling or accidental spills.
Tetrachloroethene (PCE)	Solvent storage areas, degreasing stations.	Exposure during degreasing processes or from leaks in storage containers.
Perchlorate	Propellant manufacturing areas, pyrotechnic workshops.	Accidental spills or leaks during propellant production or handling.
Hexavalent Chromium	Metal plating facilities, paint shops.	Inhalation or skin contact during metal plating or paint application.
Trivalent Chromium	Chrome plating facilities, metal finishing workshops.	Inhalation or skin contact during chrome plating operations.
1,4-Dioxane	Chemical synthesis labs, plastic manufacturing areas.	Exposure during solvent-based processes or from contaminated water sources.

Chemical Hazards Mitigation

- Implement strict protocols for handling and storing chemicals.
- Provide appropriate Personal Protective Equipment (PPE) such as gloves, goggles, and respirators.

- Conduct regular training sessions on chemical safety and emergency response procedures.
- Ensure proper ventilation and containment systems are in place to minimize exposure.

Physical Hazards

Hazards include flammability/explosive nature, hazards associated with heavy equipment, slip-trip-fall hazards, lifting hazards, tool and equipment hazards, heat stress hazards, and noise.

- Implement standard safety procedures to minimize explosive atmospheres and provide proper firefighting equipment.
- Ensure all heavy equipment operators are trained and follow safety protocols.
- Maintain good housekeeping to minimize slip-trip-fall hazards.
- Train employees on proper lifting techniques and provide assistance for lifting heavy objects.
- Conduct regular maintenance of tools and equipment and provide appropriate PPE.
- Implement measures to prevent heat stress, such as worker rotation, rest periods, and hydration.
- Use hearing protection in high noise areas and implement engineering controls to reduce noise levels where feasible.
- Workers' compensation during absence and paid training upon the employee's return to work.

Biological Hazards

Exposure to biological hazards such as snake bites, insect bites and stings, and pathogenic microorganisms can lead to various health issues including allergic reactions, infections, and respiratory problems.

Biological Hazards Mitigation

- Educate personnel on avoiding contact with hazardous animals and insects.
- Conduct regular inspections for ticks and signs of infected bites.
- Provide emergency antidotes for personnel with severe allergies and ensure supervisors are prepared for medical emergencies.
- Follow first aid procedures set by the American Red Cross for biological hazards.

Machine Shop Hazards

Hazards in the machine shop include eye injuries, cuts and abrasions, chemical reactions/burns, slip and fall accidents, burns, and electric shock.

Machine Shop Hazards Mitigations

1. Provide appropriate PPE such as safety glasses, gloves, and hearing protection.
2. Maintain a clean and organized work area to minimize slip and fall accidents.
3. Implement proper training on machine operation and safety procedures.
4. Conduct regular inspections of equipment for potential hazards.

By implementing these mitigations, the EEL can significantly reduce the risks associated with personnel hazards during the construction of the Endurance rover. Regular training, strict adherence to safety protocols, and maintaining a culture of safety awareness are essential for ensuring the well-being of team members.

5. Activity Plan

5.1. Project Management Approach

Determining the personnel needed to complete the mission promptly is critical to its success. The five core personnel types essential to the mission are managers, administrators, scientists, technicians, and engineers. The baseline personnel for each phase is 33, with a maximum of 39 to adhere to the allocated personnel budget constraints through the mission life cycle. To maintain mission efficiency and adhere to the allocated personnel budget, the personnel in each type will fluctuate between mission phases. The amount of administration and management for the mission will not fluctuate throughout mission phases unless additional staff is required for scope fluctuations. The management personnel include the Project Manager, the Deputy Project Manager of Resources, the Lead Systems Engineer, and the Lead Scientist. All leads will be present throughout the duration of the mission. The administrative personnel include the Program Analyst, Risk Assurance Specialist, and Outreach Officer, who will be present throughout each mission phase.

Phase C will span through FY24 and FY25 and involves determining the final design components in preparation for full-scale operations and assembly, which occurs in Phase D. Phase C also includes developing integration plans and procedures, ensuring facilities and personnel are prepared for full-scale operations, and that a CDR is completed to demonstrate the maturity of the design which moves the team into Phase D upon approval. ("NASA Space Flight Program and Project Management Handbook," n.d.). The team will have 33 personnel during Phase C. Due to the heavy emphasis on engineering design and systems engineering activities, engineering personnel will account for 45% of the team. In addition, technicians will comprise 21% of the team to assist the engineering team during the final design process. The dominance of engineering and technical staff is required to accomplish the final design of the rover within the estimated two-year span of Phase C. The amount of science personnel, accounting for 12% of the team, will remain as such for both fiscal years. The science personnel is kept at a lower percentage of the team to help ensure scientific goals and objectives are met while allowing engineering and technical personnel to perform efficiently with the most team members. The administrative and management personnel account for 21% of the team throughout Phase C.

Phase D, spanning three fiscal years, involves completing the final design and integrating the full system assembly interface. Due to a significant shift toward assembly and manufacturing, engineering personnel will increase from 15 to 20 for FY26, and technicians will increase from 7 to 8. The increase in engineering and technician personnel will allow the team to accomplish full assembly integration per the Phase D timeframe while maintaining quality control. As Phase D progresses into the next two fiscal years, the number of engineers and technicians decreases by 6% and 0.5%, respectively, to match the diminishing need for assembly as the rover reaches the final stages of assembly. By the last year of Phase D, engineering personnel will decrease to 12, accounting for 36% of the team. Science personnel are increased by 8% in preparation for Phases E and F, which will primarily involve evaluating scientific data and mission closeout. The administrative and management personnel will remain consistent throughout FY26, FY27, and FY28. Management and administrative personnel will maintain and adhere to the cost and budget constraints throughout Phases C and D while managing communication with stakeholders and addressing risk management.

Phases E and F occur in FY29 and involve the operations and evaluation of mission data and reports. Due to the spacecraft being launched at this mission stage, the need for technicians is eliminated, and engineering personnel is significantly decreased. Science personnel are increased to facilitate data analysis, mission closeout, and lessons learned. Rising from 21% to 60% of the team composition, science personnel will be more than doubled to account for gathering and interpreting scientific data, closeout reports, and maximizing team efficiency to keep to the mission schedule and constraints. The spacecraft will be launched by Phases E and F, eliminating technicians on the team. Technicians work directly on manufacturing and assembling the rover. So, their responsibilities have been fulfilled with the rover in orbit or on Mars. The engineering personnel has been cut significantly due to the launch of the rover and most engineering responsibilities being fulfilled. 18% of the team will be engineering personnel to support science personal efforts and data collection. In the event of any instrumentation issues, the remaining engineers on the team will be able to address these concerns or circumstances to allow the rover to remain fully operational.

Figure 71 - Personnel Chart

Team Endurance: Personnel Chart						
	Phase C	**Phase C**	**Phase D**	**Phase D**	**Phase D**	**Phase E-F**
# People of Team	FY24	FY25	FY26	FY27	FY28	FY29
Science Personnel:	4	4	4	4	4	19
Engineering Personnel:	15	15	20	15	12	6
Technicians:	7	7	8	7	7	0
Administration Personnel:	3	3	3	3	3	3
Management Personnel:	4	4	4	4	4	4

The management personnel includes the lead scientist, lead systems engineer, deputy project manager of resources (DPMR), and the project manager (PM). The PM and DMPR have significant budgeting authority and reserves. The PM and DPMR may be the ultimate deciding factor over budget allocation and changes. The lead systems engineer primarily controls subsystem budget allocation and will determine which subsystems may be affected during scope change. The lead scientist also directly impacts the mission requirements and objective scope and the budget allocation towards scientific instruments. All team members must be skilled communicators with adept organizational and time management abilities. The DPMR should have proficient skills in navigating budgeting tools such as MCCET and an understanding of financial management. The lead systems engineer and lead scientist are expected to have experience and the ability to learn about various engineering management and science management skills and tools, respectively.

In the programmatics subteam, the project manager oversees communication throughout all subteams and facilitates communication between the mission team and the Mission Directorate. The PM sets the pace and works closely with the leads to develop KDP (Key Decision Point) and ensure the mission will meet the science objectives on schedule and by mission constraints. The PM works closely with the DPMR, who manages the programmatic administration team. The DPMR works closely with the program analyst, outreach officer, and risk assurance specialist to determine the mission's budget allocation, scheduling, risk assessments, and outreach efforts. The program analyst is the primary overseer of the mission budget and reports back regularly to the DPMR if budget allocation issues arise. The program analyst determines the mission's outreach, personnel costs, travel, and direct costs. The risk assurance specialist coordinates the mission's risk assessment, maintenance, and tracking efforts. The risk assurance specialist works with the DPMR to facilitate communication between the engineering, science, and programmatic teams to discover and accurately document mission risks. The outreach officer organizes the outreach efforts for the mission, broadcasting the purpose of the mission to educate the public and foster support for the mission's science objectives.

The engineers, scientists, and administrators teams are further divided into sub teams and have separate systems and responsibilities. A lead is assigned to each team, coordinating communication between their team and the project manager. Each subteam has a designated subteam lead who facilitates communication between the subteam and the team lead and is responsible for regular check-ins and progress reports. Each subteam has the autonomy to analyze and propose potential engineering, science, and programmatic decisions that best fit the mission scope. However, the team lead overseeing each subteam has the ultimate say regarding major subteam decisions.

The engineering team has various subteams based on the mission's needs. All subteams report to the lead systems engineer, who coordinates the overall guidance of all engineering sub-teams. The lead systems engineer works closely with the PM, DPMR, and lead scientist to regularly evaluate that science objectives are being met, mission constraints are being met, and engineering risks are being addressed. The mechanical engineers are responsible for the design and manufacturing of the mechanical components of the rover, such as the chassis, wheels, and other structural elements included. Mechanical engineers work closely with technicians during Phases C and D to ensure structural integrity, safety, and optimization. Thermal engineers design and choose the thermal components of the rover, which includes the heating and insulation systems that will be integrated into the design. The electrical engineers manage the rover's power and coordinate with other engineering teams to determine the power draw of each subsystem. The electrical engineers balance the power subsystems across each rover component. Guidance, Navigation, and Control (GNC) engineers develop the navigation and guidance systems for the rover. Command and Data Handling (CDH) engineers integrate data processing, telecommunications, and software architecture into the rover. Technicians will be incorporated to work on the rover in later phases under the lead system engineer's guidance.

The lead scientist is a critical position that facilitates all scientist teams. The lead scientist coordinates communication between the science team and the other team leads and ensures the development of mission science objectives and goals. The science team assists with interfacing payload requirements for the rover, which includes determining the methods for collecting samples and data. The scientist subteams are expanded to include disciplines directly related to Martian geology. Geologists are critical members of the science team who help evaluate the landing location and sample collection processes. Geologists also work closely with mechanical engineers to determine several structural components of the rover, as wheels are directly impacted by Martian regolith and must be optimized to withstand the terrain. Hydrologists assist geologists in determining the optimal landing location for the rover by mission objectives. Hydrologists determine the type of samples the mission should collect, where these samples are best located on Mars, and what scientific instruments should be incorporated into the rover design to retrieve the samples. Researchers assist in the creation of general science objectives, goals, and payload development.

5.2. Mission Schedule

5.2.1. Schedule Assumptions

In developing the schedule for the upcoming mission, specific insights from previous NASA missions, including SAMPEX, Insight, Mars Pathfinder Rover, and Psyche, were utilized to inform planning and estimation processes. These missions provided valuable data and benchmarks for understanding the complexities inherent in space exploration endeavors. Here are the key schedule assumptions, succinctly outlined, incorporating the preliminary schedule estimate information:

Leveraging data from missions such as SAMPEX, Insight, Mars Pathfinder Rover, and Psyche, alongside a preliminary schedule estimate, timelines were adjusted to be 25% longer on average to accommodate unforeseen challenges. Several updates were made to analog mission data to reflect technological advancements and lessons learned, especially for manufacturing/procurement. Specifically, NASA’s JPL facility was the primary source for the payload and mechanical subsystem parts for the Endurance rover. Hence, the schedule was adapted by splitting the team faculty by the respective subsystems to the necessary parts in an efficient/sequential manner.

Additionally, many specific subtasks that were expected to occur during the Endurance integration process were implemented into the Mission Schedule through subtasks under major documents. For example, important milestone documents such as the CDR and the ORR are expected to appear in the Mission Schedule. Therefore, appropriate assumptions for specific subsystems integrations, document subtasks, and milestone subtasks were incorporated for a more in-depth schedule estimation.

The rough estimate includes the appropriate major documents and their respective phase locations, referencing the SEH 3.0 NASA Program/Project Life Cycle. Document durations are estimated based on a SMART mission time duration chart shared in the programmatics role meeting, resulting in a month-long mission duration. Also, the margin allocated between the integration and the launch of Endurance has been increased to adhere to the NASA guidelines of 1 week of margin per 1 month of activity. This increase accommodates possible cases in which starting tasks may not be able to start due to concurrent tasks and the respective delays for individual subsystem testing.

5.2.2. Mission Schedule

The schedule introduction will provide a basic overview of the life cycle the mission plans to proceed through. Firstly in part C guidance suggests that as time progresses, longer projects should be broken down into smaller, clearly defined projects, which can last as long as a month. This breakdown is a close tracking of progress, identifying obstacles or issues that may arise, change project requirements or circumstances, or modify and improve.

Similarly, Section D, which covers activities such as system communication, integration, and testing, recommends defining the workflow necessary for requirements verification, communication, integration of hardware and software components are identified.

This emphasis on division of labor and clarity continues in Phase E, which focuses on performance and sustainability. Here, delayed tasks are further divided into more manageable subtasks, with a particular focus on describing discrete tasks required for lock-in operations and operations which maintain stability

Overall, control, and flexibility throughout the project lifecycle by breaking tasks down into clearly defined sub-groups as the implementation progresses This approach allows for more efficient management, the identification of dependencies, and ultimately a successful completion of the mission.

Figure 72 Gnatt chart - Major milestones

Phase	Docs	General Activity	Specific Milestones
Phase C (Start)	CDR/SIR	Critical Design Review. Fabrication, assembly, integration and test, Review technical overview. Mission performance and requirements cost and schedule constraints. Detailed Design. Testing and Evaluation. Finalized Design Documentation. Manufacturing Initiated. Integration and Verification Planning.	4/24/2024 - Begin Fabrication Finalize Systems Review Test all components JPL Manufacturing/Procurement System integration review 9/21/24 - CDR

Phase D	TRRs, ORR, FRR	System Integration Review. components and subsystem integration into system progress report. Integration of parts, facilities, and plans, Review procedures to implement integration System Integration and Testing. Operational Readiness System Engineering Involvement Early Planning. Assembly and Integration Complete Verification and Validation Testing Flight Readiness Review (FRR) Launch Preparation	4/13/25 - Manufacturing Complete 11/15/28 - Shipped to KSC for Authenticate rover functionality Final Assembly and Launch 12/31/28 - Launch Date
Phase E	PLAR, CERR, DR	Spacecraft cruise and monitoring. Operational Readiness Review. Examination of system procedures. System support: ground, softwear, personnel, procedures. Accurately reflects the system procedures Systems Engineering Involvement Evolution and Adaptation Continued Software Development: Initial Operations Phase (IOP) Begins Performance Monitoring and Adjustment Potential Mission Extensions End of Mission Declared Data and Sample Analysis Completed Systems Decommissioned and Disposed Final Report and Closeout Documentation Submitted	Cruise and sustainment (240 day cruise) 8/28/29 - Arrival on Mars Conduct mission/data transmission
Phase F	DRR	Decommissioning Review. Closeout Procedures. Complexities and Considerations. End of Mission Declared Data and Sample Analysis Completed Systems Decommissioned and Disposed Final Report and Closeout Documentation Submitted	Document lessons learned Baseline mission report 9/23/29 - End of Main Scheduled Surface Operations

High level overview

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
1	CDR		0%	4/23/24	5/12/24	20	2
1.1	Finalize Systems Review	All	Not complete	4/23/24	4/24/24	2	
1.2	CDR Draft	All	Not complete	4/24/24	5/8/24	15	
1.3	CDR Revision	All	Not complete	5/8/24	5/10/24	3	
1.4	CDR Final Draft	All	Not complete	5/10/24	5/10/24	1	
1.5	Schedule Margin			5/10/24	5/11/24	2	
1.6	◆ CDR Presentation	All	Not complete	5/12/24	5/12/24	1	
2	JPL Manufacturing/Procurement		0%	5/13/24	4/30/25	353	29
2.1	Payload MI	Science	Not complete	5/13/24	10/20/24	161	

2.2	Mechanical Wheels/Chassis/Suspension	Mechanical	Not complete	10/20/24	12/13/24	55	
2.3	GNC Hazcam	GNC	Not complete	12/14/24	2/2/25	51	
2.4	Thermal Subsystem	Thermal	Not complete	2/2/25	3/2/25	29	
2.5	Testing at JPL	All	Not complete	3/2/25	4/2/25	32	
2.5	Schedule Margin			4/2/25	4/30/25	29	
2.6	◆ Tested every JPL part	All	Not complete	4/30/25	4/30/25	1	
3	Systems Development & Procurement		0%	5/13/24	4/30/25	353	29
3.1	Mechanical Rotary and MOMA	Science, Mechanical	Not complete	5/13/24	1/2/25	235	
3.2	Bae Systems, L3 Harris, STAR-Dundee Procurement	CDH	Not complete	6/13/24	10/11/24	121	
3.3	Sodern, Moog Inc. GNC Software	GNC	Not complete	7/13/24	12/13/24	154	
3.4	Electrical Subsystem	Electrical	Not complete	12/12/24	3/2/25	81	
3.5	Testing for all parts	All		3/2/25	4/2/25	32	

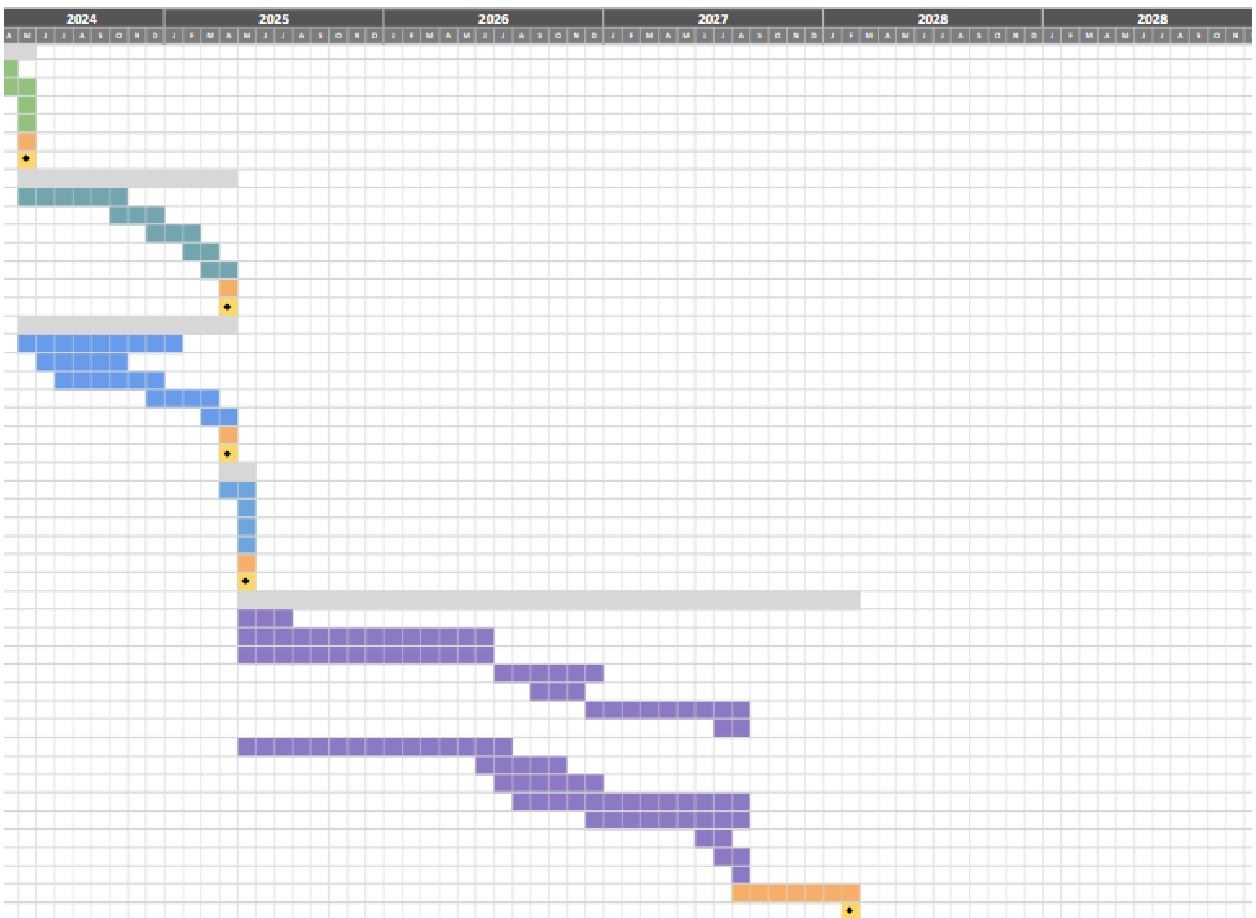
3.5	Schedule Margin			4/2/25	4/30/25	29	
3.6	◆ Tested every other part	All	Not complete	4/30/25	4/30/25	1	
4	SIR		0%	4/30/25	5/7/25	8	2
4.1	Identify and update risks	All	Not complete	4/30/25	5/7/25	8	
4.2	SIR Draft	All	Not complete	5/7/25	5/24/25	18	
4.3	SIR Revision	All	Not complete	5/24/25	5/26/25	3	
4.4	SIR Final Draft	All	Not complete	5/26/25	5/26/25	1	
4.5	Schedule Margin			5/6/25	5/7/25	2	
4.6	◆ SIR Presentation	All	Not complete	5/7/25	5/7/25	1	
5	Integration and Assembly		0%	5/7/25	2/24/28	1024	178
5.1	MOMA and MI Testing	Engineering, Science		5/7/25	7/7/25	62	
5.2	TRR Payload	All	Not complete	5/13/25	6/8/26	392	
5.3	Deployment Mechanisms	Engineering		5/17/25	6/30/26	411	

5.4	TRR Mechanical	Engineering	Not complete	7/9/26	12/16/26	161
5.5	Structural Integrity	Engineering		9/3/26	11/25/26	84
5.6	TRR Electrical	Engineering	Not complete	12/17/26	8/18/27	245
5.7	Identify and rectify thermal risks	Science, Programmatics	Not complete	7/30/27	8/19/27	21
5.8	TRR Thermal	Engineering	Not complete	5/13/25	7/8/26	422
5.9	Thermal Control Systems	Engineering		6/26/26	10/18/26	114
5.1.1	TRR CDH	Engineering, Science	Not complete	7/9/26	12/16/26	161
5.1.2	Training Sodern Navigation	Engineering, science		8/18/26	8/20/27	389
5.1.3	TRR GNC	Engineering, Science	Not complete	12/10/26	8/26/27	260
5.1.4	Systemwide Integration	All	Not complete	6/3/27	7/14/27	42
5.1.5	Confirm system integrity & durability	All	Not complete	7/14/27	8/24/27	42
5.1.6	Transport Endurance to Cape Canaveral	Programmatics		8/24/27	8/29/27	5
5.1.6	Schedule Margin			8/29/27	2/22/28	178

5.1.7	◆ Rover is reassembled	All	Not complete	2/22/28	2/24/28	3	
6	Critical Reviews and Documents		0%	2/23/28	12/31/28	313	165
6.1	Authenticate rover functionality	Engineering		2/20/28	3/11/28	20	
6.2	Examine overall system characteristics	Engineering, Science	Not complete	2/23/28	3/12/28	19	
6.3	ORR	All		4/25/28	7/18/28	84	
6.6	Implement outreach social media strategies	Programmatics	Not complete	6/5/28	7/19/28	45	
6.4	Validate systems and support	Engineering, Science	Not complete	3/13/28	3/31/28	19	
6.5	Prepare and baseline manuals	All	Not complete	4/1/28	6/4/28	65	
6.6	Safety review and config audits	All		5/20/28	7/19/28	60	
6.5	FRR	All	Not complete	6/5/28	7/19/28	45	
6.5	Schedule Margin			7/20/28	12/31/28	165	
6.6	◆Launch	All	Not complete	12/31/28	12/31/28	1	
7	Conduct mission		0%	12/31/28	10/4/29	278	15

7.1	Cruise and sustainment	All	Not complete	12/31/28	8/27/29	240	
7.2	Post-deployment evaluation	All		1/1/29	8/23/29	235	
7.3	PLAR	All	Not complete	8/23/29	8/27/29	5	
7.4	Landing	All		8/27/29	8/27/29	1	
7.5	Confirm project readiness	All		8/27/29	8/28/29	2	
7.6	CERR	All	Not complete	8/28/29	9/2/29	6	
7.7	Conduct mission/data transmission	All	Not complete	8/27/29	9/20/29	25	
7.8	Schedule Margin			9/20/29	10/4/29	15	
7.9	◆DR	All	Not complete	10/4/29	10/4/29	1	
8	Closeout		0%	10/4/29	12/16/29	74	30
8.1	Document lessons learned	All	Not complete	10/4/29	10/27/29	24	
8.2	Archive data	All	Not complete	10/4/29	11/5/29	33	
8.3	Baseline mission report	All	Not complete	11/5/29	11/25/29	21	

8.4	Dispose processes	Engineering	Not complete	11/12/29	11/17/29	6
8.5	Schedule Margin			11/17/29	12/16/29	30
8.6	◆ DRR	All	Not complete	12/16/29	12/16/29	1



High level overview Narrative

The team arrived at the scheduling estimate through a comprehensive process outlined in the planning report, which included a strategic approach to planning and scheduling

Time estimated based on historical data, expert judgment and information from the stakeholders. Inter-process dependencies were identified based on logical sequence of projects, ensuring completion of prerequisites prior to commencement of subsequent projects. Careful consideration of critical factors with availability of personnel, equipment and materials including to ensure project continuity and within budget

In addition, risks and uncertainties were systematically assessed and mitigated throughout the process. Plans were made to deal with possible delays or more budget cuts, and schedule variances were included to accommodate unexpected circumstances These variances allowed for flexibility in planning and allowed for deviations from timelines of the planned.

Phase C work begins with critical milestones needed for system modification and acquisition. From the final decision of the design review, it is ensured that the design components are thoroughly evaluated and the design is modified to meet the project specifications. Then, the Critical Design Review (CDR) process begins, which includes drafting, modification and finalization. At this stage careful attention is paid to drafting a comprehensive CDR document outlining proposed design solutions taking into account stakeholder feedback for necessary changes, JPL performance/ procurement activities will begin, acquiring critical components such as critical loads, mechanical wheels/chassis/suspension, GNC Hazcam, and thermal subsystem s at this stage Also includes planning and procurement , which requires coordination with suppliers to acquire mechanical, rotary and MOMA systems, as well as software and electrical subsystems All of these activities are carefully considered in planning margins to manage delays a it can be addressed.

Moving forward into Phase D, integration and convergence will be a major focus, notably Technical Readiness Reviews (TRRs) to assess system readiness for integration Efforts are directed to repair and activities have been initiated to ensure alignment with project objectives. Assembly and assembly activities culminate in rover assembly and testing, proper design and implementation are required to ensure functionality and reliability Transition to Phase D Phase 2, additional testing to be carried out on system quality and systems validation is the most important contribution. Operational Readiness Reviews (ORRs) and Flight Readiness Reviews (FRRs) are conducted to ensure operational performance

Then, Part E focuses on missions, with critical activities such as landing, load landing and recovery (PLAR), command event reporting (CERR), and mission information transmission These activities include strategic planning to ensure mission success It was important to operate. Similarly, the phase focuses on completing missions, which includes activities such as writing lessons, gathering information, launching mission reports, etc. Planning and executing plans also and are dealt with in this section. During phase E and all in between, system interfaces are monitored to manage any unexpected delays and ensure mission success and completion.

5.3. Budget

5.3.1. Budget Assumptions

Constructing the budget there were various assumptions that were made ranging from the lack of certainty in the specifics of the materials going to be used and overall generalities of the mission. During Phases A and B of the mission, the conceptual and technological development of the project is created. During this time we have acknowledged several assumptions. Some of the assumptions related to budget seem to be equipment cost, weight requirements, and assurance of not using any prohibited equipment. Keeping these assumptions in mind, the programmatics team cross-functionally collaborated with engineers and scientists to construct a list of equipment that could be used that follows the equipment and weight constraints.

Following the development of this list, searches for this equipment and costs were searched. In the research process, the assumption was made that the manufacturer we had chosen was able to provide an adequate amount of material without any delays - ultimately costing the team more time and money. Due to these assumptions being made, we kept the costs of products as calculated by our research with the addition of the appropriate inflation increase. This assumption allows for progression in the development and design of the mission to get an accurate estimate - if any issue arises, then this allows for adjustments.

This led to more assumptions being made such as our rover design and overall development process. The assumption was made that the design that was developed by our engineers would work perfectly and not need any further alterations at later phases of the mission. This assumption means that there were no extra costs added for any extra parts leaving all material costs and margins as is. Assuming that these parts all would work efficiently the first time in development and were all tested already, we did not allocate any further funds for extra.

One of the main equipment assumptions we made was that the pieces of equipment for the rover that were chosen were necessary for our data collection goals. This led to other assumptions to be made, which was that the accurate materials and costs’ from online searches were accurate. Finding the most reliable sources for the materials to get the closest estimates, assumed that the sites were reliable manufacturers and that the team had found the accurate material. Not only did the team have to assume the correct equipment was chosen, but the price point was accurate as well for an accurate equipment budget.

In addition, the assumption of the rate of inflation remaining constant for the years of the mission to remain the same as previous years, was made. Because this assumption was made, the program analyst had to make the assumption that the rate remained constant, which was then applied to all aspects of the project. Furthermore, this will also impact the prices of lodges for the stay of the mission for the launch. Overall, personnel, equipment, and timeframes are all assumptions that had to be made with the understanding of the mission of the team. Copious amounts of research and resources were used to understand and provide educated assumptions.

Bottom Line

The current estimated cost projection is $216,040,000.

Figure 73 - Final Cost Calculations

FINAL COST CALCULATIONS							
Total F&A	$ 1,231	$ 1,263	$ 591	$ 605	$ 620	$ -	**$ 4,311**
Total Projected Cost	$ 29,189	$ 53,984	$ 22,441	$ 22,361	$ 28,642	$ 3,970	**$ 160,587**
Total Cost Margin	$ 13,312	$ 17,460	$ 7,146	$ 7,132	$ 9,213	$ 1,191	**$ 55,454**
Total Project Cost	$ 42,501	$ 71,444	$ 29,587	$ 29,494	$ 37,855	$ 5,160	**$ 216,040**

5.3.2. Personnel Budget

The total budget of personnel for the mission is estimated to total $21,400,000. The personnel budget in regards to the mission has been an evolution throughout the lifespan of this project. The mission will maintain a level of 4 management and 3 administrators will remain the same; however, more personnel could be added if needed. For the other personnel, they will definitely fluctuate depending on phase of the mission.

Phase C (Year 1 + Year 2)

This phase of the mission will be the completion of the critical design review. This will be done by beginning fabrication, finalizing all systems review and begin to test all the components, have JPL manufacturing/Procurement, and having system integration review.

This phase will last a total of 2 years. Both years in Phase C will include the following personnel: 4 management, 3 administrators, 4 scientists, 15 engineers, and 7 technicians.

Figure 74 - Phase C Year 1 Budget Table

Role	Number of Employees Per Phase	Salary ($ USD)
Management	4	120,000
Administrator	3	60,000
Scientists	4	80,000
Engineers	15	80,000
Technicians	7	60,000

In terms of monetary value, 4 management will constitute $480,000 ($120,000 x 4) per year. This phase will have a duration of 2 years, totaling to $960,000 for this phase. The 3 administrators will constitute $180,000 ($60,000 x 3) per year. This phase will have a duration of 2 years, totaling $360,000 for this phase. The 4 scientists will constitute $320,000 ($80,000 x 4) per year. This phase will have a duration of 2 years, totalling $640,000 for this phase.The 15 engineers will constitute $1,200,000 ($80,000 x 15) per year. This phase will have a duration of 2 years, totaling $3,360,000 for this phase. The 7 technicians will constitute $420,000 ($60,000 x 7) per year. This phase will have a duration of 2 years, totaling $840,000 for this phase. The total spent on personnel for Phase C for both years totals out to $5,200,000.

Figure 75 - Phase C Year 1 + Year 2 Budget Table 2

Role	Number of Employees Per Phase	Salary ($ USD)	Phase C Personnel Budget Year 1 ($ USD)	Phase C Personnel Budget Year 2 ($ USD)	Phase C Year 1 + Year 2 Total ($ USD)
Management	4	120,000	480,000	480,000	960,000
Administrator	3	60,000	180,000	180,000	360,000
Scientists	4	80,000	320,000	320,000	640,000
Engineers	15	80,000	1,200,000	1,200,000	2,400,000
Technicians	7	60,000	420,000	420,000	840,000
Total					**5,200,000**

Phase D (Year 3)
This phase of the mission will be the phase of preparation for launch. For launch to occur the team has to complete manufacturing, ship all materials to KSC for authentication of the rovers functionality, final assembly, and lastly to launch. This phase will last a total of 3 years but has been broken down by year (Year 3, Year 4, and Year 5).

Year 3 will comprise 4 management, 3 administrators, 4 scientists, 20 engineers, and 8 technicians.

Figure 76 - Phase D Year 3 Budget Table

Role	Number of Employees Per Phase	Salary ($ USD)
Management	4	120,000
Administrator	3	60,000
Scientists	4	80,000
Engineers	20	80,000
Technicians	8	60,000

In terms of monetary value, 4 management will constitute $480,000 ($120,000 x 4) per year. The 3 administrators will constitute $180,000 ($60,000 x 3) per year. The 4 scientists will constitute $320,000 ($80,000 x 4) per year. The 15 engineers will constitute $1,600,000 ($80,000 x 20) per year. The 7 technicians will constitute $480,000 ($60,000 x 8) per year. The total spent on personnel for Phase D Year 3 totals out to $3,060,000.

Figure 77 - Phase D Year 3 Budget Table 2

Role	Number of Employees Per Phase	Salary ($ USD)	Phase D Personnel Budget Year 3 ($ USD)
Management	4	120,000	480,000
Administrator	3	60,000	180,000
Scientists	4	80,000	320,000
Engineers	20	80,000	1,600,000

Technicians	8	60,000	480,000
Total			**3,060,000**

Phase D (Year 4)
This phase of the mission will be the phase of preparation for launch. For launch to occur the team has to complete manufacturing, ship all materials to KSC for authentication of the rovers functionality, final assembly, and lastly to launch. This phase will last a total of 3 years but has been broken down by year (Year 3, Year 4, and Year 5).

Year 4 will comprise 4 management, 3 administrators, 4 scientists, 15 engineers, and 7 technicians.

Figure 78 - Phase D Year 4 Budget Table

Role	**Number of Employees Per Phase**	**Salary ($ USD)**
Management	4	120,000
Administrator	3	60,000
Scientists	4	80,000
Engineers	15	80,000
Technicians	7	60,000

In terms of monetary value, 4 management will constitute $480,000 ($120,000 x 4) per year. The 3 administrators will constitute $180,000 ($60,000 x 3) per year. The 4 scientists will constitute $320,000 ($80,000 x 4) per year. The 15 engineers will constitute $1,200,000 ($80,000 x 15) per year. The 7 technicians will constitute $420,000 ($60,000 x 7) per year. The total spent on personnel for Phase D Year 4 totals out to $2,600,000.

Figure 79 - Phase D Year 4 Budget Table 2

Role	**Number of Employees Per Phase**	**Salary ($ USD)**	**Phase D Personnel Budget Year 4 ($ USD)**
Management	4	120,000	480,000

Administrator	3	60,000	180,000
Scientists	4	80,000	320,000
Engineers	15	80,000	1,200,000
Technicians	7	60,000	420,000
Total			**2,600,000**

Phase D (Year 5)
This phase of the mission will be the phase of preparation for launch. For launch to occur the team has to complete manufacturing, ship all materials to KSC for authentication of the rovers functionality, final assembly, and lastly to launch. This phase will last a total of 3 years but has been broken down by year (Year 3, Year 4, and Year 5).

Year 5 will comprise 4 management, 3 administrators, 7 scientists, 12 engineers, and 7 technicians.

Figure 80 - Phase D Year 5 Budget Table

Role	Number of Employees Per Phase	Salary ($ USD)
Management	4	120,000
Administrator	3	60,000
Scientists	7	80,000
Engineers	12	80,000
Technicians	7	60,000

In terms of monetary value, 4 management will constitute $480,000 ($120,000 x 4) per year. The 3 administrators will constitute $180,000 ($60,000 x 3) per year. The 7 scientists will constitute $560,000 ($80,000 x 7) per year. The 12 engineers will constitute $960,000 ($80,000 x 12) per year. The 7 technicians will constitute $420,000 ($60,000 x 7) per year. The total spent on personnel for Phase D Year 5 totals out to $2,600,000.

Figure 81 - Phase D Year 5 Budget Table 2

Role	Number of Employees Per Phase	Salary ($ USD)	Phase D Personnel Budget Year 5 ($ USD)
Management	4	120,000	480,000
Administrator	3	60,000	180,000
Scientists	7	80,000	560,000
Engineers	12	80,000	960,000
Technicians	7	60,000	420,000
Total			**2,600,000**

Phase E and F (Year 6)

Phase E of the mission will be the phase of cruise and sustainment in preparation for the rovers arrival on Mars for data collection . In addition, Phase F of the mission will be the phase of closing out documentation and submitting final reports. Phase E and F will be conducted in the same year, Year 6.

These phases will comprise 4 management, 3 administrators, 20 scientists, 6 engineers, and 0 technicians.

Figure 82 - Phase E and F Year 6 Budget Table

Role	Number of Employees Per Phase	Salary ($ USD)
Management	4	120,000
Administrator	3	60,000
Scientists	20	80,000
Engineers	6	80,000
Technicians	0	60,000

In terms of monetary value, 4 management will constitute $480,000 ($120,000 x 4) per year. The 3 administrators will constitute $180,000 ($60,000 x 3) per year. The 20 scientists will constitute $1,600,000 ($80,000 x 20) per year. The 6 engineers will constitute $480,000 ($80,000 x 6) per year. The 0 technicians will constitute $0 ($60,000 x 0) per year. The total spent on personnel for Phase E and F Year 6 totals out to $2,740,000.

Figure 83 - Phase E and F Year 6 Budget Table 2

Role	Number of Employees Per Phase	Salary ($ USD)	Phase E &F Personnel Budget Year 6 ($ USD)
Management	4	120,000	480,000
Administrator	3	60,000	180,000
Scientists	20	80,000	1,600,000
Engineers	6	80,000	480,000
Technicians	0	60,000	0
Total			**2,740,000**

Totals

Figure 84 - Total Per Year Budget Table

Role	Total Per Year					
	1	**2**	**3**	**4**	**5**	**6**
Management	480,000	480,000	480,000	480,000	480,000	480,000
Administrator	180,000	180,000	180,000	180,000	180,000	180,000
Scientists	320,000	320,000	320,000	320,000	560,000	1,600,000
Engineers	1,200,000	1,200,000	1,600,000	1,200,000	960,000	480,000
Technicians	420,000	420,000	480,000	420,000	420,000	0
Total	**5,200,000**	**5,200,000**	**3,060,000**	**2,600,000**	**2,600,000**	**2,740,000**

Personnel Total for the Mission: $21,400,000.

Conclusion

Throughout the entirety of the mission the amount of personnel is limited to a cap of 40. The 4 management personnel and 3 administrators are not changed to maintain a cohesive leadership. The amount of scientists, engineers, and technicians are the positions that vary corresponding to the respective time during the mission. Several measures were taken to account for changes in personnel throughout the development of each phase.

Figure 85 - Personnel Table by Phase

	Phase C	Phase C	Phase D	Phase D	Phase D	Phase E-F	
# People on Team	FY 1	FY 2	FY 3	FY 4	FY 5	FY 6	
Science Personnel:	4	4	4	4	7	20	55
Engineering Personnel:	15	15	20	15	12	6	
Technicians:	7	7	8	7	7	0	
Administration Personnel:	3	3	3	3	3	3	
Management Personnel:	4	4	4	4	4	4	
	33	33	39	33	33	33	

NASA L'SPACE Mission Concept Academy Budget - *ENDURANCE*

Mission Phase	Phase C	Phase C	Phase D	Phase D	Phase D	Phase E-F	
Year	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative Total**
				PERSONNEL			
Science Personnel	$ 320	$ 328	$ 337	$ 345	$ 618	$ 1,808	$ 3,756
Engineering Personnel	$ 1,200	$ 1,231	$ 1,683	$ 1,294	$ 1,060	$ 542	$ 7,010
Technicians	$ 420	$ 431	$ 505	$ 453	$ 464	$ -	$ 2,272
Administration Personnel	$ 180	$ 185	$ 189	$ 194	$ 199	$ 203	$ 1,150
Project Management	$ 480	$ 492	$ 505	$ 517	$ 530	$ 542	$ 3,067
Total Salaries	$ 2,600	$ 2,668	$ 3,219	$ 2,803	$ 2,870	$ 3,096	**$ 17,256**
Total ERE	$ 726	$ 745	$ 898	$ 782	$ 801	$ 864	**$ 4,816**
TOTAL PERSONNEL	$ 3,326	$ 3,412	$ 4,118	$ 3,585	$ 3,672	$ 3,960	**$ 22,072**

5.3.3. Travel Budget

The calculated travel expenditure for the mission is $224,284, but with added margin for unforeseen events, the total travel expenditure is $250,000. Personnel travel expenses, which include transport, lodging, and meals, are expected throughout the mission program. Throughout the program duration, personnel will travel to different sites to conduct meetings, conduct inspections at manufacturing, testing, and assembling facilities, and attend Standing Review Boards (SRB). The majority of the 54 total mission personnel will be present for the spacecraft launch event at Cape Canaveral. Travel expenses for this event will be significantly greater than previous events as the majority of the personnel will be attending, and therefore a separate launch event budget will be allocated.

Personnel from various domestic locations across the country will embark on a five-day, nonstop round trip to and from Orlando, Florida.To factor in the various locations of the personnels' origin, the top ten airports around the nation with the most frequent flights into Orlando was used to approximate the average airfare. The top airfare of the top priced economy seat flights into Orlando from the ten airports is $686, adjusted for inflation using the current rate of 2.6%. The total airfare expenditure of all 54 personnel amounts to $78,782.

Upon arrival, all personnel will be transported by a charter bus from Orlando International Airport to the Country Inn & Suites by Radisson hotel. The 56-Passenger Charter Bus Rental from National Charter Bus has a daily rate of $2,156 at most, and a 5 day rental will cost $10,776, all adjusted for inflation. Each personnel will have their own hotel room, priced at $175 per night, totalling $783 for four nights including taxes and fees adjusted for inflation. The per diem lodging rate will cover a large majority of the lodging expenses, and only $1,724 will be expended to cover remaining tax and fees for lodging of all personnel. Projected per diem rates, adjusted accordingly for inflation, will compose of $185 for lodging, $19 for continental breakfast, $20 for lunch, $39 for dinner, and $6 for incidentals. This totals to $269 per diem per personnel for days between travel days. The 75% reduced per diem rate on travel days allocates $248 on the day of arrival and $63, excluding the lodging rate, on the day of departure for each personnel. The total per diem of the travel for each personnel is $1,117, amounting to $44,690 for total personnel.

The total expenditure for the launch event, taking into account inflation and the highest margin for costs, includes $78,782 in airfares, $37,776 for transportation, $44,690 for total per diem, and $1,724 for remaining lodging fees, totaling $80,284.

Figure 86 - Travel Budget

Total Flights Cost	$ 7	$ 7	$ 7	$ 7	$ 44	$ 7	**$ 78**
Total Hotel Cost	$ 1	$ 1	$ 1	$ 1	$ 94	$ 1	**$ 101**
Total Transportation Cost	$ 4	$ 4	$ 4	$ 4	$ 19	$ 4	**$ 37**
Total Per Diem Cost	$ 1	$ 1	$ 1	$ 1	$ 5	$ 1	**$ 8**
Total Travel Costs	$ 12	$ 13	$ 13	$ 13	$ 179	$ 14	$ 224

5.3.4. Outreach Budget

Given the allocated budget of $2,686,000, the minimum projected total spending is $1,517,000 and the maximum projected total spending is $2,430,000. The Endurance Outreach budget is developed by allocating 1% of the total mission budget. The maximum allocation of $2,500,000 was chosen to allow greater flexibility in spending and additional budget implementation in future programs as outreach circumstances tend to be dynamic following the progression of the mission.

The outreach plan constitutes complex website development and management, website content development, social media management, in-person STEM Fair hostings, and challenge program developments. The development and management of the Endurance Mission website is accomplished by paid web developers. The contents of the website are subject to regular change as the mission progresses and as further resources are available to be presented on the site. Due to the dynamic condition of the website, a baseline budget of $820,000 will be allocated for the initial development and management of the complex website and a ceiling budget of $1,650,000 will be kept throughout the mission duration.

Similarly, website content exclusive to the Endurance Mission, including graphics, videos, and photography, will be dynamic in production. Integration of graphics on the website will have a baseline budget of $52,000 and a ceiling of $105,000. Videography and photography will range from $20,000 to $50,000. Social media specialists can develop, produce, and manage content and engagement on various popular social media platforms. The upper margin of the salary for NASA social media specialists is $125,000.

In-person STEM fairs will be conducted by multiple NASA scientist staff at various event locations. Travel and per diems will be accommodated for each staff, along with venue and additional material costs necessary for the showcase. Because of the ambiguity of the event locations and travel expenses, a fixed budget of $300,000 will be allocated for the STEM fairs.

The challenge programs are to be developed by NASA personnel. A fixed budget of $200,000 will allow flexible budget allocation for personnel to develop the program, and the remaining budget to be used as an incentive bonus for challenge completion.

Figure 87 - Outreach Budget

Total Outreach Materials	$ 250	$ 250	$ 250	$ 250	$ 250	$ 250	
Total Outreach Venue Costs	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100	
Total Outreach Costs	$ 448	$ 448	$ 448	$ 448	$ 448	$ 448	**$ 2,686**

5.3.5. Direct Costs

The total estimated value of direct costs is $107,904,000 before margin. This comprises components for the Mechanical, Power, Command & Data Handling, Thermal, GNC, and Payload subsystems. Since manufacturing will happen with Phase C in 2025, an inflation rate of 170.23% will be used in the Mission Concept Cost Estimate Tool (MCCET) when estimating direct costs. Formulas from the NASA Instrument Cost Model (NICM) are used for determining the Cost Estimating Relationships (CERs) for each subsystem. These formulas require that subsystem mass and power draw is constrained, and these values were taken from the spacecraft overview table, shown in Appendix 2.

The total direct cost of the Mechanical subsystem is estimated to be $16,512,000. This includes the costs to manufacture, test, and assemble the chassis, arm, wheels, suspension system, and drill. With an estimated total mass and max power draw of 10 kg and 90 W respectively, the CER formula, 219 * MechMass^0.41 * TotalMaxPwr^0.52, can be used to obtain a CER of 5843.19. Putting this into the MCCET gives the total manufacturing cost of $12,672,000, test facility cost of $3,840,000, and total cost of $16,512,000.

The total direct cost of the Power subsystem is estimated to be $18,336,000. This includes costs to manufacture, test, and assemble the Solar Array and Power Distribution system which includes a Li-ion battery pack. The estimated total mass of the electrical power system is 7.2 kg. This comes from an estimated 2 kg solar array (thin-film, flexible) with 1kg for a deployment mechanism, 3.2 kg Li-ion battery pack, 1kg power distribution unit. With this mass, the CER formula 1516 * ElecMass^0.74 can be used to obtain a CER of 5848.83. Through the MCCET, we can calculate the manufacturing cost to be $14,112,000 and the test facility cost to be $4,224,000, totalling $18,336,000.

The total direct cost of the CDH subsystem is estimated to be $13,632,000. This includes costs to manufacture, test, and assemble the three antennas, processor, and data storage system. Since CDH costs comprise significantly of both hardware and software, CER equations for both electrical and software subsystems were added together to estimate the cost. With an estimated total mass 4 kg the CER formulas 1516 * ElecMass^0.74 for electronics and 236 * ElecMass^0.69 for software can be used to obtain a CER of 4843.1. Putting this into the MCCET gives a total manufacturing cost of $10,464,000 and a test facilities cost of $3,168,000 totalling to $13,632,000.

The total direct cost of the Thermal subsystem is estimated to be $4,896,000 This includes costs to manufacture, test, and assemble the heat pipes, radiator, heat switches, patch heaters and aerogel insulation. The total mass of the Thermal Control System (TCS) is estimated to be 5 kg, and have a max power draw of 50 W, though the wattage is not used in the CER formula. The CER formula used was 642 * ThermMass^0.62, which gives a CER value of 1741.39. This, put through the MCCET, outputs a manufacturing cost of $3,744,000 and test facility cost of $1,152,000, totalling, once again, to $4,896,000.

The total direct cost of the Guidance, Navigation and Control (GNC) subsystem is estimated to be $10,944,000. This includes costs to manufacture, test, and assemble the six external cameras for navigation and hazard avoidance, as well as the integrated navigation computer. With a total estimated subsystem mass of 3 kg, CER equations for both electrical hardware and software can be added together: (1516 * ElecMass^0.74) + (236 * ElecMass^0.69). This equation gives a CER of 3921.62 for the GNC subsystem.

Running this value through the MCCET returns a manufacturing cost of $8,448,000 and a test facility cost of $2,496,000, totalling to $10,944,000.

The total direct cost of the scientific instruments is estimated to be $43,584,000. This includes costs to manufacture, test, and assemble both the mass spectrometer and micro-imager (MI). The mass spectrometer is about 9 kg and uses a maximum of 65 W while the MI is 0.21 kg and uses only 3 - 4.8 W. Together, the total mass and max power draw (rounding up) is 9.2 kg and 70 W respectively. Using the CER formula for “Arm/Mast Mounted In-Situ Instruments” (1,363 * TotalMass^0.42 * TotalMaxPwr^0.35) gives a CER of 15313.38. Using these values in the MCCET tool then outputs estimated manufacturing and test facility costs of $33,504,000.00 and $10,080,000.00 respectively, totalling $43,584,000.

All together, each subsystem combined results in an estimated direct cost of $107,904,000. This is a parametric cost estimate, so it may change as more precise manufacturing and testing costs are realized. To split the costs up between Phase C and Phase D, the MCCET breakdown was followed. This allocates 57% of the costs to Phase C, and 39% to Phase D. The leftover 4% is spent in Phase B and is sunk cost at this point. The MCCET also estimates that manufacturing costs will be approximately 3.34 times the test facilities costs. The manufacturing facility cost in the budget template is left blank as this was accounted for in each subsystem.

Figure 88 - Direct Costs

DIRECT COSTS							
|> Mechanical Subsystem	$ 3,762	$ 3,762	$ 1,716	$ 1,716	$ 1,716	$ -	**$ 12,672**
|> Power Subsystem	$ 4,190	$ 4,190	$ 1,911	$ 1,911	$ 1,911	$ -	**$ 14,112**
|> Thermal Control Subsystem	$ 1,112	$ 1,112	$ 507	$ 507	$ 507	$ -	**$ 3,744**
|> Comms & Data Handling Subsystem	$ 3,107	$ 3,107	$ 1,417	$ 1,417	$ 1,417	$ -	**$ 10,464**
|> Guidance, Nav, & Control Subsystem	$ 2,508	$ 2,508	$ 1,144	$ 1,144	$ 1,144	$ -	**$ 8,448**
|> Science Instrumentation	$ 9,947	$ 9,947	$ 4,537	$ 4,537	$ 4,537	$ -	**$ 33,504**
Total Vehicle Costs	$ 24,624	$ 25,264	$ 11,816	$ 12,108	$ 12,400	$ -	**$ 86,213**
|> Manufacturing Facility Cost	$ -	$ -	$ -	$ -	$ -	$ -	**$ -**
|> Test Facility Cost	$ 7,410	$ 7,410	$ 3,380	$ 3,380	$ 3,380	$ -	**$ 24,960**
Total Facilities Costs	$ -	$ 7,603			$ 3,732	$ -	**$ 11,334**
Manufacturing Margin	$ 12,312	$ 16,433	$ 5,908	$ 6,054	$ 8,066	$ -	**$ 48,773**
Total Direct Costs	$ 36,936	$ 49,300	$ 17,724	$ 18,162	$ 24,197	$ -	**$ 146,320**
Total MTDC	$ 12,312	$ 12,632	$ 5,908	$ 6,054	$ 6,200	$ -	**$ 43,106**

5.4. Scope Management

A change is identified and tracked throughout the team by conducting regular internal reviews of core mission elements affecting scope to solidify current processes and plans. Internal reviews are done per NPR 7120.5 and NPR 7123.1 (“NASA Space Flight Program and Project Management Handbook,” n.d.) . During these internal reviews, mission elements such as the current budget, risk management and identification, management, and technical approach are all evaluated based on mission standards and constraints.The team will track stakeholder feedback through Decision Memorandums, which provide both internal and external tracking requirements for cost and schedule reporting. The Decision Memorandum provides a summary of the program, the decision made, technical content, approved cost and schedule estimates, key assumptions, the resulting actions from the change request, and corresponding signatures of approval.

Any changes requested through RFAs (Request for Actions) or advice will be received through the PM, who will format a corresponding review process. The PM will determine a one-step or two-step review process. A one-step review process involves the assessment of the mission's programmatic standing and technical maturity against six assessment criteria, those including comparing the current technical baseline to cost, schedule, and risk. ("NASA Space Flight Program and Project Management Handbook," n.d.). A one-step review process is typically utilized when all required technical work has been defined. A two step-review, in contrast, will occur if the program's cost and schedule have not been fully integrated with the technical work. This would entail the first step of this process entails the finalization of technical work, and the second step being the integration of technical work with preliminary cost, risk, and schedule. ("NASA Space Flight Program and Project Management Handbook," n.d.).

After each mission phase, a life-cycle review will evaluate the current mission activity and scope management. The PM and associated Decision Authority conduct the life-cycle review, finalized through a Decision Memorandum ("NASA Space Flight Program and Project Management Handbook," n.d.) signage. Each internal review and life-cycle review result will be communicated throughout the team to determine if any adjustments need to be made to fit within the mission scope. In the event of downscoping, the team leads have approved several methods following each mission element. Scope changes are handled through early detection, documentation, and a structured change control process. In the event that the team considers submitting a change request, several steps and considerations would be involved in deciding whether to determine a potential change. These processes include the identification of need, impact assessments, trade studies, cost-benefit analysis, and risk assessments. Management personnel can identify needs for change throughout the mission development and require clear communication throughout the team to ensure that these needs for change are identified early on and communicated to management. After an identification of need is identified, an impact assessment will take place by management and administrative personnel. The evaluation process includes the analysis of effects on the technical feasibility, schedule, budget, risks, and overall project performance that may occur due to the change being implemented. In addition, trade studies can be conducted to objectively determine the most effective approach to a change utilizing predetermined factors such as cost and risk, along with the evaluation of technical performance changes.

In the event of overrun costs or schedules, the team structure, procurement and manufacturing methods, and scientific mission scope will be reviewed for potential alterations. In the event of overrun costs, personnel may be reduced, and mission planning and operations will be examined to discover optimizations. Reducing subsystem redundancies, sourcing more cost-effective suppliers, and considering manufacturing alterations to reduce costs may be employed to address overrun costs. If all options are exhausted, the mission scope may significantly reduce the mission's cost and scientific capabilities. Any cost reduction measures must be reviewed and analyzed heavily, as cost-cutting procedures may increase component and mission risk. If the schedule is or is projected to overrun, the team will expand the workforce to manage additional responsibilities and support underperforming teams. Additional personnel must be reviewed and weighed with a cost-benefit analysis to prevent budget overrun. The team has implemented additional margins for the budget and schedule to avoid cost-cutting or schedule adjustments preemptively. If not needed, the extra margin may be invested into additional outreach or mission redundancy and safety measures to increase the likelihood of mission success.

A change request will be submitted to request a change. The change request goes through various processes, from submitted to reviewed and closed. Change requests can be generated at any stage of the project life-cycle and are conducted after internal reviews or a life-cycle review is undertaken and mission scope issues arise ("SYSTEMS ENGINEERING," n.d.). Changes are traceable, documented following approval, and implemented and included within the mission's traceability matrix. The PM, lead systems engineer, lead scientist, or the DPMR are directly involved throughout this process, ensuring the submission of change requests and the resulting implementation. If a change request is approved, the approved change is implemented per the project's change management procedures, including ensuring the change's traceability, documentation, implementation, and communication. The change is integrated into the traceability matrix, ensuring all project elements, requirements, and deliverables are updated to reflect the approved change. Stakeholders, including the project team and relevant external parties, are informed of the approved change and its implications. As a result, any needed adjustments per the changes for the project executive or deliverables are also communicated. In the event of a change request denial. Proper documentation, communication, reviews, and alternatives are considered in order to address the concerns associated with the change request. Informing relevant stakeholders and the team about the denial, along with clear explanations of why the change was not approved in order to manage expectations and ensure transparency in the team’s decision-making. In some cases, a denied change request may be addressed through a review of alternative solutions or approaches to address the underlying issue that led the team to the change request.

The team has formulated a Knowledge Management Plan (KMP) to implement and communicate changes, establishing best practices in capturing, identifying, and transferring knowledge (“SYSTEMS ENGINEERING,” n.d.). To track and communicate changes and identify possible needs for change, a three-step process throughout the team development ensures that change control is implemented correctly and monitored. According to the KMP, the three phases are the Formulation Phase, Implementation Phase, and Project Closeout. The formulation phase entails learning from previous NASA projects, missions, mistakes, and successes. Reviewing relevant databases and case studies for information about the team's mission provides a foundation of shared knowledge across the team from which to execute. The implementation phase involves the direct identification of lessons learned from the collected case studies and reports, consolidating them into team learning, which elevates the ability of the team to address and identify early potential risks. The final stage is project closeout, which involves sharing the team's lessons from the mission within 60 days of launch.

5.5. Outreach Summary

The purpose of the Endurance Mission Outreach Plan is to elevate public awareness, engagement, and appreciation for the mission's objectives, while cultivating inclusivity and community involvement. This plan involves a multifaceted website approach that involves various targeted activities and initiatives to catalyze interest across diverse demographics. The primary aim of the outreach plan is to empower individuals to actively participate and invest their time into space exploration and science throughout the timeline of Endurance.

The outreach efforts are directed towards a spectrum of audiences, including K-12 students, educators, university and college students with interests in geology/biology. Additionally, any interested researchers, community centers, organizations, and underrepresented communities are to be supported by this outreach initiative through mutual and affirmative action. And so forth, any community comprising minority groups, low-income neighborhoods, or rural areas can also engage with the outreach activities.

Website Development:

The creation of a dedicated website for the Endurance Rover mission stands as a cornerstone of the outreach strategy. This platform will host a wealth of educational resources, interactive features, and timely updates on mission progress, providing visitors with a comprehensive insight into the mission's objectives and achievements. Content-wise it will host an assembly of exciting content that the public can enjoy and invest their time in through commissioned behind the scenes recordings and short comics. This modular website also aims to provide the audience with not only a lasting impression but also a platform to navigate through more NASA resources that may be relevant to their situation.

STEM Fairs and Community Events:

The organization of STEM fairs and community events is envisioned as dynamic platforms for direct engagement. By collaborating with schools, universities, and community centers, the outreach plan aims to facilitate interactive demonstrations, presentations, and hands-on activities led by NASA scientists and experts, thereby fostering a deeper understanding and appreciation for space exploration.

Challenge Opportunities:

The implementation of challenge programs tailored for students and enthusiasts will offer invaluable hands-on experience in scientific research and engineering relevant to the mission. Through strategic partnerships with educational institutions and industry stakeholders, the outreach plan will provide mentorship and guidance from NASA experts, effectively nurturing the next generation of space explorers. These challenge opportunities are designed to be open and accessible in order to accommodate more interested candidates. Furthermore, these challenge activities are intended to help prepare participants eligible for NASA programs, MAIANSE and MUERP, to take the next step.

Some examples of these challenge programs include small-scale open innovation initiatives modeled after the NASA Tournament Lab and NASA's CoECI. (Center of Excellence of Collaborative Innovation). These challenge programs seek to leverage crowdsourcing and prize challenges to solve complex problems and to help advance technology development. Moreover, for the strengthening of community and engagement, partnerships including activities like public library class hosting or accessible family programs are strongly considered. Through these opportunities, children and young adults alike can be exposed to more local resources and establish a healthy environment where learning is encouraged.

Social Media Management and Promotion:

Social media platforms will be leveraged to achieve the overarching goal of increased public awareness and active engagement. Developing a robust social media strategy and creating compelling content, including posts, videos, and graphics, aims to expand reach, foster meaningful conversations, and cultivate a vibrant online community around Endurance. This is to encourage and sustain an everlasting interest in space exploration and science.

Inclusivity and Community Engagement:

In line with the commitment to inclusivity and diversity, active outreach will be conducted towards underrepresented communities through tailored programming, resources, and partnerships. Developing culturally relevant initiatives and fostering dialogue and collaboration aims to create pathways for equitable participation in STEM fields, ensuring that the benefits of space exploration are accessible to all.

Concisely, the Endurance Outreach Plan includes a central website hub, equipped with a search engine and database containing a multitude of NASA resources. This site serves as a multipurpose platform that hosts the majority of Endurance related updates as well as an educational site that provides NASA resource navigation for interested participants. Additionally, it features various behind-the-scenes content and timely released short comics to conserve public interest. This website is constructed with the consideration of the general public in mind, meaning that the website is written in a straightforward and accessible manner while being user friendly.

Website-aside, the outreach plan also includes various in-person experiences for K-12 and university/college students. Through STEM Fairs and speaking events at participating schools, public awareness about Endurance can be increased while strengthening NASA cooperation with the public. A virtual and in-person approach aims to maximize impact and reach across a broad audience, while ensuring accessibility in all initiatives. Overall, a successful execution of the Endurance Outreach Plan will result in heightened public awareness across a diverse demographic while providing multiple opportunities within the STEM field.

Note:

This plan outline serves as a foundational framework for the implementation of the Endurance Rover Mission Outreach Plan. Progressing through the planning and execution phases, further refinement and details will be added in collaboration with stakeholders and partners, ensuring the success and sustainability of outreach efforts.

Figure 89 - Sample Website Content

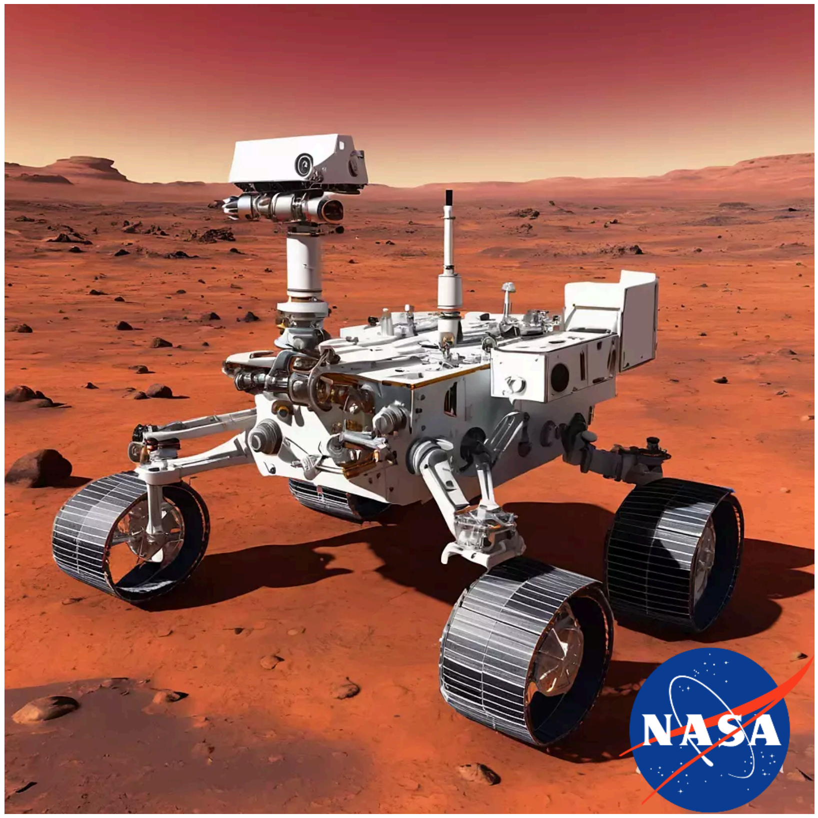
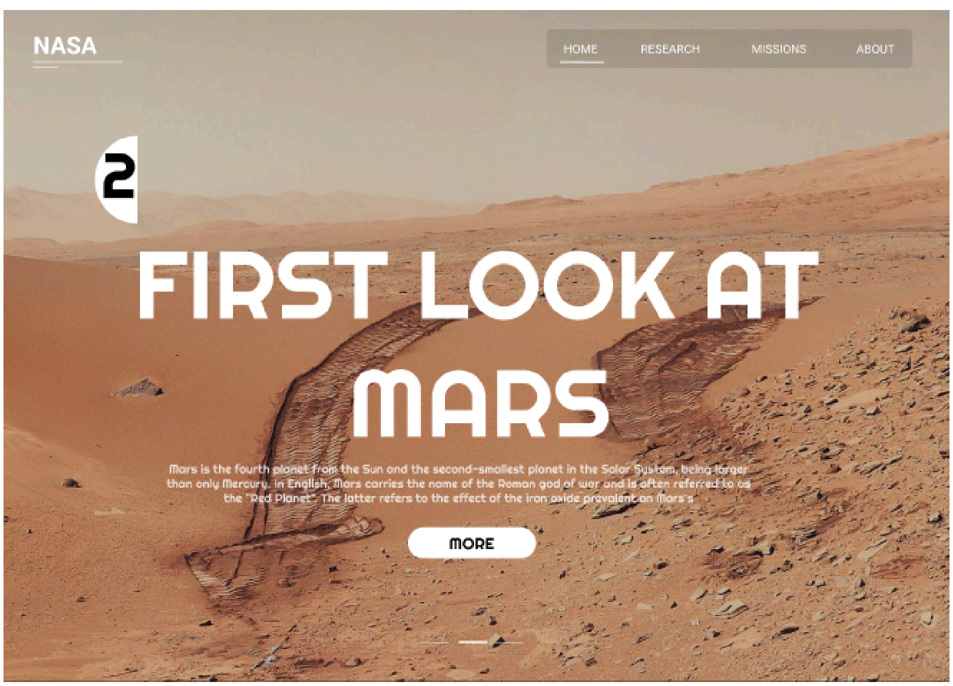


Figure 90 - Sample Website FIGMA



"NASA - Homepage | Figma," Figma, n.d.,

https://www.figma.com/community/file/1288453491600238379/nasa-homepage.

6. Conclusion

The Endurance mission represents a step forward in discovering Mars' geological history and the potential for past and present life. The Endurance Rover was designed to investigate surface and subsurface sediment isotopic fractionations and the layering, age, composition, and origin of ice deposits on Mars. The team has analyzed the mission and system architecture following mission constraints and requirements. A mission location, rover design, and procurement operations have been determined. The team has conducted critical trade studies to identify subsystem requirements, components, and instruments. The system and mission architecture have been formed per program constraints, requirements, and available resources. Mission risks have been identified and mitigated to an acceptable level. The vehicle systems have been conceptualized to meet scientific objectives and requirements while adhering to mission constraints. Each subsystem's preferred vendor and procurement strategies have been outlined and incorporated into the mission schedule lead time.

Further risk and safety considerations have been identified, managing risks for all aspects of the mission. Engineering, science, mission environment, programmatic, planetary protection, and personnel hazards and risks that may affect the mission and subsequent mitigation strategies have been identified and approved. A Failure Mode and Effect Analysis (FMEA) has been conducted to determine the most critical risks to mission success and key mission-level failure points. The budget and schedule timelines have been finalized to meet mission constraints. If given more time, the team would have expanded on all sections with prior deliverable feedback, particular subsystem sub. The team would have provided more detail and content to Sub-Assembly Overviews and refined budget assumptions and scope management. Moving forward into the Critical Design Review (CDR), the team will prepare to demonstrate that the rover design's maturity meets the requirements for proceeding with assembly, full-scale fabrication, testing, and integration. The team will determine the technical and system components and development to ensure that the performance and functionality requirements are met within the defined schedule and cost constraints while maintaining acceptable risk levels.

Bibliography

Abarca, H., Deen, R., Hollins, G., Zamani, P., Maki, J., Tinio, A., Pariser, O., Ayoub, F., Toole, N., Algermissen, S., Soliman, T., Lu, Y., Golombek, M., Calef, F., Grimes, K., De Cesare, C., & Sorice, C. (2019, February 18). Image and data processing for InSight Lander Operations and Science - Space Science Reviews. SpringerLink. https://link.springer.com/article/10.1007/s11214-019-0587-9

Brushless DC Motor (BLDC motor) speed control systems. Oriental Motor U.S.A. Corp. (n.d.). https://www.orientalmotor.com/brushless-dc-motors-gear-motors/index.html

PDS Geosciences Node, W. U. in St. L. (n.d.). Analyst's notebook help. Analyst's Notebook. https://an.rsl.wustl.edu/help/Content/About%20the%20mission/MER/Instruments/MER%20Hazcam.htm#:~:text=The%20Hazcams%20are%20attached%20to,of%20the%20Warm%20Electronics%20Box

Ning, X. L., Bajracharya, M., Barshan, B., Chen, X., Di, K. C., Han, H. S., Huntsberger, T., & Janiczuk, P. M. (2014, July 5). An innovative high-precision sins/CNS deep integrated navigation scheme for the Mars rover. Aerospace Science and Technology. https://www.sciencedirect.com/science/article/abs/pii/S1270963814001151

Yang, S., Feng, W., Wang, S., & Li, J. (2022). A sins/CNS integrated navigation scheme with improved Mathematical Horizon reference. Measurement, 195, 111028. https://doi.org/10.1016/j.measurement.2022.111028

Fallahlalehzari, F. (n.d.). Company. The Design Verification Company - Aldec, Inc. https://www.aldec.com/en/company/blog/188--how-does-the-mars-perseverance-rover-benefit-from-fpgas-as-the-main-processing-units

Rtems real time operating system (RTOS). RTEMS Real Time Operating System (RTOS) | Real-Time and Real Free RTOS. (n.d.). https://www.rtems.org/

"Cables - Star-Dundee." STAR, May 9, 2019. https://www.star-dundee.com/spacewire/spacewire-users-guide/spacewire-links/physical-level/cables/

"SpaceWire Lab Cables - Star-Dundee." STAR, September 10, 2021. https://www.star-dundee.com/products/spacewire-lab-cables/?attribute_pa_length=0-5m&attribute_type=Type%2BA#product_features

RAD750® radiation-hardened powerpc microprocessor. Accessed April 15, 2024. https://www.baesystems.com/en-media/uploadFile/20210404045936/1434555668211.pdf

Laboratory, NASA's Jet Propulsion. "Qualification of UHF Antenna for Extreme Martian Thermal Environments." Tech Briefs, October 12, 2013. https://www.techbriefs.com/component/content/article/16604-npo-48475

"Satellite Solar Panels." n.d. Sparkwing. https://sparkwing.space/satellite-solar-panels/.

"How Much Does a 6kW Solar Power System Cost and How Much Electricity Does It Produce?" n.d. Solar Reviews. https://www.solarreviews.com/blog/how-much-does-a-6kw-solar-power-system-cost-and-how-much-electricity-does-it-produce.

Selzer, Michelle. 2023. "How Much Does a Lithium-Ion Battery Cost in 2023?" Lawn Care Blog | Lawn Love. February 24, 2023. https://lawnlove.com/blog/lithium-ion-battery-cost/#:~:text=Most%20lithium%20batteries%20cost%20%2410.

"Custom Battery Pack Lead Times for Prototypes and Production Orders." n.d. Www.epectec.com. Accessed April 15, 2024. https://www.epectec.com/batteries/battery-pack-standard-lead-times-and-prototypes.html.

admin. 2023. "Pricing & Lead Time." Raptorpwr.com. October 26, 2023. https://raptorpwr.com/pricing-lead-time.

"Eaton Metered Input Rack PDU | EatonGuard.com." n.d. Www.eatonguard.com. Accessed April 15, 2024. https://www.eatonguard.com/Eaton-Metered-Input-PDU.asp#pricing.

"Launch Booster Control and Power Distribution Unit | L3Harris® Fast. Forward." n.d. Www.l3harris.com. Accessed April 15, 2024. https://www.l3harris.com/all-capabilities/launch-booster-control-and-power-distribution-unit.

"Lithium Ion." EaglePicher. Accessed March 16, 2024. https://www.eaglepicher.com/technology/battery-chemistries/lithium-ion/.

"BOOSTER CONTROL and POWER DISTRIBUTION UNIT (BCPDU) Line Replaceable Unit." n.d. Accessed April 15, 2024. https://www.l3harris.com/sites/default/files/2021-04/ims-eo-ce-datasheet-BCPDU.pdf

"The Radiation Showstopper for Mars Exploration." ESA. Accessed April 15, 2024. https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/The_radiation_showstopper_for_Mars_exploration

"Spacecraft Communications." L3Harris® Fast. Forward. Accessed March 24, 2024. https://www.l3harris.com/all-capabilities/spacecraft-communications

"BAE Systems Processors and Mapping Software Support NASA's Curiosity While Roving on Mars." BAE Systems | United States, September 14, 2012. https://www.baesystems.com/en-us/article/bae-systems-processors-and-mapping-software-support-nasas-curiosity-while-roving-on-mars

"Space Systems." BAE Systems | United States. Accessed March 24, 2024. https://www.baesystems.com/en-us/capability/space-systems

"About Star-Dundee - Star-Dundee." STAR, May 7, 2019. https://www.star-dundee.com/about-us/

"Missions Using Spacewire - Star-Dundee." STAR, May 9, 2019. https://www.star-dundee.com/spacewire/spacewire-users-guide/the-spacewire-data-handling-network/example-spacewire-mission-architectures/missions-using-spacewire/

St, in. "Microscopic Imager (MI)." *Wustl.edu*, Accessed April 16, 2024 an.rsl.wustl.edu/help/Content/About%20the%20mission/MER/Instruments/Microscopic%20Imager.htm

Goesmann, Fred, William B Brinckerhoff, François Raulin, Walter Goetz, Ryan M Danell, Stephanie A Getty, Sandra Siljeström, et al. "The Mars Organic Molecule Analyzer (Moma) Instrument: Characterization of Organic Material in Martian Sediments." Astrobiology, July 1, 2017. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5685156/.

The Mars Organic Molecule Analyzer (moma) instrument: Characterization of organic material in martian sediments | astrobiology. Accessed April 16, 2024. https://www.liebertpub.com/doi/10.1089/ast.2016.1551.

Li, Xiang, et al. "Detection of Trace Organics in Mars Analog Samples Containing Perchlorate by Laser Desorption/Ionization Mass Spectrometry." *Astrobiology*, vol. 15, no. 2, 1 Feb. 2015, pp. 104–110, https://doi.org/10.1089/ast.2014.1203.

mars.nasa.gov. "Microscopic Imager (MI)." *Mars.nasa.gov*, mars.nasa.gov/mer/mission/instruments/mi/.

"Microscopic Imager (MI)." NASA. Accessed April 16, 2024. https://mars.nasa.gov/mer/mission/instruments/mi/.

2024. Rustoleum.com. 2024. https://www.rustoleum.com/-/media/6E44197BC8724635BD05F4BE264965C8.ashx.

2024. Rustoleum.com. 2024. https://www.rustoleum.com/-/media/813A5E06F9EC48FCA84D374D78142972.ashx.

2023. Kaptontape.com. 2023. https://www.kaptontape.com/images/KPT-200.jpg.

2024. Buyaerogel.com. 2024. https://www.buyaerogel.com/wp-content/uploads/2013/08/classic-silica-block.jpg.

2024. Buyaerogel.com. 2024. http://www.buyaerogel.com/wp-content/uploads/2013/08/carbon-450x450.jpg.

2024. Speedwaymotors.com. 2024. https://www.speedwaymotors.com/_next/image?url=https%3A%2F%2Fcontent.speedwaymotors.com%2FProductImages%2F917340_L1600_ec3c1eb9-9fe0-46b3-a28a-f68b7c9e6c25.jpg&w=1280&q=75.

2024. Digikey.com. 2024. https://mm.digikey.com/Volume0/opasdata/d220001/medias/images/331/MFG_SKV-Series-Copper-Skived.jpg.

2024. Digikey.com. 2024. https://mm.digikey.com/Volume0/opasdata/d220001/medias/images/1777/MFG_110584.jpg.

2024. Newark.com. 2024. https://www.newark.com/productimages/standard/en_GB/1082189-40.jpg.

2024. Cloudfront.net. 2024. https://dpk3n3gg92jwt.cloudfront.net/domains/minco/images/products/3.1PolyimideKaptonHKSub.jpg.

“Features and Benefits.” n.d. Accessed April 16, 2024. https://www.eaglepicher.com/sites/default/files/LP33081%2030%20Ah%20Space%20Cell%20%200123.pdf.

2024. Nasa.gov. 2024. https://www.jpl.nasa.gov/nmp/st8/images/solar_array_photo1.jpg.

2024. L3harris.com. 2024. https://www.l3harris.com/sites/default/files/2020-07/ims_eo_product_BCPDU.png.

2024. Ipd.com.au. 2024. https://www.ipd.com.au/images/6bb8f449-b779-4a37-b167-c5059664ce44.png.

2024. Wikimedia.org. 2024. https://upload.wikimedia.org/wikipedia/commons/thumb/0/0a/Triple_Modular_Redundancy.JPG/350px-Triple_Modular_Redundancy.JPG.

Belton, M. J.S. , Malin, . Michael C. and Carr, . Michael H.. "Mars." Encyclopedia Britannica, February 9, 2024. https://www.britannica.com/place/Mars-planet

Britannica, T. Information Architects of Encyclopaedia. "Mars." Encyclopedia Britannica, February 12, 2024. https://www.britannica.com/facts/Mars-planet.

Fornaro, Teresa, et al. “Catalytic/Protective Properties of Martian Minerals and Implications for Possible Origin of Life on Mars.” Life, vol. 8, no. 4, 5 Nov. 2018, p. 56, https://doi.org/10.3390/life8040056.

Malespin, Charles. “SAM.” NASA, April 28, 2022, https://mars.nasa.gov/msl/spacecraft/instruments/sam/.

“Mars: Facts - NASA Science,” 2024. https://science.nasa.gov/mars/facts/.

“Mars Education | Developing the Next Generation of Explorers,” n.d. https://marsed.asu.edu/mep/583.

“Mars Fact Sheet,” n.d. https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

National Aeronautics and Space Administration, “NASA Systems Engineering Handbook,” Dec. 2007.

Steigerwald, William. “NASA’s Curiosity Takes Inventory of Key Life Ingredients on Mars - NASA.” NASA, 27 June 2022, www.nasa.gov/solar-system/nasas-curiosity-takes-inventory-of-key-life-ingredient-on-mars/#:~:text=%E2%80%9CWe%20found%20at%20least%20200. Accessed 12 Feb. 2024.

van Zuilen, Mark. “Stable Isotope Ratios as a Biomarker on Mars.” *Space Science Reviews*, vol. 135, no. 1-4, 9 Oct. 2007, pp. 221–232, https://doi.org/10.1007/s11214-007-9268-1. Accessed 28 Sept. 2021.

“What Is Mars? (Grades 5-8) - NASA.” *NASA* (blog), February 7, 2024. https://www.nasa.gov/learning-resources/for-kids-and-students/what-is-mars-grades-5-8/#:~:text=The%20average%20temperature%20on%20Mars,and%20wind%20just%20like%20Earth.

“APPENDIX B SITE HEALTH and SAFETY PLAN CONTENTS.” n.d. Accessed March 27, 2024. https://jplwater.nasa.gov/docs/NAS710345F.pdf.

“NASA System Safety Handbook Volume 2: System Safety Concepts, Guidelines, and Implementation Examples.” 2014. https://ntrs.nasa.gov/api/citations/20150015500/downloads/20150015500.pdf.

Darpel, Scott, and Sean Beckman. n.d. “Early Engagement of Safety & Mission Assurance Expertise Using Systems Engineering Tools: A Risk-Based Approach to Early Identification of Safety and Assurance Requirements.” Accessed March 27, 2024. https://ntrs.nasa.gov/api/citations/20160014878/downloads/20160014878.pdf.

“General Shop Hazards | Processes Lab | NC State ISE.” n.d. Processes Lab.

https://www.ise.ncsu.edu/processes/laboratory-safety-processes/general-shop-hazards/.

Lindsey, Nancy, John W. Evans, Frank Groen, Lui Wang, Shira Okon, Rebekah Austin, Arthur F. Witulski, Nagabhushan Mahadevan, Steven L. Cornford, and Martin S. Feather. 2018. “Towards a Framework for Reliability and Safety Analysis of Complex Space Missions.” International Journal of Human Factors Modelling and Simulation 6 (2/3): 203. https://doi.org/10.1504/ijhfms.2018.10014219.

1 mil kapton tapes. Accessed March 23, 2024. https://www.kaptontape.com/1_Mil_Kapton_Tapes.php.

110584_REV1 wakefield-vette | fans, thermal management | DigiKey. Accessed March 24, 2024. https://www.digikey.com/product-detail/en/wakefield-vette/110584_REV1/345-1189-ND/5114258.

“Carbon Aerogel.” BuyAerogel.com. Accessed March 23, 2024. http://www.buyaerogel.com/product/carbon-aerogel/.

“Catalog.” Minco, February 22, 2024. https://www.minco.com/catalog/?catalogpage=product&cid=3_1_1-polyimide-WA-thermofoil-heaters&id=HK6900.

“Catalog.” Minco, February 22, 2024. -https://www.minco.com/catalog/?catalogpage=product&cid=3_1_2-polyimide-FEP-thermofoil-heaters&id=HK5160R157L12A.

“Classic SilicaTM Block.” BuyAerogel.com. Accessed March 23, 2024. http://www.buyaerogel.com/product/block/.

“Complete List of Schedule Risks.” Construx, November 24, 2020. https://www.construx.com/books/software-project-survival-guide/complete-list-of-schedule-risks/.

“Honeywell Thermostat Switches.” Newark. Accessed March 23, 2024. https://www.newark.com/c/sensors-transducers/sensors/temperature-sensors/thermostat-switches?brand=honeywell.

“Rust-Oleum Specialty 12 Oz. High Heat Flat White Spray Paint 7751830.” The Home Depot. Accessed March 23, 2024. https://www.homedepot.com/p/Rust-Oleum-Specialty-12-oz-High-Heat-Flat-White-Spray-Paint-7751830/100189390.

“Rust-Oleum Specialty Rust-Oleum Specialty 12 Ounce High Heat Ultra Semi-Gloss Black Spray Paint 241169.” The Home Depot. Accessed March 23, 2024. https://www.homedepot.com/p/Rust-Oleum-Specialty-Rust-Oleum-Specialty-12-Ounce-High-Heat-Ultra-Semi-Gloss-Black-Spray-Paint-241169/203161184.

“Rust-Oleum Specialty Rust-Oleum Specialty 12 Ounce High Heat Ultra Semi-Gloss Black Spray Paint 241169.” The Home Depot. Accessed March 23, 2024. https://www.homedepot.com/p/Rust-Oleum-Specialty-Rust-Oleum-Specialty-12-Ounce-High-Heat-Ultra-Semi-Gloss-Black-Spray-Paint-241169/203161184.

“Rust-Oleum Specialty Rust-Oleum Specialty 12 Ounce High Heat Ultra Semi-Gloss Black Spray Paint 241169.” The Home Depot. Accessed March 23, 2024. https://www.homedepot.com/p/Rust-Oleum-Specialty-Rust-Oleum-Specialty-12-Ounce-High-Heat-Ultra-Semi-Gloss-Black-Spray-Paint-241169/203161184.

SKV909010-cu Wakefield-Vette | fans, thermal management | DigiKey. Accessed March 24, 2024. https://www.digikey.com/product-detail/en/wakefield-vette/SKV909010-CU/345-2040-ND/10108377.

Speedway double pass aluminum radiator, Chevy. Accessed March 24, 2024. https://www.speedwaymotors.com/Speedway-Double-Pass-Aluminum-Radiator-Chevy,23864.html.

“Thermal Switches.” Honeywell Aerospace. Accessed March 23, 2024. https://aerospace.honeywell.com/us/en/products-and-services/product/hardware-and-systems/sensors/thermal-switches.

“Spacecraft Communications.” L3Harris® Fast. Forward. Accessed March 24, 2024. https://www.l3harris.com/all-capabilities/spacecraft-communications.

“BAE Systems Processors and Mapping Software Support NASA’s Curiosity While Roving on Mars.” BAE Systems | United States, September 14, 2012. https://www.baesystems.com/en-us/article/bae-systems-processors-and-mapping-software-support-nasas-curiosity-while-roving-on-mars

“Space Systems.” BAE Systems | United States. Accessed March 24, 2024. https://www.baesystems.com/en-us/capability/space-systems.

“About Star-Dundee - Star-Dundee.” STAR, May 7, 2019. https://www.star-dundee.com/about-us/.

“Missions Using Spacewire - Star-Dundee.” STAR, May 9, 2019. https://www.star-dundee.com/spacewire/spacewire-users-guide/the-spacewire-data-handling-network/example-spacewire-mission-architectures/missions-using-spacewire/.

“Aluminum Sheets & Coils 7075.” MTS. Accessed March 25, 2024. https://www.materialtech.com/aluminum-sheets-coils-7075.

“Mars Rover.” Wikipedia, March 20, 2024. https://en.wikipedia.org/wiki/Mars_rover#:~:text=As%20of%20May%202021%2C%20there,Perseverance%20(2021%E2%80%93present).

“NASA’s Perseverance Mars Rover Gets Its Wheels and Air Brakes.” NASA, September 29, 2023. https://www.nasa.gov/solar-system/nasas-perseverance-mars-rover-gets-its-wheels-and-air-brakes/.

“Products.” Honeybee Robotics. Accessed March 25, 2024. https://www.honeybeerobotics.com/products/drills/.

“Reinvent the Rover Wheel Challenge.” Future Engineers. Accessed March 25, 2024. https://www.futureengineers.org/reinventtheroverwheel#:~:text=The%20new%20and%20improved%20tire,Spirit%2C%20Opportunity%2C%20and%20Curiosity.

“Rotary Percussive Corer Drill – NASA Mars Exploration.” NASA. Accessed March 25, 2024. https://mars.nasa.gov/resources/25565/rotary-percussive-corer-drill/#:~:text=Honeybee%20Robotics%20designed%20its%20rotary,collect%20rock%20samples%20on%20Mars.

“Rover Body.” NASA. Accessed March 25, 2024. https://mars.nasa.gov/mars2020/spacecraft/rover/body/

“Rover Sojourner Mechanical Thermal and Mobility Subsystem (MTM).” NASA. Accessed March 25, 2024. https://mars.nasa.gov/MPF/rover/mtm.html.

“The Mars Exploration Rovers Update Special Report: Opportunity….” n.d. The Planetary Society. Accessed March 26, 2024. https://www.planetary.org/articles/06-mer-update-opportunity-dust-storm-sleep.

"Review of Rover on Mars Is Stuck in Idle after Error in Communication." The New York Times, July. https://www.nytimes.com/1997/07/12/us/rover-on-mars-is-stuck-in-idle-after-error-in-communication.html

“Llis.” n.d. Llis.nasa.gov. https://llis.nasa.gov/lesson/1805.

“SYSTEMS ENGINEERING.” n.d. https://www.nasa.gov/wp-content/uploads/2018/09/nasa_systems_engineering_handbook_0.pdf.

“NASA Space Flight Program and Project Management Handbook.” n.d. https://ntrs.nasa.gov/api/citations/20150000400/downloads/20150000400.pdf.

“Curiosity Wheel Damage: The Problem and Solutions.” The Planetary Society, 19 Aug. 2014, www.planetary.org/articles/08190630-curiosity-wheel-damage.

https://appel.nasa.gov/wp-content/uploads/2018/04/Advice-for-Building-a-KM-Plan.pdf

“NASA Procedural Requirements NPR 7123.1D COMPLIANCE IS MANDATORY for NASA EMPLOYEES.” 2023. https://nodis3.gsfc.nasa.gov/npg_img/N_PR_7123_001D_/N_PR_7123_001D_.pdf.

"NASA Procedural Requirements NPR 7120.5F COMPLIANCE IS MANDATORY for NASA EMPLOYEES NASA Space Flight Program and Project Management Requirements W/Change 3 Responsible Office: Associate Administrator NASA Space Flight Program and Project Management Handbook." 2021. https://nodis3.gsfc.nasa.gov/npg_img/N_PR_7120_005F_/N_PR_7120_005F_.pdf.

"ST8 UltraFlex 175." n.d. Www.jpl.nasa.gov. Accessed March 27, 2024. https://www.jpl.nasa.gov/nmp/st8/tech/solar_array2.html.

Lithium Ion Cells | Lithium Battery Cells | EaglePicher. (n.d.). Www.eaglepicher.com. https://www.eaglepicher.com/technology/battery-chemistries/lithium-ion/

"Space Power Systems | L3Harris® Fast. Forward." n.d. Www.l3harris.com. Accessed March 27, 2024. https://www.l3harris.com/all-capabilities/space-power-systems.

White, Steve, Brian Spence, Thomas Trautt, and Paul Cronin. n.d. "ULTRAFLEX-175 on SPACE TECHNOLOGY 8 (ST8) -VALIDATING the NEXT- GENERATION in LIGHTWEIGHT SOLAR ARRAYS." Accessed March 27, 2024. https://esto.nasa.gov/conferences/nstc2007/papers/Banicevich_D1P3_NSTC-07-0048.pdf.

Maki, J. N., C. M. McKinney, R. G. Sellar, D. S. Copley-Woods, D. C. Gruel, D. L. Nuding, M. Valvo, T. Goodsall, J. McGuire, and T. E. Litwin. 2016. "Enhanced Engineering Cameras (EECAMs) for the Mars 2020 Rover." NASA ADS 1980 (October): 4132. https://ui.adsabs.harvard.edu/abs/2016LPICo1980.4132M/abstract.

Zhao, Yunan, Xinlong Wang, Qunsheng Li, Dun Wang, and Yuanwen Cai. 2019. "A High-Accuracy Autonomous Navigation Scheme for the Mars Rover." Acta Astronautica 154 (January): 18–32. https://doi.org/10.1016/j.actaastro.2018.10.036.

mars.nasa.gov. n.d. "Routine Inspection of Rover Wheel Wear and Tear." NASA Mars Exploration. Accessed March 5, 2024. https://mars.nasa.gov/resources/routine-inspection-of-rover-wheel-wear-and-tear/.

mars.nasa.gov. n.d. "Rock Abrasion Tool (RAT)." Mars.nasa.gov. https://mars.nasa.gov/mer/mission/instruments/rat/.

"VIPER Rover and Instruments - NASA Science." n.d. Science.nasa.gov. Accessed March 5, 2024. https://science.nasa.gov/mission/viper/rover-and-instruments.

https://www.jpl.nasa.gov. n.d. “Phoenix Lander Prepares for Microscopy, Wet Chemistry on Mars.” NASA Jet Propulsion Laboratory (JPL).

“NASA’s Airless Tire Technology Rethinks Rover Tire Design with Earth Applications | T2 Portal.” n.d. Technology.nasa.gov. https://technology.nasa.gov/page/nasas-airless-tire-technology-re.

NASA. 2019. “Wheels | Rover – NASA’s Mars Exploration Program.” NASA’s Mars Exploration Program . 2019. https://mars.nasa.gov/msl/spacecraft/rover/wheels/.

“DDR4 SDRAM Space Qualified Memory - 3D PLUS.” *3D PLUS*, https://www.3d-plus.com/products/space-radiation-tolerant-ddr4-sdram/. Accessed 4 Mar. 2024.

Cypress Semiconductor Corporation. (2019, June 12). Static RAM with RadStop Technology. https://www.infineon.com/dgdl/Infineon-CYRS1049DV33_4_MBIT_(512K_X_8)_STATIC_RAM_WITH_RADSTOP_TECHNOLOGY-DataSheet-v11_00-EN.pdf?fileId=8ac78c8c7d0d8da4017d0ec337e33821

“NASA’s Perseverance Mars Rover Gets Its Wheels and Air Brakes - NASA.” 2020. April 3, 2020. https://www.nasa.gov/solar-system/nasas-perseverance-mars-rover-gets-its-wheels-and-air-brakes/.

“7.0 Thermal Control.” NASA, February 14, 2024. https://www.nasa.gov/smallsat-institute/sst-soa/thermal-control/.

Gilmore, David G., ed. *Spacecraft Thermal Control Handbook Volume 1: Fundamental Technologies*. El Segundo, Calif: Aerospace Press, 2002.

“Solar Flux on Mars Surface.” Space Exploration Stack Exchange, March 1, 2018. https://space.stackexchange.com/questions/26937/solar-flux-on-mars-surface.

“Technology Readiness Levels.” NASA, September 27, 2023. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

Thermal vacuum and vibration testing of the differential ... Accessed March 5, 2024. https://ntrs.nasa.gov/api/citations/20230007610/downloads/Thermal Vacuum and Vibration Testing of the Differential Thermal Expansion Thermal Switch_final.pdf

RAD750® radiation-hardened powerpc microprocessor. Accessed March 5, 2024. https://www.baesystems.com/en-media/uploadFile/20210404045936/1434555668211.pdf

→ well connected - spacewire - ESA. Accessed March 5, 2024. http://spacewire.esa.int/content/Home/documents/SpW%20article.pdf

"Spacewire Links for Signal Integrity." SpaceWire Links | High Data Rate| Assemblies | Axon' Cable. Accessed March 4, 2024. https://www.axon-cable.com/en/03_assemblies/02_high-data-rate/03/index.aspx

"Thin, Light, Flexible Heaters Save Time and Energy." NASA, 2007. https://spinoff.nasa.gov/Spinoff2007/ip_7.html

"Command & Data-Handling Systems." NASA. Accessed March 4, 2024. https://mars.nasa.gov/mro/mission/spacecraft/parts/command/

"Mars Organic Molecule Analyzer: Animations." SVS, May 24, 2018. https://svs.gsfc.nasa.gov/20231#:~:text=MOMA%20marks%20the%20first%20use,search%20for%20life%20beyond%20Earth

"The Mars Organic Molecule Analyzer (MOMA) Instrument: Characterization of Organic Material in Martian Sediments," July 2017
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5685156/

"Microscopic Imager (MI)," PDS Geosciences Node, Washington University in St. Louis.
https://an.rsl.wustl.edu/help/Content/About%20the%20mission/MER/Instruments/Microscopic%20Imager.html

"Overview of Spirit Microscopic Imager Results." Journal of Geophysical Research: Planets 124, no. 2 (February 1, 2019): 528–84.
https://doi.org/10.1029/2018je005774

Herkenhoff, K. E., S. W. Squyres, R. E. Arvidson, Shoshanna B. Cole, R. Sullivan, Aileen Yingst, Nathalie A. Cabrol, et al. 2019. "Overview of Spirit Microscopic Imager Results." *Journal of Geophysical Research: Planets* 124 (2): 528–84. https://doi.org/10.1029/2018je005774.

Encyclopedia, NASA. "SEH 3.0 NASA Program/Project Life Cycle." NASA, July 26, 2023.

https://www.nasa.gov/reference/3-0-nasa-program-project-life-cycle/#hds-sidebar-nav-9.

Platt, Jane, ed. “Planetary Instrument for X-Ray Lithochemistry (PIXL).” NASA. Accessed March 4, 2024. https://mars.nasa.gov/mars2020/spacecraft/instruments/pixl/

2024. Els-Cdn.com. 2024. https://ars.els-cdn.com/content/image/1-s2.0-S135943111633277X-gr2.jpg.

2024. Satsearch.com. 2024. https://cdn.satsearch.com/product-images/satsearch_product-image_el10zp_zoppas-industries-space_stock-polymid-flexible-heater.jpg.

2024. Exactdn.com. 2024. https://celsiainc-com.exactdn.com/wp-content/uploads/2020/12/Variable-Conductance-Heat-Pipe-VCHP.png?strip=all&lossy=1&ssl=1.

Da Poian, Victoria, Eric Lyness, Ryan Danell, Xiang Li, Bethany Theiling, Melissa Trainer, Desmond Kaplan, and William Brinckerhoff. “Science Autonomy and Space Science: Application to the Exomars Mission.” Frontiers, April 8, 2022. https://www.frontiersin.org/articles/10.3389/fspas.2022.848669/full.

Goesmann, Fred, William B. Brinckerhoff, François Raulin, Walter Goetz, Ryan M. Danell, Stephanie A. Getty, Sandra Siljeström, et al. 2017. “The Mars Organic Molecule Analyzer (MOMA) Instrument: Characterization of Organic Material in Martian Sediments.” *Astrobiology* 17 (6-7): 655–85. https://doi.org/10.1089/ast.2016.1551.

Herkenhoff, Ken E, Steve W Squyres, Raymond E Arvidson, Shoshanna B Cole, Rob Sullivan, Aileen Yingst, Nathalie Cabrol, et al. 2019. “Overview of *Spirit* Microscopic Imager Results.” *Journal of Geophysical Research. Planets* 124 (2): 528–84. https://doi.org/10.1029/2018je005774.

Li, Xiang, Ryan M. Danell, Veronica T. Pinnick, Andrej Grubisic, Friso van Amerom, Ricardo D. Arevalo, Stephanie A. Getty, et al. 2017. “Mars Organic Molecule Analyzer (MOMA) Laser Desorption/Ionization Source Design and Performance Characterization.” *International Journal of Mass Spectrometry* 422 (November): 177–87. https://doi.org/10.1016/j.ijms.2017.03.010.

Appendices

Appendix 1: Changes Table

Changes Table	
Section	Change
Thermal Requirements	Revised requirements to adhere to SMART requirement development methodology.
Thermal Requirements	Revised to include requirements for component performance.
Thermal Overview	Revised to include discussion of interaction with other systems.
Thermal Overview	Included full system TRL
Thermal Overview	Included mass/power/volume table
Thermal Requirements	TCS-2: UV tends to be more degrading than IR (higher energies, more interaction). Rewrote to be more specific on intent.
Thermal Requirements	TCS-2.1 Revised to not require paint, but instead the performance characteristics generally shared by thermal coatings.
Payload STM	Revised the scope of the physical requirements needed to satisfy science objectives.
Mission Requirements	Landing zone and CAD renderings are completed for the Endurance Rover.
ConOps	Updated and flushed out the major milestones required for the mission schedule estimate.
Coordinates and Timelines	Determined an appropriate landing zone that satisfies science objectives.
Mass and Power Draw Estimates	Acquired and evaluated accurate mass and power draw estimates for the system.
Electrical Manufacturing Components	Accessed and determined manufacturing dates for the electrical components for the subsystem.

Budget	Accommodated feedback and budget for fields for necessary fields.
Outreach Development Plans	Developed and flushed out plans that addressed the target audiences with details concerning certain strategies.
Cost Estimates	Updated the Cost Estimates Section that were addressed in the MDR for budget and personnel.
Thermal Subsystem	Improved thermal subsystem overview and the associated heat maps.
Navigation System	Determined the appropriate navigation system for Endurance.

Appendix 2: Subsystem Trade studies

Appendix 2.1 Mechanical Subsystem Trade Studies

Appendix 2.1.1 - Chassis Material Trade Study

Chassis Material							
Criteria	**Explanation**	**Grade**	**Weight**	**Aluminum**	**Steel**	**Titanium**	**Composite Materials**
Strength/ Durability	All mechanical components shall maintain structural integrity throughout the duration of the mission. (MEC-3)	10 = Material possess high strength and durability characteristics 1 = Does not possess high strength and durability characteristics	13%	7	9	8	7
Low Temperature Tolerance	Structural material shall maintain material strength and durability in low temperatures of the landing site environment.	10 = Material maintains strength qualities in lower temperatures 1 = Material becomes brittle and weak in lower temperatures	13%	8	3	7	5
Complexity	A material complexity may increase difficulty in use if too high, and possibly delay the mission if too complex to work with and build upon.	10 = Low complexity 1 = High complexity	15%	7	3	7	2
Mass (kg)	The rover must not exceed a total mass of 45kg (MEC-1)	10 = High material strength to mass ratio 1 = Low material strength to mass ratio	30%	7	2	5	9
TRL	A material used before for	10 = Material applied	15%	7	6	5	3

	space missions proves reliability and incorporating these into the rover design increases TRL.	to structure in previous rover mission 0 = Material not considered					
Cost	The total mission cost must not exceed a total cost of $300M. (MR-4)	10 = Low cost material 1 = High cost material	15%	6	7	5	8
		TOTALS:	**100%**	69.75%	45.00%	59.25%	61.50%

Appendix 2.1.2 - Chassis Aluminum Alloys Trade Study

Aluminum Alloys for Chassis												
Criteria	**Explanation**	**Grade**	**Weight**	**2014**	**2024**	**2219**	**3003**	**5052**	**6061**	**6063**	**7050**	**7075**
Corrosion Resistance	The harsh environment on Mars, including the weather and the presence of chemicals like perchlorates in Martian soil, can leave a rover susceptible for corrosion if not made resistant.	10 = High resistance 1 = Low resistance	25%	3	3	3	8	7	5	5	5	5
Fatigue Strength	Without the ability for repair, the rover must have a high level of structural integrity to ensure the longevity of component life cycle.	10 = High MPa 1 = Low MPa	18%	5	5	4	3	4	4	3	8	6
Ultimate Tensile Strength	The amount of mechanical stresses while maintaining structural integrity must be optimized, ensuring the rover has enough strength to endure harsher Martian environmental conditions.	10 = High MPa 1 = Low MPa	20%	4	6	4	2	3	4	4	7	8
Specific Strength (Tensile Strength/Density)	To enable a lightweight yet durable design, the efficiency of a high strength-to-density ratio properties take into account specified alloy strengths.	10 = High MPa/g/cc 1 = Low MPa/g/cc	22%	4	6	5	3	3	4	3	7	8
TRL	An aluminum alloy used before for space missions proves reliability and incorporating these into the rover design increases TRL.	10 = Material applied in NASA Mars rover missions 6 = Material applied in aerospace 1 = Material not considered	15%	5	6	4	4	5	5	5	5	7
		TOTALS:	**100%**	40.80%	50.70%	39.70%	42.00%	44.80%	44.00%	40.00%	63.80%	67.40%

Appendix 2.1.3 - Wheel Type Trade Study

Wheel Type

Criteria	Explanation	Grade	Weight	Chevron	Flat Line	SMA Tire
Durability	Determining that the wheel can withstand the harsh operational conditions without compromising on functionality is key to increasing the rover's mission life cycle.	10 = Sufficient durability to support mission lifetime 1 = Insufficient durability	25%	5	7	8
Traction	Wheel treads must offer adequate traction for the rover to remain stable.	10 = Sufficient traction for mission terrain 1 = Lacking traction design	20%	6	6	6
Temperature Tolerance	The wide range of temperatures that the rover will encounter at the landing site and throughout mission duration may impact tire functionality, so the wheel must be able to withstand extreme temperature conditions.	10 = Composition of wheel structure tolerant of environment temperatures 1 = Intolerant of temperature ranges	10%	8	8	6
Mass (kg)	The rover must not exceed a total mass of 45kg (MEC-1)	10 = Low mass respective of total rover mass 1 = Higher mass respective of total rover mass	15%	6	7	4
TRL	A material used before for space missions proves reliability and incorporating these into the rover design increases TRL.	10 = Applied in mission with satisfactory results 1 = No consideration of material	20%	6	7	3
Cost	The total mission cost must not exceed a total cost of $300M. (MR-4)	10 = Low cost of material/development 1 = Cost out of scope of budget	10%	7	7	5
		TOTALS:	**100%**	60.50%	69.00%	55.00%

Appendix 2.1.4 - Wheel Material Trade Study

Wheel Material							
Criteria	**Explanation**	**Grade**	**Weight**	**Aluminum**	**Steel**	**Titanium**	**Compo-site Material**
Strength/Durability	All mechanical components shall maintain structural integrity throughout the duration of the mission. (MEC-3)	10 = Material possess high strength and durability characteristics 1 = Does not possess high strength and durability characteristics	25%	7	9	8	7

Low Temperature Tolerance	Wheel material shall maintain material strength and durability in low temperatures of the landing site environment.	10 = Material maintains strength qualities in lower temperatures 1 = Material becomes brittle and weak in lower temperatures	25%	8	3	7	5
Mass (kg)	The rover must not exceed a total mass of 45kg (MEC-1)	10 = High material strength to mass ratio 1 = Low material strength to mass ratio	20%	7	2	5	9
TRL	A material used before for space missions proves reliability and incorporating these into the rover design increases TRL.	10 = Material applied to wheel in previous rover mission 0 = Material not considered	15%	7	6	5	4
Cost	The total mission cost must not exceed a total cost of $300M. (MR-4)	10 = Low cost material 1 = High cost material	15%	6	7	5	7
		TOTALS:	**100%**	71.00%	53.50%	62.50%	66.00%

Appendix 2.1.5 - Wheel Aluminum Alloys Trade Study

Aluminum Alloys for Wheel												
Criteria	**Explanation**	**Grade**	**Weight**	**2014**	**2024**	**2219**	**3003**	**5052**	**6061**	**6063**	**7050**	**7075**
Corrosion Resistance	The harsh environment on Mars, including the weather and the presence of chemicals like perchlorates in Martian soil, can leave a rover susceptible for corrosion if not made resistant.	10 = High resistance 1 = Low resistance	30%	3	3	3	8	7	5	5	5	5
Fatigue Strength	Without the ability for repair, the rover wheels must have a high level of structural integrity to ensure the longevity of the component life cycle.	10 = High MPa 1 = Low MPa	19%	5	5	4	3	4	4	3	8	6
Ultimate Tensile Strength	The amount of mechanical stresses while maintaining structural integrity must be optimized, ensuring the rover has enough strength to endure harsher Martian environmental conditions.	10 = High MPa 1 = Low MPa	16%	4	6	4	2	3	4	4	7	8
Specific Strength (Tensile Strength/ Density)	To enable a lightweight yet durable design, the efficiency of a high strength-to-density ratio properties take into account specified alloy strengths.	10 = High MPa/g/cc 1 = Low MPa/g/cc	20%	4	6	5	3	3	4	3	7	8
TRL	An aluminum alloy used before for space missions proves reliability and incorporating these into the rover design increases TRL.	10 = Material applied in NASA Mars rover missions 6 = Material	15%	5	6	4	4	5	5	5	5	7

		applied in aerospace 1 = Material not considered										
		TOTALS:	**100%**	40.40%	49.10%	39.00%	44.90%	46.90%	44.50%	40.60%	62.90%	65.70%

Appendix 2.1.6 - Suspension System Trade Study

Suspension System						
Criteria	**Explanation**	**Grade**	**Weight**	**Rocker-Bogie**	**Indepen-dent Suspen-sion Systems**	**Multi-Link Suspen-sion System**
Mass (kg)	The rover must not exceed a total mass of 45kg (MEC-1)	10 = Low mass 1 = High mass	20%	7	6	6
Durability	All mechanical components shall maintain structural integrity throughout the duration of the mission. (MEC-3)	10 = High durability 1 = Low durability	20%	9	7	5
Adaptability	The adaptability directly impacts the rover's ability to traverse Martian terrains.	10 = High adaptability 1 = Low adaptability	20%	9	5	8
Energy Efficiency	The amount of overall power consumption of the rover impacts mission duration and the ability for the rover to conduct scientific objectives.	10 = High operation/power draw ratio 1 = Low operation/power draw ratio	20%	8	6	5
TRL	A material used before for space missions proves reliability and incorporating these into the rover design increases TRL.	10 = Suspension used in Mars rover 1 = Suspension concept not considered	20%	7	4	3
		TOTALS:	**100%**	80.00%	56.00%	54.00%

Appendix 2.1.7 - Sample Collection Device Trade Study

Robotic Arm					
Criteria	**Explanation**	**Grade**	**Weight**	**Shoulder-Arm-Wrist**	**Telescopic Collector**
Range of Motion	The range of motion of the robotic arm determines the ease of sample collection and manipulation	10 = high 1 = low	35%	10	2
Carrying Capacity	The robotic arm must be able to support the weight of the sample.	10 = high 1 = low	20%	7	4
Durability	Upon repeated usage, the robotic arm will be subject to wear due to the environment conditions. Less moving mechanical parts contribute to better durability.	10 = high 1 = low	25%	5	6

TRL	A robotic arm used before for space missions proves reliability and incorporating these into the rover design increases TRL.	10 = high, 1 = low	20%	4	1
		TOTALS:	**100%**	69.50%	32.00%

Appendix 2.1.8 - Sample Collection Device Trade Study

Sample Collection Device						
Criteria	**Explanation**	**Grade**	**Weight**	**Drill**	**Scooper**	**Rock Abrasion Tool (RAT)**
Efficiency	To ensure that diverse and compelling Marian samples are collected within the projected mission life cycle, the collection device must be efficient at collecting samples.	10 = High efficiency 1 = Low efficiency	25%	8	4	6
Capacity	The quantity of samples a sample collection device can intake can allow for more comprehensive analysis of Martian geology.	10 = High capacity 1 = Low capacity	10%	6	7	4
Complexity	A less complex sampling collection device can positively impact ease of operation and avoid maintenance requirements and risks.	10 = Low complexity 1 = High complexity	10%	5	8	6
Durability	All mechanical components shall maintain structural integrity throughout the duration of the mission. (MEC-3)	10 = High durability 1 = Low durability	10%	6	8	7
Sample Acquisition	Sample acquisition methods that address direct mission science objectives by being capable of collecting the data the mission needs is imperative.	10 = High sample acquisition 1 = Low acquisition	30%	9	7	5
TRL	A sample collection device used before for space missions proves reliability and incorporating these into the rover design increases TRL.	10 = Device used in previous Mars sample collection mission 1 = Device not considered	15%	4	5	4
		TOTALS:	**100%**	70.50%	61.50%	53.00%

Appendix 2.2 Power Subsystem Trade Studies

Appendix 2.2.1 - Solar Cell Junctions Trade Study

Solar Cell Junctions						
Criteria	**Explanation**	**Grade**	**Weight**	**Single Junction**	**Triple Junction**	**Quad/Penta Junction**
Efficiency	Percentage of Solar Radiation converted to energy. More efficiency will allow for less solar array area and material to be used, decreasing volume and mass	10 = high 5 = medium 1 = low 0 = Fail	40%	4	8	9

Mass	The rover must not exceed a total mass of 45kg (MEC-1)	10 = low mass 5 = medium 1 = high mass 0 = Fail	10%	8	4	2
Specific Power	W/m^2 higher specific power means it needs less area of the solar panel to generate the same power.	10 = high 5 = medium 1 = low 0 = Fail	5%	4	8	10
Cost (Complexity)	The total mission cost must not exceed a total cost of $300M. (MR-4)	10 = low cost 5 = medium 1 = high cost 0 = Fail	15%	10	5	2
Durability	How long the cells are able to operate before efficiency significantly declines. This may determine the mission duration	10 = high, 5 = medium 1 = low 0 = Fail	20%	3	6	6
TRL	Solar cell configurations that have been used in this environment before will be a more reliable choice	10 = high 5 = medium 1 = low 0 = Fail	10%	10	9	5
		TOTALS:	**100%**	57.00%	68.50%	63.00%

Appendix 2.2.2 - Solar Cell Material Trade Study

Solar Cell Material						
Criteria	**Explanation**	**Grade**	**Weight**	**Silicon**	**Gallium Arsenide (GaAs/Ge)**	**Gallium Indium Phosphide (GaInP)**
Efficiency	Percentage of Solar Radiation converted to energy. More efficiency will allow for less solar array area and material to be used, decreasing volume and mass	10 = high, 5 = medium 1 = low 0 = Fail	45%	4	8	9
Mass	The rover must not exceed a total mass of 45kg (MEC-1)	10 = low mass, 5 = medium 1 = high mass 0 = Fail	10%	7	4	4
Specific Power	W/m^2 higher specific power means it needs less area of the solar panel to generate the same power.	10 = high, 5 = medium 1 = low 0 = Fail	10%	5	8	9
Cost	The total mission cost must not exceed a total cost of $300M. (MR-4)	10 = low cost, 5 = medium 1 = high cost 0 = Fail	15%	10	7	4
Durability/Reliability	How long the cells are able to operate before efficiency significantly declines. This may determine the mission duration	10 = high, 5 = medium 1 = low 0 = Fail	20%	3	7	7
		TOTALS:	**100%**	51.00%	72.50%	73.50%

Appendix 2.2.3 - Solar Array Configuration Trade Study

Solar Array Configuration						
Criteria	**Explanation**	**Grade**	**Weight**	**Body Mounted**	**Fold Ring (Phoenix)**	**Fold Wings (Spirit)**
Complexity	Subassemblies with higher complexity have a higher chance of failure	10 = low complexity 5 = medium 1 = high complexity 0 = Fail	15%	10	6	5
Stored Volume	The spacecraft shall not exceed a stored configuration volume of 100 cm x 100 cm x 100 cm. (MEC-2)	10 = low volume 5 = medium 1 = high volume 0 = Fail	20%	5	5	5
Allowed Area	A configuration that allows for more solar panel area can generate more power	10 = high 5 = medium 1 = low 0 = Fail	35%	2	8	6
Dynamic Efficiency	Ability to generate energy as solar angle varies; more dynamic efficiency means more power generation overall	10 = high 5 = medium 1 = low 0 = Fail	30%	5	7	8
		TOTALS:	**100%**	47.00%	68.00%	62.50%

Appendix 2.2.4 - Solar Array Type Trade Study

Solar Array							
Criteria	**Explanation**	**Grade**	**Weight**	**Rigid**	**Flexible**	**Thin Film Flexible**	**Concentrator**
Cost	The total mission cost must not exceed a total cost of $300M. (MR-4)	10 = low cost 5 = medium 1 = high cost 0 = Fail	25%	4	4	9	7
Areal Mass	The rover must not exceed a total mass of 45kg (MEC-1)	10 = high 5 = medium 1 = low 0 = Fail	20%	3	7	10	7
Complexity	Subassemblies with higher complexity have a higher chance of failure	10 = high 5 = medium 1 = low 0 = Fail	20%	8	6	5	4
Durability	Higher durability allows for the array to operate properly for longer in harsh conditions, which the rover may be subject to.	10 = high, 5 = medium 1 = low 0 = Fail	35%	10	6	5	6
		TOTALS:	**100%**	67.00%	57.00%	70.00%	60.50%

Appendix 2.2.5 - Battery Trade Study

Batteries (Rechargeable)						
Criteria	**Explanation**	**Grade**	**Weight**	**Li-Ion**	**LiPo**	**NiH2**

Specific Energy	[Wh/kg] Greater Specific Energy means the battery can output more power for longer. Ex. 400Wh means it can produce 400 Watts for one hour or 200 Watts for two hours	10 = high, 5 = medium 1 = low 0 = Fail	35%	8	5	3
Cycle Life	How many times the battery can charge and discharge to a certain depth of discharge (DoD). This may determine the mission duration, and could potentially cut science short if the battery can no longer hold sufficient charge	10 = high, 5 = medium 1 = low 0 = Fail	30%	6	4	10
Calendar Life	How long the battery can survive with normal operation. This likely will not determine the mission duration	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	5	8
Capacity	[Ah] Greater capacity allows the rover to operate for longer periods of time at a given voltage	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	6	5
		TOTALS:	**100%**	70.50%	49.50%	61.00%

Appendix 2.3 - CDH Subsystem Trade Studies

Appendix 2.3.1 - Processor Trade Study

Processor						
Criteria	**Explanation**	**Grade**	**Weight**	**BAE RAD750**	**Leon (GR740)**	**Atmel AT697F**
Power Consumption	The Endurance rover will be operating within 60º of the North/South pole of Mars. Sunlight here is scarce, making power a valuable commodity.	10 = high, 5 = medium 1 = low 0 = Fail	18%	8	6	5
Cost	Cost is vital when evaluating the proper antenna as the Endurance rover is constrained to $300M. Seemingly small numbers now lead to large sums once the project continues to mature.	10 = high, 5 = medium 1 = low 0 = Fail	12%	5	7	8
TRL	A high TRL showcases that the processor technology has undergone extensive testing and validation.	10 = high, 5 = medium 1 = low 0 = Fail	24%	10	6	6
Speed	Processing speeds play a crucial factor in minimizing power use, improving data processing capabilities, and data transmission, given the limited time window with the MRO.	10 = high, 5 = medium 1 = low 0 = Fail	18%	7	8	4
Radiation	Mars is highly radioactive, receiving 240-300 mSv per year. This can cause electronics to malfunction; therefore, the non-volatile storage must have a high tolerance to radiation.	10 = high, 5 = medium 1 = low 0 = Fail	14%	9	6	6

Temperature	The Endurance rover will be operating within 60º of the North/South pole of Mars. Here, temperatures can range from a frigid -153ºC to a scorching 70ºC. Therefore, the processor must remain operational under these conditions.	10 = high, 5 = medium 1 = low 0 = Fail	14%	8	6	8
		TOTALS:	**100%**	80.80%	64.80%	59.80%

Appendix 2.3.2 - Volatile Memory Trade Study

Volatile Memory						
Criteria	**Explanation**	**Grade**	**Weight**	**DRAM (DDR4)**	**Infineon SRAM**	**SDRAM**
Power	The Endurance rover will be operating within 60º of the North/South pole of Mars. Sunlight here is scarce, making power a valuable commodity.	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	9	7
Cost	Cost is vital when evaluating the proper antenna as the Endurance rover is constrained to $300M. Seemingly small numbers now lead to large sums once the project continues to mature.	10 = high, 5 = medium 1 = low 0 = Fail	20%	5	5	5
Speed	The speed of volatile storage affects power consumption, data integrity, system performance, processing, and various other factors. Furthermore, given the short 6-minute window the rover has to offload any data to the MRO, fast read and write speeds are vital.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	7	6
Temperature	The Endurance rover will be operating within 60º of the North/South pole of Mars. Here, temperatures can range from a frigid -153ºC to a scorching 70ºC. Therefore, the volatile storage must remain operational under these conditions.	10 = high, 5 = medium 1 = low 0 = Fail	15%	9	9	0
TRL	For Mars Rover applications, a high TRL showcases that the memory technology has undergone extensive testing and validation.	10 = high, 5 = medium 1 = low 0 = Fail	25%	9	9	0
		TOTALS:	**100%**	58.00%	56.50%	36.50%

Appendix 2.3.3 - Non-Volatile Storage Trade Study

Non-Volatile Storage						
Criteria	**Explanation**	**Grade**	**Weight**	**Flash Memory**	**MRAM**	**FRAM**
Power	The Endurance rover will be operating within 60º of the North/South pole of Mars. Sunlight here is scarce, making power a valuable commodity.	10 = high, 5 = medium 1 = low 0 = Fail	20%	4	9	10
Cost	Cost is vital when evaluating the proper antenna as the Endurance rover is constrained to $300M. Seemingly small numbers now lead to large sums once the project continues to mature.	10 = high, 5 = medium 1 = low 0 = Fail	14%	10	3	4

Speed	The speed of non-volatile storage affects power consumption, data integrity, system performance, processing, and various other factors. Furthermore, given the short 6-minute window the rover has to offload any data to the MRO, fast read and write speeds are vital.	10 = high, 5 = medium 1 = low 0 = Fail	14%	5	9	10
Temperature	The Endurance rover will be operating within 60º of the North/South pole of Mars. Here, temperatures can range from a frigid -153ºC to a scorching 70ºC. Therefore, the non-volatile storage must remain operational under these conditions.	10 = high, 5 = medium 1 = low 0 = Fail	12%	7	9	9
Radiation	Mars is highly radioactive, receiving 240-300 mSv per year. This can cause electronics to malfunction; therefore, the non-volatile storage must have a high tolerance to radiation.	10 = high, 5 = medium 1 = low 0 = Fail	12%	5	10	7
TRL	A high TRL showcases that the storage technology has undergone extensive testing and validation.	10 = high, 5 = medium 1 = low 0 = Fail	28%	10	3	3
		TOTALS:	**100%**	71.40%	66.00%	67.20%

Appendix 2.3.4 - Data Bus Trade Study

Data Bus						
Criteria	**Explanation**	**Grade**	**Weight**	**1553B**	**SpaceWire**	**MIL-STD-1553**
Power	The Endurance rover will be operating within 60º of the North/South pole of Mars. Sunlight here is scarce, making power a valuable commodity.	10 = high, 5 = medium 1 = low 0 = Fail	17%	9	7	9
Cost	Cost is vital when evaluating the proper antenna as the Endurance rover is constrained to $300M. Seemingly small numbers now lead to large sums once the project continues to mature.	10 = high, 5 = medium 1 = low 0 = Fail	17%	6	6	8
Speed	The transfer rate of the data bus affects power consumption, data integrity, system performance, processing, and various other factors. Furthermore, given the short 6-minute window the rover has to offload any data to the MRO, fast read and write speeds are vital.	10 = high, 5 = medium 1 = low 0 = Fail	16%	5	10	3
Temperature	The Endurance rover will be operating within 60º of the North/South pole of Mars. Here, temperatures can range from a frigid -153ºC to a scorching 70ºC. Therefore, the non-volatile storage must remain operational under these conditions.	10 = high, 5 = medium 1 = low 0 = Fail	16%	7	10	5
Radiation	Mars is highly radioactive, receiving 240-300 mSv per year. This can cause electronics to malfunction; therefore, the data bus must have a high tolerance to radiation.	10 = high, 5 = medium 1 = low 0 = Fail	17%	6	10	5

TRL	A high TRL showcases that the storage technology has undergone extensive testing and validation.	10 = high, 5 = medium 1 = low 0 = Fail	17%	7	7	7
		TOTALS:	**100%**	54.90%	71.10%	50.20%

Appendix 2.4 Thermal Subsystem Trade Studies

Appendix 2.4.1 - Heat Method Trade Study

Heat Pipe vs Resistive Heater						
Criteria	**Explanation**	**Grade**	**Weight**	**Heat Pipe**	**Resistive Heater**	**Combination**
Weight/space	MEC-1/MEC-2	10 = high, 5 = medium 1 = low 0 = Fail	15%	4	8	6
Reliability/Redundancy	The system should be stable and have some redundancy to mitigate some risks	10 = high, 5 = medium 1 = low 0 = Fail	25%	7	5	9
Functionality	TCS-2.1	10 = high, 5 = medium 1 = low 0 = Fail	50%	6	6	8
Complexity	Over complication of the system would make configuration difficult	10 = high, 5 = medium 1 = low 0 = Fail	10%	5	7	4
		TOTALS:	**100%**	58.50%	61.50%	75.50%

Appendix 2.4.2 - Heat Pipe Trade Study

Heat Pipe System								
Criteria	**Explanation**	**Grade**	**Weight**	**Looped Heat Pipes**	**Diode Heat Pipes**	**VCHPs**	**Hybrid**	**Constant-Conductance Heat Pipe**
Weight/space	MEC-1/MEC-2	10: Low Weight and Space 5 = medium 1 = low 0: Fail High Weight and Space	5%	6	5	4	5	8

Reliability/Redundancy	The system should be stable and have some redundancy to mitigate some risks or be easy to implement multiple	10: Very reliable 5 = medium 1 = low 0 : Not very reliable	20%	5	7	9	4	7
TRL	The system should have been used before in space	Based on actual TRL levels	25%	2	3	5	3	4
Functionality	TCS-3.3	10: Works very well 5 = medium 1 = low 0 = Does not work very well	40%	9	6	10	9	5
Complexity	Over complication of the system would make configuration difficult, low complexity is better	10 = high, not very complex 5 = medium 1 = low 0 = Fail. Very complex	10%	4	7	6	3	9
		TOTALS:	**100%**	58.00%	47.50%	66.00%	49.50%	47.00%

Appendix 2.4.3 - Heaters Trade Study

Heaters						
Criteria	**Explanation**	**Grade**	**Weight**	**Patch Heaters**	**Cartridge Heater**	**Q-Foil Heater**
Weight/space	MEC-1/MEC-2	10: Low Weight and Space 5 = medium 1 = low 0: Fail High Weight and Space	5%	7	9	8
Reliability/Redundancy	The system should be stable and have some redundancy to mitigate some risks or be easy to implement multiple	10: Very reliable 5 = medium 1 = low 0 : Not very reliable	20%	8	8	5
TRL	The system should have been used before in space	Based on actual TRL levels	25%	5	3	2
Functionality	TCS-3.1	10 = high, Works very well 5 = medium 1 = low 0 = Fail. Does not work very well	40%	6	4	8
Complexity	Over complication of the system would make configuration difficult	10 = high, not very complex 5 = medium 1 = low 0 = Fail. Very complex	10%	9	7	4

		TOTALS:	100%	65.00%	51.00%	55.00%

Appendix 2.4.4 - Radiators Trade Study

Radiators						
Criteria	**Explanation**	**Grade**	**Weight**	**Passive Structure Radiators**	**Body-mounted Radiators**	**Deployable Radiators**
Weight/space	MEC-1/MEC-2	10: Low Weight and Space 5 = medium 1 = low 0: Fail High Weight and Space	15%	8	5	3
Reliability/Redundancy	The system should be stable and have some redundancy to mitigate some risks or be easy to implement multiple	10: Very reliable 5 = medium 1 = low 0 : Not very reliable	25%	9	7	5
Functionality	TCS-3.1	10 = high, Works very well 5 = medium 1 = low 0 = Fail. Does not work very well	50%	9	6	10
Complexity	Over complication of the system would make configuration difficult	10 = high, not very complex 5 = medium 1 = low 0 = Fail. Very complex	10%	6	7	5
		TOTALS:	**100%**	85.50%	62.00%	72.00%

Appendix 2.4.5 - Heat Switches Trade Study

Heat Switches							
Criteria	**Explanation**	**Grade**	**Weight**	**Paraffin Heat Switch**	**Cryogenic Heat Switch**	**Gas-Gap Heat Switches**	**Differential Thermal Expansion Heat Switches**
Weight/space	MEC-1/MEC-2	10: Low Weight and Space 5 = medium 1 = low 0: Fail High Weight and Space	15%	5	3	8	3
Reliability/Redundancy	The system should be stable and have some redundancy to mitigate some risks or be easy to implement multiple	10: Very reliable 5 = medium 1 = low 0 : Not very reliable	25%	9	3	5	7

Functionality	TCS-3.2	10 = high, Works very well 5 = medium 1 = low 0 = Fail. Does not work very well	50%	5	7	4	8
Complexity	Over complication of the system would make configuration difficult	10 = high, not very complex 5 = medium 1 = low 0 = Fail. Very complex	10%	7	5	7	8
		TOTALS:	**100%**	62.00%	52.00%	51.50%	70.00%

Appendix 2.4.6 - Insulation Method Trade Study

Insulation Method							
Criteria	**Explanation**	**Grade**	**Weight**	**Aerogel**	**Foams**	**Batt**	**Gas Void Method**
Weight/space	MEC-1/MEC-2	10: Low Weight and Space 5 = medium 1 = low 0: Fail High Weight and Space	15%	8	7	6	10
Reliability/Redundancy	The system should be stable and have some redundancy to mitigate some risks or be easy to implement multiple	10: Very reliable 5 = medium 1 = low 0 : Not very reliable	25%	7	10	8	3
Functionality	TCS-3.1	10 = high, Works very well 5 = medium 1 = low 0 = Fail. Does not work very well	50%	9	6	7	10
Complexity	Over complication of the system would make configuration difficult	10 = high, not very complex 5 = medium 1 = low 0 = Fail. Very complex	10%	7	10	8	4
		TOTALS:	**100%**	81.50%	75.50%	72%	76.50%

Appendix 2.5 GNC Subsystem Trade Studies

Appendix 2.5.1 - Navcam Design Trade Study

Navcam Design						
Criteria	**Explanation**	**Grade**	**Weight**	**MER/MSL**	**ECAM**	**Modified**
Depth of Field	GNC-5	10 = low latency 5 = medium latency 1= high latency	20%	7	8	5

Angular Resolution	GNC-5	10 = low time 5 = medium time 1 = high time	25%	6	8	3
Field of View	GNC-5	10 = low power draw 5 = medium 1 = high power draw	20%	4	6	5
Spectral Bandpass	GNC-5	10 = low-cost 5 = medium-cost 1 = high-cost	15%	2	10	10
Mass	MEC-1	10 = low time 5 = medium time 1 = high time	10%	7	5	3
Cost	MR-4	10 = low time 5 = medium time 1 = high time	10%	8	4	3
		TOTALS:	**100%**	55.00%	72.00%	48.50%

Appendix 2.5.2 - Hazcam Design Trade Study

Hazcam Design						
Criteria	**Explanation**	**Grade**	**Weight**	**MER/MSL**	**ECAM**	**Modified**
Depth of Field	GNC-5	10 = low latency 5 = medium latency 1= high latency	20%	7	8	2
Angular Resolution	GNC-5	10 = low time 5 = medium time 1 = high time	25%	9	7	3
Field of View	GNC-5	10 = low power draw 5 = medium 1 = high power draw	20%	4	6	5
Spectral Bandpass	GNC-5	10 = low-cost 5 = medium-cost 1 = high-cost	15%	2	10	10
Mass	MEC-1	10 = low time 5 = medium time 1 = high time	10%	7	5	
Cost	MR-4	10 = low time 5 = medium time 1 = high time	10%	8	5	
		TOTALS:	**100%**	62.50%	70.50%	36.50%

Appendix 2.5.3 - REMS Trade Study

REMS						
Criteria	**Explanation**	**Grade**	**Weight**	**VxWorks**	**RTEMS**	**RTLinux**

Interrupt Latency (loaded system-max)	GNC-5	10 = low latency 5 = medium latency 1= high latency	30%	7	8	2
Context Switching (loaded system-max)	GNC-5	10 = low time 5 = medium time 1 = high time	25%	9	7	3
Power Consumption	EPS-2	10 = low power draw 5 = medium 1 = high power draw	20%	4	6	5
Cost	GNC-3	10 = low-cost 5 = medium-cost 1 = high-cost	25%	2	10	10
		TOTALS:	**100%**	56.50%	78.50%	48.50%

Appendix 2.5.4 - Navigation System Trade Study

Navigation System							
Criteria	**Explanation**	**Grade**	**Weight**	**SINS**	**VNS**	**CNS**	**Integrated**
Suitability for Environment	GNC-4	10 = high suitability 5 = medium suitability 1 = low suitability	25%	10	8	3	8
Accuracy	GNC-5	10 = high accuracy 5 = medium accuracy 1 = low accuracy	20%	6	10	9	10
Time calculations take	GNC-7	10 = low time 5 = medium time 1 = high time	15%	8	5	10	7
Fault Tolerance	GNC-9	10 = high tolerance 5 = medium tolerance 1 = low tolerance	25%	4	8	6	10
Power Consumption	EPS-2	10 = high power draw 5 = medium power draw 1 = low power draw	15%	9	4	8	1
		TOTALS:	**100%**	59.00%	67.50%	55.50%	75.50%

Appendix 2.6 Payload Subsystem Trade Studies

Appendix 2.6.1 - Regolith Depth Trade Study

Regolith Depth						
Criteria	**Explanation**	**Grade**	**Weight**	**Surface regolith**	**Subsurface regolith**	**Deep regolith**
Drilling difficulty	Thin atmosphere and hard regolith cause drilling problems	10: No drilling required, 1: Excessive drilling required	25%	9	5	2

Sample contamination	Cosmic radiation poses risks to sample contamination, affecting accurate analysis	10: Little to no risk of sample contamination, 1: High risk of sample contamination	25%	3	5	7
Instrument integration	Some instruments are not able to penetrate deep into regolith	10: Compatible with spectrometers and micro imagers, 1: Not compatible with spectrometers and micro imagers	25%	8	6	2
Power and weight consumption	Some drills require adjusting movements to avoid getting stuck, absorbing extra attention from rover	10: Does not require excessive power and weight consumption from rover, 1: Requires excessive power and weight consumption from rover	25%	8	6	4
		TOTALS:	**100%**	70.00%	55.00%	37.50%

Appendix 2.6.2 - Spectrometer Depth Trade Study

Spectrometer						
Criteria	**Explanation**	**Grade**	**Weight**	**Mass spectrometer**	**X-ray spectrometer**	**Thermal spectrometer**
Isotopic fractionation	Precise isotopic fractionation analysis requires specialized instruments	10: Able to perform precise isotopic fractionation, 1: Not able to perform isotopic fractionation	25%	8	4	3
Heat	Some spectrometers require samples to be heated	10: Heating samples is not needed, 1: Extreme heating of samples is needed	25%	4	8	8
Analysis times	Some spectrometers can perform immediate analysis while others can't	10: Immediate analysis, 1: +30 hour time	25%	7	5	8
Sensitivity	Higher sensitivity allows for accurate analysis of low concentration samples	10: high sensitivity, 1: low sensitivity	25%	9	8	6
		TOTALS:	**100%**	70.00%	62.50%	62.50%

Appendix 2.6.3 - Mission Compatibility Trade Study

Mission Compatibility						
Criteria	**Explanation**	**Grade**	**Weight**	**MOMA-MS**	**PIXL**	**Mini-TES**
Mass	Instruments should not take up more than 20-30% of the total mass of the rover	10: Instrument weights less than 1kg, 1: Instrument takes up half of rover's total mass	20%	5	8	8
Volume	Instruments should not take up more than 20-30% of the total volume on the rover	10: Instruments take up over 50% of rover, 1: Instruments take up less than 5% of total volume	20%	5	6	7

Power draw	Instruments should not consume excessive power	10: Minimal power consumption, 1: Excessive power consumption	20%	4	6	8
Relevancy to objectives	Instruments must support objectives	10: Crucial for all 3 objectives, 1: Somewhat helpful for 1 objective	40%	10	6	5
		TOTALS:	**100%**	68.00%	64.00%	66.00%

Appendix 2.6.4 - Durability and Integration Trade Study

Durability and Integration						
Criteria	**Explanation**	**Grade**	**Weight**	**MOMA-MS**	**Mini-Tes**	**PIXL**
Flight Heritage	Proven flight heritage of instruments in other missions.	10: used in previous missions, 1: not tested in any scenario	40%	5	8	8
Durability	Critical to mission success and instruments must be able to withstand harsh environments	10: tailor made for the scenarios, 1: not applicable in any sense	20%	5	8	7
Hardware/Software	Hardware/software fidelity in the expected scenarios.	10: does not require testing, 1: requires much testing	20%	6	7	9
Integration	Ease of implementation of the parts of the instruments within the rover.	10: no modification to implement, 1: requires much modification	20%	6	7	8
		TOTALS:	**100%**	54.00%	76.00%	80.00%

Appendix 2.6.5 - Camera Trade Study

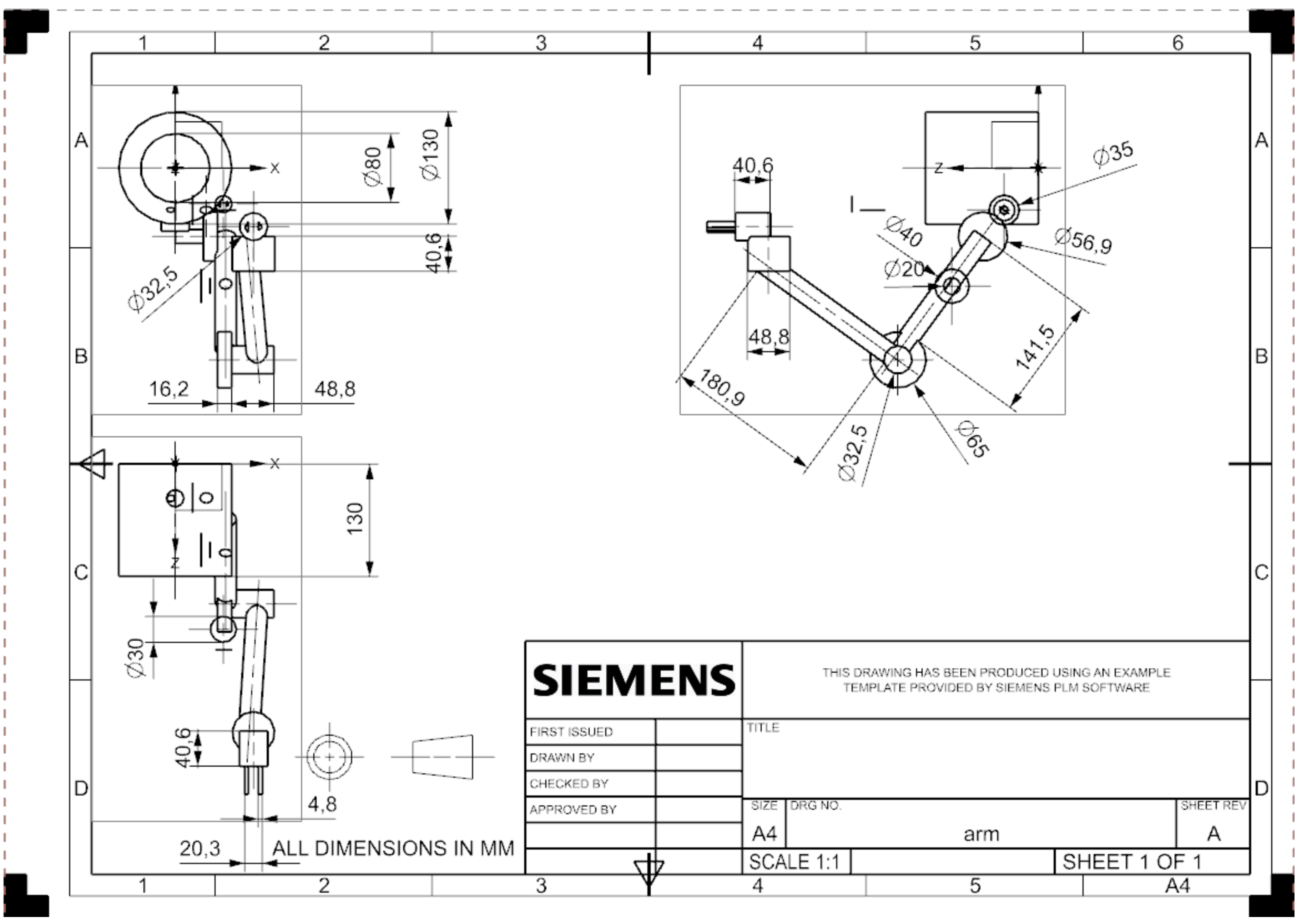
Camera						
Criteria	**Explanation**	**Grade**	**Weight**	**Pancam**	**MI**	**MastCam-Z**
Resolution	High resolution needed for analyzing the characteristics of Mars's surface	10: very high resolution, 1: very low resolution	30%	5	7	10
Mass	Instruments should not take up more than 20-30% of the total mass of the rover	10: Instruments weight less than 1kg, 1: Instrument takes up half of rovers total mass	25%	9	10	4
Durability	Operating optimally under the environmental conditions of the martian environment is essential	10: resilient in variety of conditions, 1: not resilient	15%	10	10	9
Integration with Spectrometer	Ease of integration with spectrometer is critical for operational efficiency	10: easy integrates and complements spectrometer, 1: poorly integrates	30%	7	7	9
		TOTALS:	**100%**	73.50%	82.00%	80.50%

Appendix 3: Subsystem Overview Table with CERs

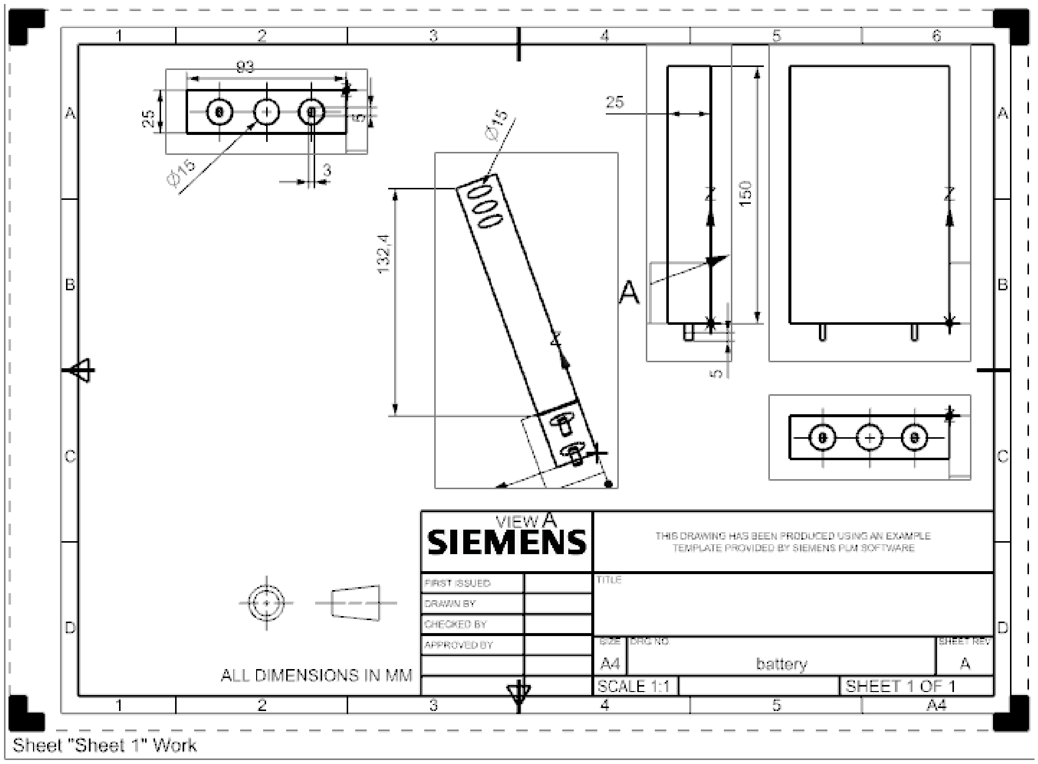
Subsystem	Mass (kg)	Stowed Volume Container (cm)	Max Power Draw (W)	CER (Budget)
EPS	6.2	20x20x5 + 2*(4x4x6)	N/A	5848.830714
TCS	5	10 x 10 x 10	50	1741.391542
MECH	10	58 x 52 x 38 (chassis shelled)	90	5843.192845
CDH	4	20 x 20 x 15	30	4843.096152
GNC	3	17 x 17 x 17	10	3921.621702
Payload	9.2	20 x 20 x 25	70	15313.37992
TOTAL	**37.4**	**WILL FIT IN 100x100x100cm**	**250**	

Appendix 4: CAD Drawings

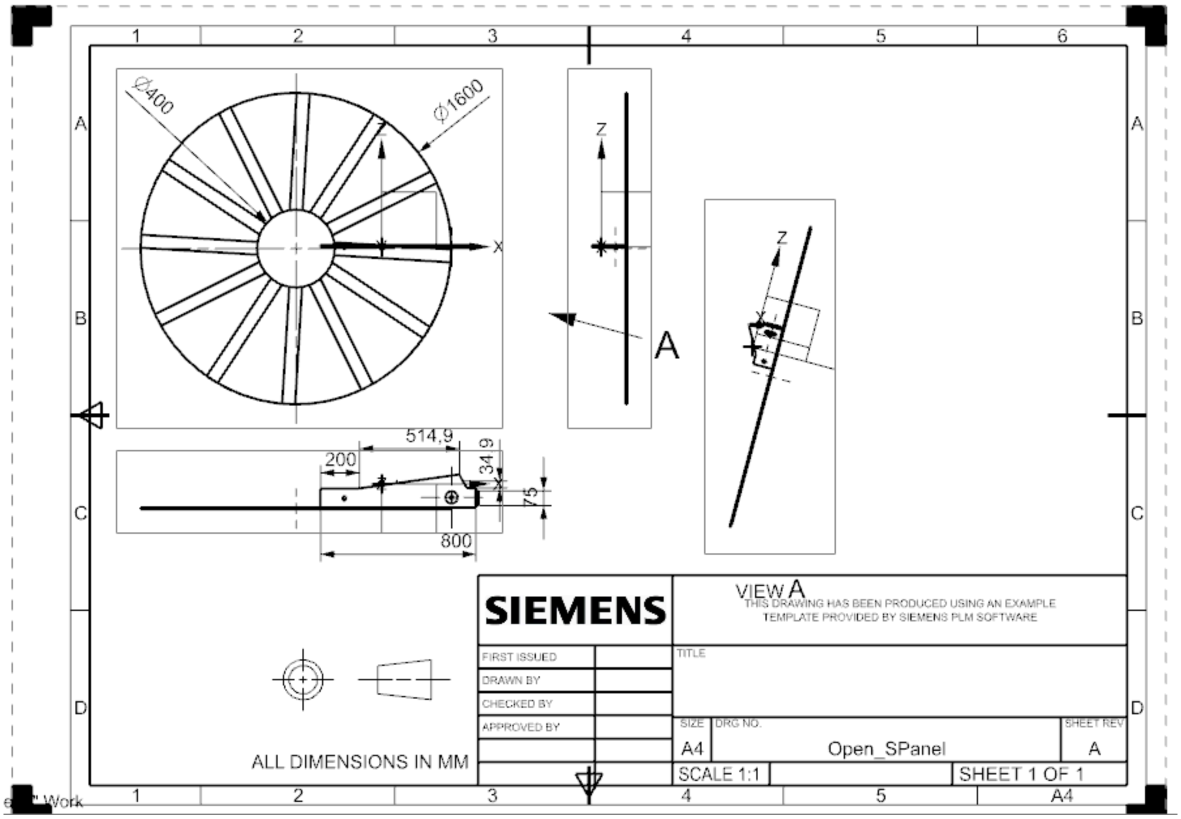
Appendix 4.1 - Arm



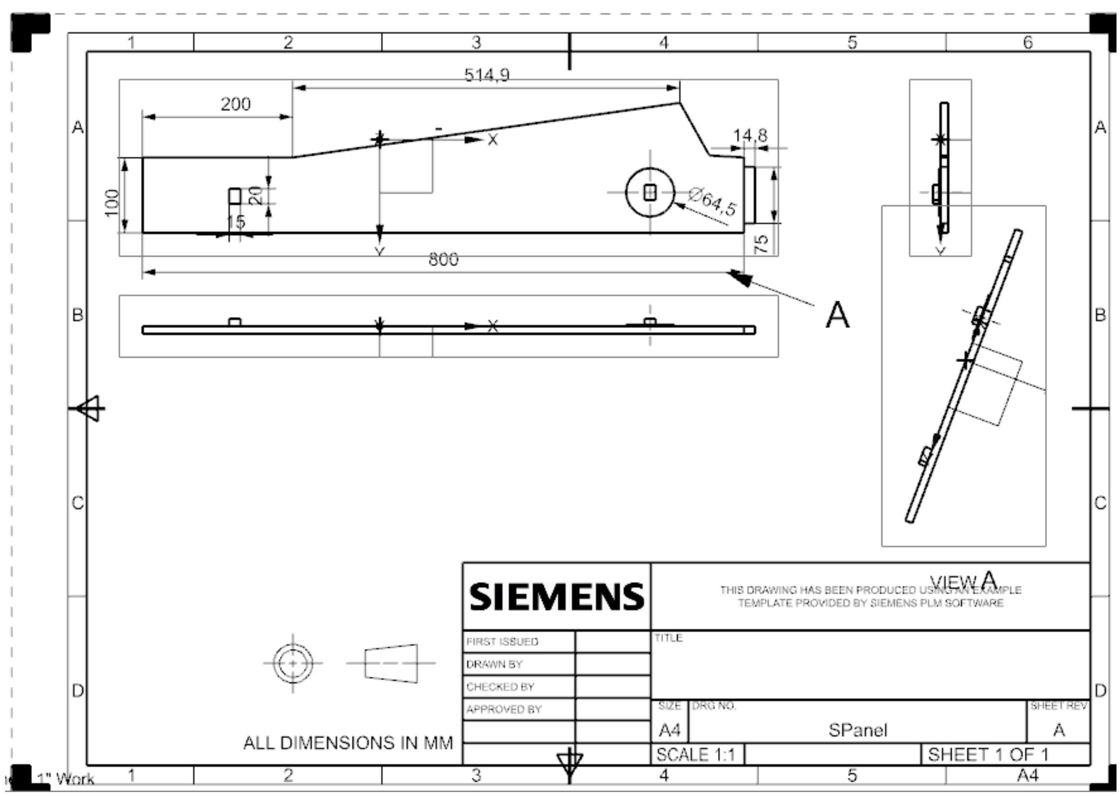
Appendix 4.2 - Battery



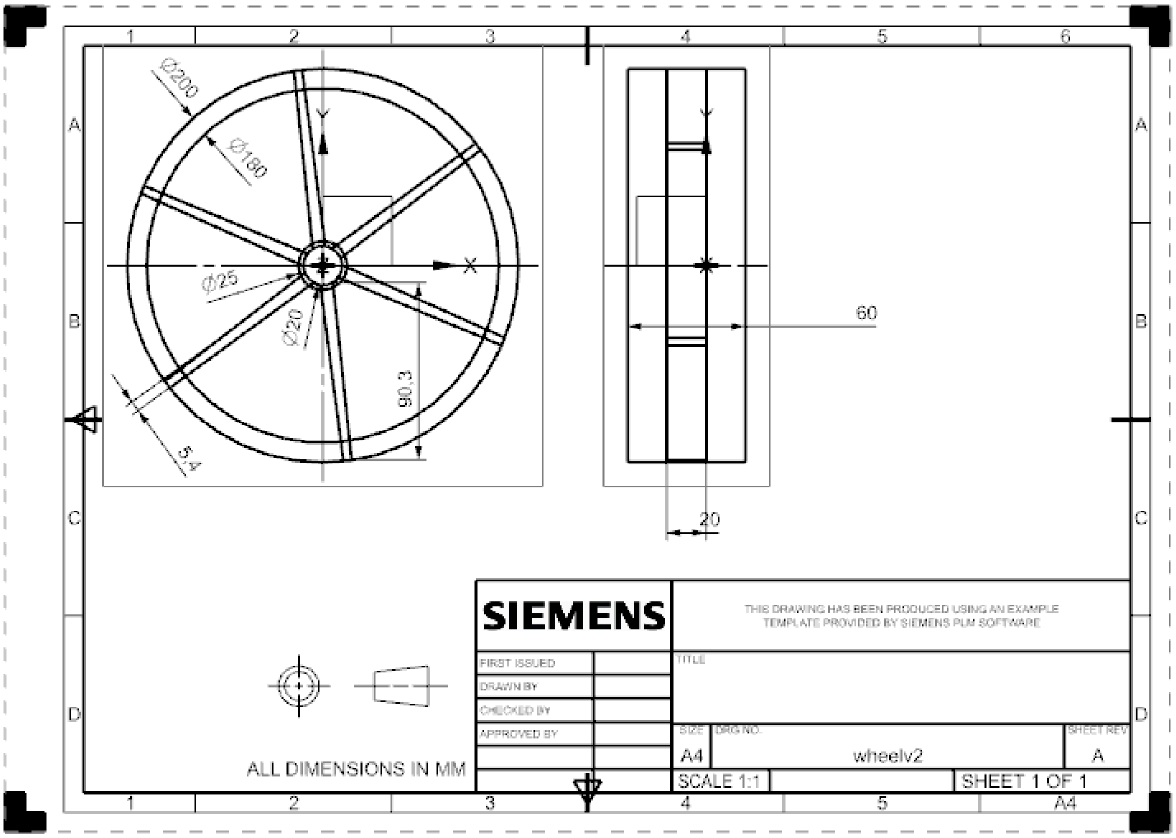
Appendix 4.3 - Open Solar Panel



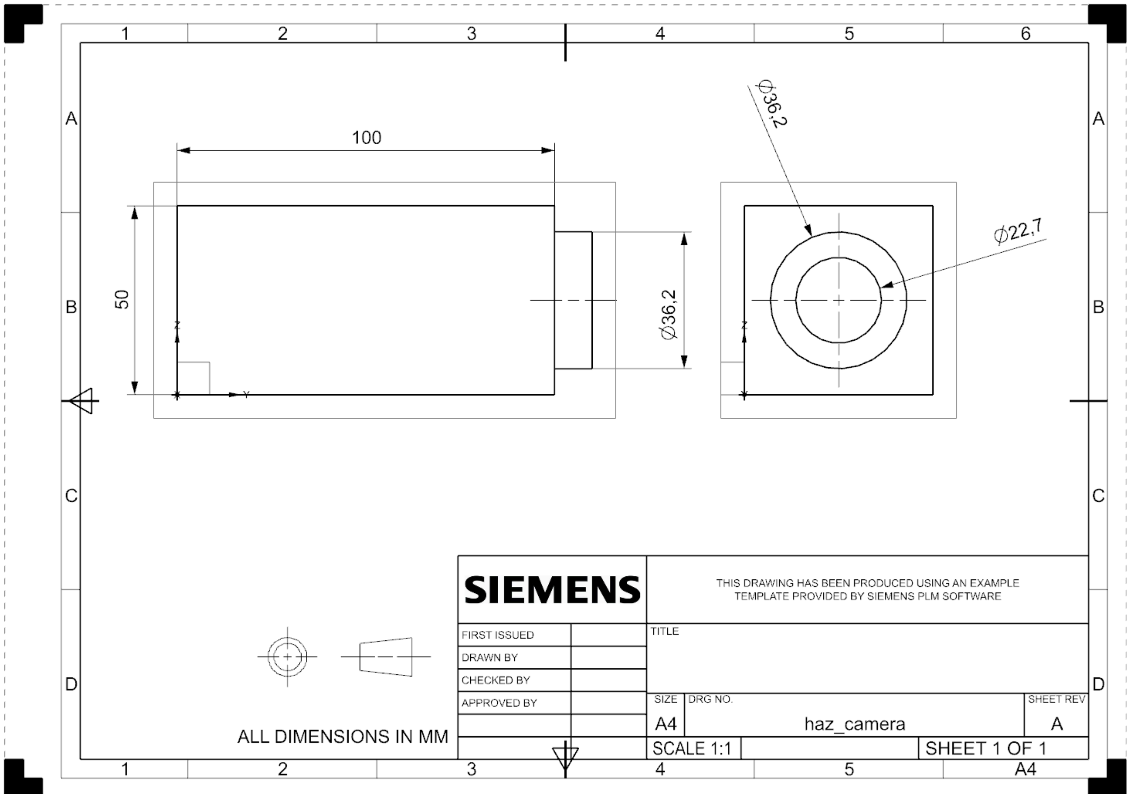
Appendix 4.4 - Closed Solar Panel



Appendix 4.5 - Wheel



Appendix 4.6 - Hazcam



Appendix 4.7 - NavCam