Mu3 Maverick

In Response to AIAA Dual Mars Ascent Vehicle Design Competition

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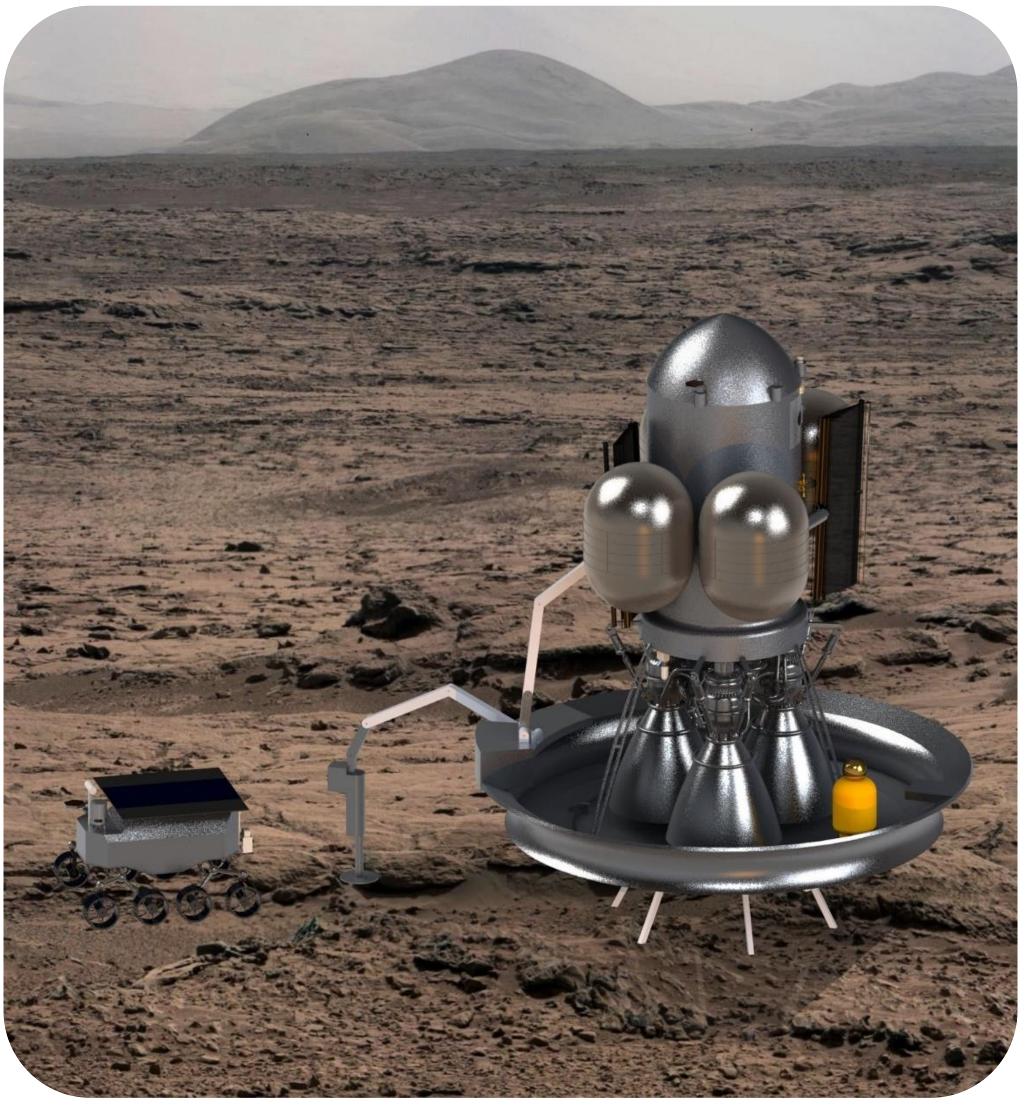

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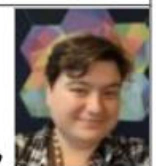
Chief of Operations Ashley Anderson AIAA ID: 1406861 Signature: 	**Payload Systems** Amanda Ewing AIAA ID: 1389661 Signature: 
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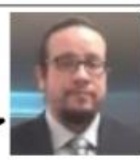
Manufacturing Cesar Villa AIAA ID: 1422246 Signature: 	**Mission Assurance** Edgar Romero AIAA ID: 1315190 Signature: 
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1.3 List of Acronyms

ACS: Attitude Control System

AI: Artificial Intelligence

AutoNav: Autonomous Navigation

CBE: Current Best Estimate

CD&H: Command and Data Handling

COSPAR: Committee on Space Research

COTs: Customer off the Shelf

DOD: Depth of Discharge

DSN: Deep Space Network

DST: Deep Space Transport

ECLSS: Environmental Control & Life Support System

EDL: Entry, Descent, Landing

ENav: Enhanced Navigation

EOM: End of Mission

FOM: Figure of Merit

FOV: Field of View

FSPU: Fission Surface Power Unit

FY: Fiscal Year

GEF: Government Furnished Equipment

GFLOPS: Giga Floating Point Operations Per Second

HIAD: Hypersonic Inflatable Aerodynamic Decelerator

IAU: Integrated Avionics Units

ISS: International Space Station

LiOH: Lithium Hydroxide

LMO: Low Mars Orbit

MAV: Mars Ascent Vehicle

MLV: Mars Lander Vehicle

MEDA: Mars Environmental Dynamics Analyzer

MEV: Maximum Expected Value

MGA: Mass Growth Allowance

MRN: Mars Relay Network

MMH: Monomethyl Hydrazine

NI: No Information

NTO: Dinitrogen Tetroxide

OBC: On Board Computer

PCEC: Project Cost Estimating Capacity

P&ID: Parts and Instrumentation Diagram

Rad-hard: Radiation-hardened

RAM: Random Access Memory

RFP: Request for Proposal

RFL: Refuel Lander

RMU: Redundancy Management Unit

RTOS: Real Time Operating System

SPDR: Smart Propellant Delivery Rover

SRP: Solar Radiation Pressure

SSAP: Sample Safety Assessment Protocol

Tb: Terabit

TB: Terabyte (8Tb)

TRL: Technology Readiness Level

UHF: Ultra High Frequency

WBS: Work Breakdown Structure

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2.0 Executive Summary

Mu3 believes bringing astronauts back from Mars to be the natural evolution of spaceflight and the beginning of a new era of space exploration. Given the unique challenges posed by this project, NASA has determined a dual-lander ascent vehicle is the most pragmatic option for the mission. Mu3 proposes MAVERICK, a program to develop the architectures and technology to safely transport astronauts from Mars to an awaiting Deep Space Transit Vehicle in a 5-sol orbit [1]. The core of MAVERICK depends on two separate landers and architectures; The first architecture is named the MAV, whilst the second is a fuel transport rover affectionately named SPDR, pronounced 'SPIDER'. As reflected in the order of this paper, the mission itself can be divided into two parts: Ground Phase and Ascent Phase. Ground Phase includes autonomous propellant transfer between the RFL and MAV, while the ascent phase includes the MAV launch, ascent, and docking. The development of this project required the collaboration of different divisions, including propulsion, power, life support, structural systems, thermal management, and systems engineering. The highly integrated nature of this program required a deep understanding and interplay between all divisions to ensure mission success, in addition to requiring technological advancements and innovation. With this groundbreaking endeavor, Mu3 envisions a future where astronauts can be safely transported back from Mars, marking a significant milestone in human space exploration. The MAVERICK program aims to pave the way for further advancements and discoveries in the realm of space travel, pushing the boundaries of what humanity can achieve in our quest to explore the cosmos.

Exploring Mars is a complex challenge, but one that holds significant consequences for humanity's future. Mars presents a unique opportunity to delve into scientific mysteries, our understanding of the universe, and explore the possibility of life on other celestial bodies.

A successful mission is defined as the completion of objectives as identified during development, including the safe transport of astronauts from the surface of Mars to an awaiting orbital transport vehicle. To save costs and ensure timely development, requirements informed the design drivers for both MAV and SPDR. Requirements provided by AIAA include a maximum cost, mass and size constraints, scientific sample return, autonomous fuel transfer, and launch readiness timeline.

The overall cost of the mission development, including manufacturing, design, maintenance, and Earth telecommunications, must not exceed $4 billion (FY2022). The cost does not include development of the landers as elaborated in the Mission Scope section. To keep costs down, Mu3 has decided to follow a highly integrated top-down development style and model-based systems engineering. Additionally, costs were calculated with a 10% margin to account for unexpected price increases or inflation during the development period. This ensures a greater compliance buffer and encompasses the manufacturing engineering principles of 'First Time Right' and concurrent development.

Additionally, the overall diameter of both architectures stowed must fit within an 8.4-meter diameter payload fairing. Trade studies and current technology readiness indicate that the only launch vehicle capable of meeting this is the Space Launch System Block 2B (SLS Block2). This is also the only launch vehicle to meet our maximum payload capacity of 25 metric tons per landed architecture. This maximum landed weight refers to the maximum *payload* allowable, in which lander weight is not considered. Initial mass estimates for all subsystems were provided using *Elements of Spacecraft Design* by Charles D. Brown [2] which utilizes historical crewed missions to show a rough mass relationship between all subsystems.

This mass further includes the capacity to transport a 50 kg Mars sample with the crew. The samples are classified under Category V of the PPP and must adhere to the requirements from the COSPAR for sample return missions. These operational constraints will limit the cross-contamination of samples and ensure astronaut safety.

The MAV must be able to support crew Mars launch by July 1st, 2040 with both architectures landing on Mars no later than July 2038. Mu3 has determined that different launch dates for each architecture will aid in mission success. Orbital launch analysis from Earth indicates a launch date of June 26, 2035, for the MAV portion of the mission and an arrival date of January 4, 2036. Five months after the MAV lands, the SPDR will launch from Earth on June 12, 2036, and arrive on Mars on April 12, 2037. Launch dates were staggered as a matter of safety and cost. As elaborated on in the concept of operations, after the MAV Lander makes its safe landing, it has approximately 5 months to conduct and verify nominal system checks and signal to Earth-based crews that it is safe to launch the RFL portion of the mission. Furthermore, after the RFL safely lands and all systems are checked and approved, the SPDR rover will dismount and autonomously conduct a total of 13 trips between RFL and MAV over a period of about 1 year with redundancy and delays accounted for in the mission timeline.

The autonomous system follows a 20-second ‘pause-and-calculate’ pathfinding algorithm. This is preferred due to the possibility of unforeseen detritus in previous paths or obstruction caused by dust storms. Multiple LiDAR sensors and cameras provide pathfinding accuracy.

These requirements informed the overarching mission design and the various design drivers, including overall propellant mass, power, bus layout, thermal controls, structural analysis, and materials selection. Indicative of the shared nature between all subsystems, one decision directly affected all other subsystems as seen in how propellant choice affected overall launch mass.

Trade analyses identified Nitrogen Tetroxide and Monomethylhydrazine as the ideal propellants due to their storable nature and longer flight heritage. This fuel selection directly affected our engine selection, the Aestus RS-72 engine, which was selected for its excellence and balance of thrust, specific impulse, and overall size. The Aestus RS-72 is a regeneratively cooled turbopump liquid engine developed by Rocketdyne (now Aerojet Rocketdyne) based on the Aestus rockets utilized by the Ariane 5 upper-stage family. The RS-72 has a remarkable 55.4 kN thrust capacity with 340 seconds of specific impulse [3]. Using 3 of these rocket engines provides the MAV with a thrust-to-weight ratio of 2 at Mars liftoff and an overall thrust of 130 kN. All 3 engines are throttleable and capable of sequence switching which is important to ensure the crew does not experience inhospitable g forces during launch. They are also gimballed at the MAV’s base to allow for small orbital maneuvers and thrust vectoring during ascent. Additionally, by selectively using a single engine during the coast and orbit transfer phase, the MAV is more capable of precisely timed maneuvers with an added benefit of engine redundancy during this phase.

To aid in the more precise maneuvers, especially during docking, Mu3 has selected the Moog Monarc-22-6 thrusters to provide attitude control [4]. These thrusters have a 22 N thrust capability with an ISP of 230 seconds and utilize hydrazine as fuel. 12 of these monopropellant rocket thrusters will provide pitch, roll, and yaw capabilities. Mu3, to simplify the propellant system, will contract with Moog to develop an MMH-based version of these thrusters to use the same propellant as our RS-72 engines. As with the RS-72, helium will be used as pressurant.

The propellant will be stored within titanium alloy Ti-13V-11Cr-3Al tanks with steel bracers for added rigidity. Analysis shows that fully loaded with propellant, the maximum displacement is 1mm while undergoing launch loads. Minimal displacement under the worst-case scenario adds confidence to this design. Internal thermal insulation and heating elements prevent the fuel from freezing or evaporating over design limits. Micrometeorite protection is provided by layered Whipple shields [2].

Due to this being a crew crewed mission, a robust life support system was a major consideration and design driver. The primary subsystems for life support include crew water, food, cargo, atmospheric regulation, and thermal controls. Thus, the MAV must be on standby to support life whilst awaiting crew arrival and support the crew while in orbit and while boarding.

Accounting for the weights of all subsystems including propellant, propulsion, life support, and attitude control, the overall maximum launch mass was calculated to be 22,556 kg wet mass. Therefore, subtracting the propellant mass, the overall maximum dry mass was found to be at an upper limit of 5,108 kg.

The MAVERICK program paves the way for further advancements and discoveries in space travel, pushing the boundaries of what humanity can achieve in our quest to explore the cosmos. It represents a culmination of years of research, engineering, and collaboration, and it holds the promise of safely bringing astronauts back from Mars, marking a remarkable achievement in human space exploration.

3.0 Introduction

3.1 Mission Overview and Scope

After the 2020s manned missions to the moon, humanity will set its sights on the new frontier of a crewed Mars mission. The 2023 AIAA Design competition features a Dual Lander Mars Ascent Vehicle architecture to accomplish such a goal. The RFP stipulates that two landers shall depart Earth no later than 2037 and have the capability to each land twenty-five metric tons to the surface of Mars. One of the landers will carry a MAV, while the other will transport fuel, a rover, or any other components required for an autonomous fuel transfer system. The autonomous fuel transfer system must complete refueling before the astronauts land on Mars. The scope of our mission starts from EDL and continues until the MAV undocks from the DST. However, human landing and their perspective ground operations are outside the scope of our design. Due to the scientific opportunities of a crewed mission, especially with the potential for sample collection and return, the RFP states that the design will also have the capability to return 50kg of Martian samples. Also, the design of the landers themselves is out of our scope, which will be discussed in a later section. Consequently, trajectory analysis and the journey leaving Earth to rendezvous with Mars is also not within our scope. As such, our design will only support two crew members from transit from the surface of Mars to the DST. The MAV will dock with the DST at a 5-sol parking orbit. As requested by the RFP, an FSPU will also be carried aboard one of the landers and will be used throughout the duration of the mission [1].

4.0 Systems Engineering

4.1 Design Approach

First, the design process started with a close-reading of the AIAA RFP where mission-level requirements and initial design concepts were discussed. A period of extensive research followed, mostly focused on past missions or applicable technologies of the RFP. A crewed Mars mission had not been designed yet, as such, the Apollo missions of the ‘60s and ‘80s, the ISS missions, the new Orion mission, and the planned lunar missions were all used as design references. The Apollo missions were viable for the ascent portion of mission, as the Lunar Ascent Module had extensive documentation. However, the Mars Sample Return mission was also useful for expected Mars ascent conditions.

After the preliminary research period, derived requirements were then written. Specifically, the derived Life Support requirements were based on NASA standards as well as our architecture type, such as a transport vehicle instead of a habitat vehicle. NASA standards were specifically impactful in MAV’s derived requirements, as NASA standards also influence the structural design of a crewed module.

Once derived requirements were documented, the analysis and design portion began. Firstly, the seven main subsystems of spacecraft were identified: attitude control, command and data, payload, power, propulsion, structures, and thermal. Each subsystem was researched, and potential COTs were identified. From derived requirements, FOMs were quantified. These FOMs were used to perform trade studies, ensuring chosen COTs components were the most advantageous for our design. For example, a trade study for the main engine of the MAV is shown in **Appendix B-11.1.**

After COTS were selected, the overarching design and interfaces were considered. Interface requirements, such as those between the landers and the design architectures, were also accounted for. Thorough analysis and simulations were run to size components, such as solar panels. They were also run to ensure that the overarching design met requirements.

4.2 Mission and Derived Requirements

The preceding sections provide a broad outline of the architecture and the scope of our mission, but this section will delve into the specific design requirements outlined in the RFP and our own derived requirements. The following requirements presented in **Table 4.2-1** were directly provided by the RFP. Derived requirements for both the rover and MAV architectures will be discussed later in this section. It is important to highlight that the requirement numbers adhere to the NASA WBS numbering system. A comprehensive overview of the WBS for the architectures can be found in **Appendix A**.

Table 4.2-1 Mission Level Requirements

Req. #	Description
0.01	The cost for the vehicle shall be less than $4 Billion US Dollars (in FY22).
0.02	Both landers shall arrive at Mars at no later than July of 2038.
0.03	MAV shall be ready to transport crew by or before July 1, 2040.
0.04	One of the landers shall carry a 10kW Fission Surface Power unit with a control mass of 5 metric tons.
0.05	MAV shall return 50kg of Mars samples.
0.06	Each lander shall fit within the allocated launch vehicle payload space of 8.4 m diameter.
0.07	Each lander shall have a landed payload capacity of 25 metric tons.
0.08	The MAV shall transport 2 crew members from ascent to 5-sol orbit.
0.09	An autonomous robotic system shall be used for propellant transfer.

The requirements presented below in **Table 4.2-2** are derived requirements either relating to the SPDR architecture, or both architectures. Most of the requirements can be traced from the given requirements. For example, due to a given requirement of landing on Mars in 2038, Req. #6.1.02 stipulates a minimum TRL of 6. Even though the journey from Earth to Mars is outside the scope of our design, the launch vehicle and its associated loads are considered throughout the design. For instance, both Req. #5.1.01 and Req. #5.2.4.04 deal with the NASA SLS launch interfaces. For our calculations, the launch conditions on Earth were assumed to be the worst case. Requirements featured in this table for both architectures will not be repeated in the following MAV's derived requirements table.

Table 4.2-2 Common Derived Requirements

Req. #	Req. Description
4.1.1	The Propellant must be storage stable for a minimum of 2 years (+/- 3 months)
4.1.1.01	The refuel rover shall transfer 10,000 (+/- 3,000) kg of propellant to MAV
4.1.1.02	The refuel rover shall be able to travel at least 1 km without recharging.
6.1.02	Both the MAV and SPDR shall use systems of a TRL 6 or higher
5.1.01	The combined height of the SPDR or MAV and selected NASA landers shall not exceed 19 meters
5.2.2.02	Both the MAV and SPDR telecoms shall have the capability to communicate with the MRN
5.2.2.03	The MAV and SPDR shall have the capability to communicate directly with Earth
5.2.2.05	The MAV and SPDR telecom system shall have a data rate of at least 2 megabits/sec
5.2.3.01	The SPDR power system shall power mission critical instruments during Martian dust storms
5.2.4.01	The propellant tanks shall have an MS of 2 or higher
5.2.4.04	Both the MAV and SPDR shall survive the launch load of 4.1g from Earth
5.5.01	The SPDR shall keep the NTO at a stable temperature (-5 to 15 C) for transfer

Table 4.2-3 is a list of relevant MAV requirements to the presented proposal. Unlike the previous table, these requirements are for the MAV architecture. The MAV must sustain launch loads from Earth, Mars surface environments, and ascent and orbital environments. The MAV also has the added complexity and challenge of supporting two crew members for the duration of transportation. Human mission and subsequent life support requirements will be discussed later in **Section 6.8**. Requirements presented in this section are related to the design of the MAV. For conciseness, requirements from multiple subsystems are presented in the same table. The main drivers in the design and the requirements were mass. Note that Req. # 4.1.2 sets a hard constraint on the MAV. This was due to the combination of the landed payload mass, as well as the capability to launch with the mass of propellant. Further design considerations and drivers of the MAV will be discussed in later sections of analysis.

Table 4.2-3 MAV Derived Requirements

Req. #	Req. Description
4.1.2	The MAV mass shall not exceed 7,000 kg
5.2.1.01	The ACS shall have an ISP over 200 secs
5.2.1.03	The ACS systems shall be 3-axis stabilized
5.2.2.01	The MAV shall have two independent flight computers
5.2.3.02	The MAV power system shall power ECLSS critical instruments during eclipse periods
5.2.3.03	The ECLSS power system shall have redundancy and circuit protection
5.2.4.02	The MAV cabin shall have a MS of 2 or higher when pressurized
5.2.4.05	The MAV shall survive a maximum dynamic pressure of 540 Pa during ascent
5.4.01	The ISP of the main engine propellant shall be greater than 250 secs
5.4.02	The height of the engine shall be less than 4 meters tall
5.4.06	The propulsion system shall throttle engine thrust during ascent
5.4.07	Engine shall be able to reignite

4.3 NASA Vehicle Selections

As stated in the introduction, the design of the launch from Earth, transit to Mars, and EDL at Mars is not within the scope of this project. However, several assumptions were made regarding the potential vehicles provided for this task in order to have enough information to make design decisions and to have a reference lander for interface definition.

For launch from Earth, the only requirement provided in the RFP is that the payload shall be limited to a diameter of 8.4m. This is compatible with the NASA SLS Block 1B or Block 2 fairing configuration.

The interface to the landing vehicle is a more significant driver in the design of our architecture. Based on the requirements provided by the RFP, the primary constraint is that the maximum mass that can be delivered to the Martian cannot exceed 25 metric tons [1]. However, given the difficulty in baselining a design configuration that is completely agnostic to interfaces, a reference lander was chosen to aid in developing both the concept of operations and the initial design.

For the landers, we chose a concept based on NASA's designs for a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) as shown in **Figure 4.3-1** [5] . This technology is currently TRL 7 and has been demonstrated by NASA's LOFTID mission [6].This vehicle fits within the 8.4m constraint imposed on the launch vehicle but inflates to 16m when fully deployed to provide maximum aerodynamic braking during EDL. After aerothermal heating and deceleration, the HIAD lander uses supersonic retro-propulsion (SSRP) to slow to a soft landing on the surface. After landing, the heatshield body is deflated and can be retracted to aid in access to the payload. The payload is mounted on top of the flat lander platform, providing maximum flexibility in configuration management. The top deck of the lander is 4.3m above ground level; this drives the required egress, access, and reach considerations for our architecture.

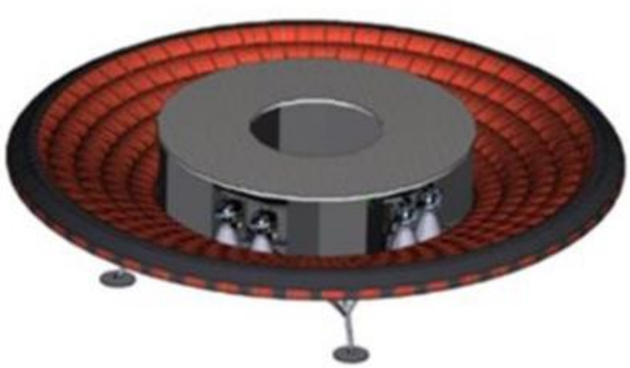


Figure 4.3-1 Baseline HIAD Concept

4.4 Landing Sites

Having already discussed the selection and rationale behind the HIAD landers, our subsequent design consideration centered around identifying potential landing sites and the corresponding operational locations for our rover. As previously mentioned, the SPDR will require approximately thirteen trips to refuel the MAV, which will take place over the course of a year. Further details of the ground operations wheel and configuration of the rover will be discussed in **Section 5.1** and **5.3** respectively. Although the RFP does not explicitly address landing sites, the unique terrain and environment on Mars pose a substantial design constraint, particularly for a rover tasked with covering vast distances. This constraint has a significant impact on the design considerations, particularly within the SPDR architecture. The selection of landing sites was primarily driven by scientific potential, historical significance, and considerations of previous mission engineering constraints. Valuable insights from past rover missions on Mars played a vital role in informing our decision-making process. Our design incorporates the capability to land at three potential sites: Holden Crater, Melas Chasma, and Meridiani Planum. Our design has the potential of operating at all three landing sites, however, due to the well-documented environment and scientific findings from the previous mission Opportunity mission, Meridiani Planum would be the primary landing selection. The landing sites and their relative location to each other is shown below in **Figure 4.4-1** [7]**.**

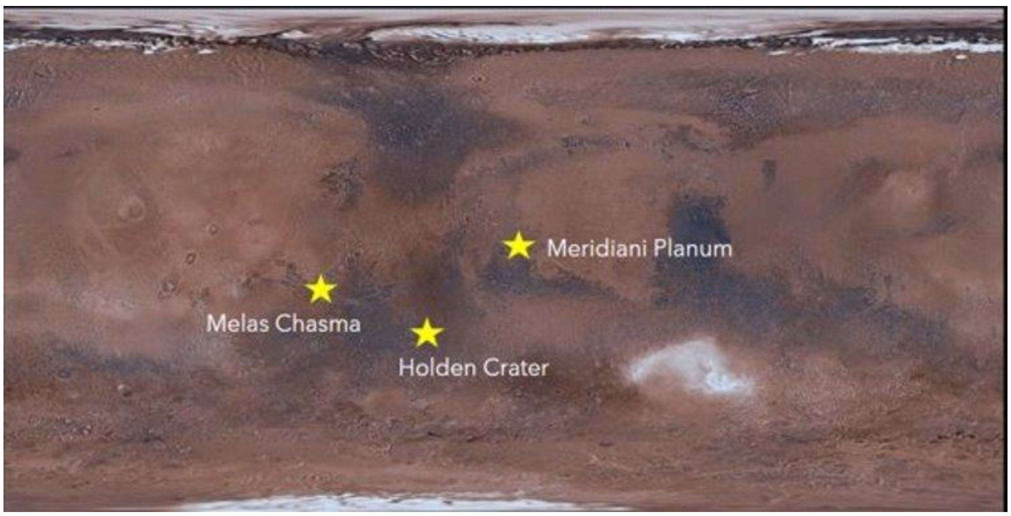


Figure 4.4-1 Potential Landing Sites on Mars

For engineering constraints, Mu3 selected landing sites based on elevation, latitude, surface slopes, and rock population [7]. Landing at decreased latitudes has the advantage of having less CO_2 frost, which can degrade camera quality and wheel operations. The decision to launch at this latitude range was due to several reasons including the climate and the higher average of solar irradiance which will enable more efficient power generation. Moreover, launching from latitudes around +/- 45 degrees takes advantage of the higher rotational velocity near the equator, optimizing trajectory planning, navigation, and control, resulting in fuel savings and improved mission performance. Rock population was another significant factor as the probability of encountering a rock .55 m tall in an area of 4 m^2 had to be less than 0.5% [5].

4.5 Concept of Operations

As stated in the RFP, the mission begins at Mars entry since we were instructed not to consider transit to Mars [1]. We intend to launch the MAV from Earth by June 26, 2035 first to ensure its safe transit and landing on Mars before then launching the RFL and SPDR from Earth about 5 months later. The RFL will arrive at Mars around June 26, 2037. To prevent burning up in entry, the HIAD will deploy from the lander. The inflatable heat shield allows the design to have the largest footprint possible dedicated to the MAV and Refuel System design while still allowing for adequate thermal protection on entry. The HIAD also allows for greater aerodynamic deceleration than without a large solid heat shield. The lander's final descent is slowed with retro propulsion. Since the lander itself is treated as a black box as per the mission scope, the exact ΔV for entry is unknown. Both vehicles require a soft landing for successful mission operations. The entire descent process will take both vehicles about 8 minutes between entry and touchdown. Once landed, the HIAD will deflate and retract while both vehicles will perform systems check to make sure all systems are still nominal [5]. The last step of the landing and mission set-up portion of the Con-Ops is the system deployment. This includes the SPDR release from the lander base via a payload fairing on the rover belly, the rover solar array deployment, the ramp or other rover ingress/ egress system deployment, and the power unit radiator deployment. The Fission Surface Power unit is also considered to be a black box but other current fission power units often have radiators so this is the time it would be deployed. Total lander deployments should take approximately 5 hours to complete. This leg of the mission can be seen in **Figure 4.5-1**

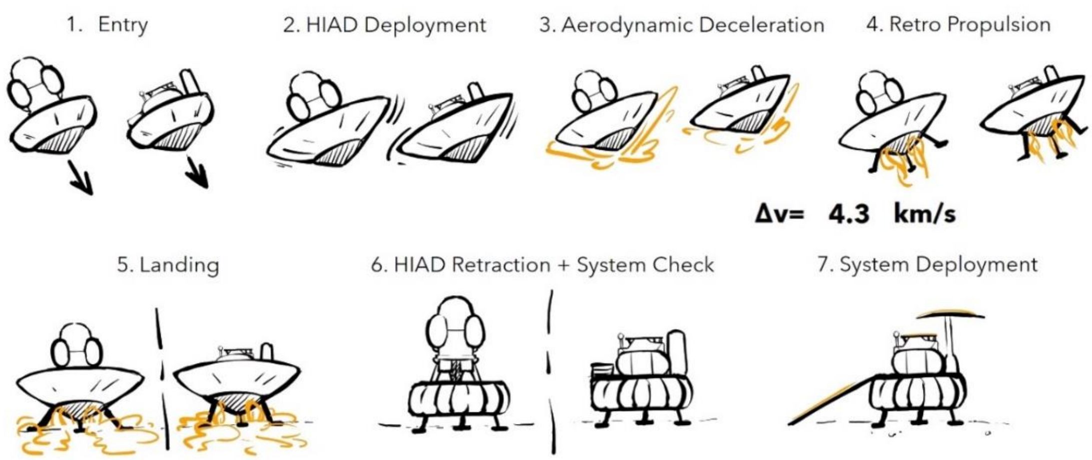


Figure 4.5-1 Landing Ops

Once both landers are on the surface of Mars and all systems are in their mission configuration, the ground operations can begin. The rover first takes an hour to connect to the RFL through the rover refuel arm. The docking interface consists of a refuel port for oxidizer transfer and a power port for rover charging. The refuel port will be an Orbit Fab RAFTI [8].which is discussed in detail in **Section 5.4**. After docking, the RFL will take about 4 hours to pump 1000kg of NTO onto the transfer rover and top off the batteries before the rover departs. Departing involves the rover disconnecting from the refuel interface and carefully driving down the ramp. The SPDR will then make its way to the MAV. The first trip it takes will also be used for mapping so the following trips can be faster. Each trip between landers can take between 3 and 15 days, not including stalls for dust storms. Once at the MAV, it will perform another hour of docking, pull the oxidizer from the SPDR through the refuel arm to the MAV refuel leg, and into the oxidizer tanks. Again, the fuel transfer time will take about 4 hours. After refueling, the MAV, the SPDR will travel back to the RFL and start the process over again. These steps must take place 13 times to fully load the MAV with oxidizer required for launch. The SPDR returning to the RFL is technically only repeated 12 times as the rover does not need to make a final trip to the RFL and a third person camera point of view closer to the MAV could provide beneficial data. To end the refueling process, the rover and RFL will perform their end-of-mission procedures. The MAV will begin prepping for humans by powering on the life support to make sure everything is working properly. Humans will then be given the go-ahead to land where they will perform their mission separately. With no human consumption, these resources will be kept for a few weeks until the crew arrives. The ground-ops can be seen in **Figure 4.5-2.**

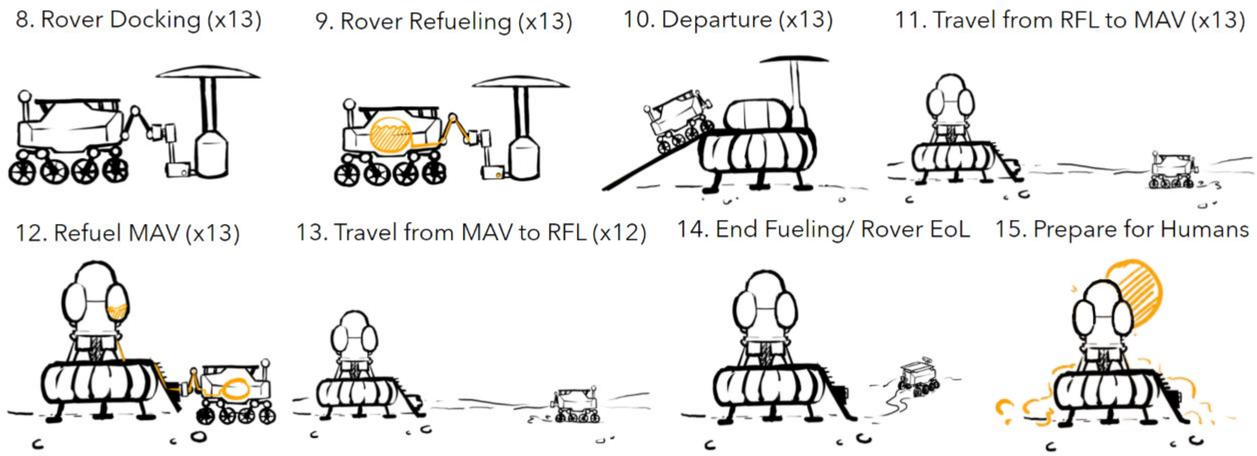


Figure 4.5-2 Ground Ops

Once astronauts arrive on Mars, they will first signal to the MAV's onboard computer their arrival. This will cause the MAV to begin preparing for launch. As discussed in detail in **Section 6.3**, the ladder, which is hinged at the bottom, will hydraulically lower from the HIAD to the ground. If the hydraulic system on the ladder fails, the design allows astronauts to manually lower the ladder. From here astronauts will carry equipment to the HIAD base and then raise the ladder to the MAV body. The ladder's top will latch onto awaiting mates on the MAV body beneath the crew ingress hatch. From here astronauts will signal to the MAV to open its hatch which may also be opened manually if necessary. Astronauts will then load materials onboard including the hermetically sealed Martian samples. Then, after confirming nominal systems and communications with Earth and the DST, astronauts will prepare for launch. They will verify propellant levels and unlatch the MAV from the HIAD. After final system checks, they will detach the ladder from the MAV, close the ingress hatch, and then commence life support operations which include pressurization of the cabin with breathable air.

When the MAV launches, no later than July 1, 2040, it will leave the MLV base, the refuel lander, and the rover on the surface. Once the propellants are depleted in the first two tanks, they will be dropped to decrease flight mass. The launch sequence is estimated to take about 30 minutes. The MAV will then enter Low Mars Orbit. The LMO for this mission is an elliptical orbit with a 100 km altitude periapsis and 250 km apoapsis [9]. The required ΔV from launch to apoapsis is 3.3 km/s [10]. Next the MAV will transfer into the 5-Sol parking orbit. The 5-Sol orbit for this mission is a highly elliptical orbit with

100km altitude periapsis and 119,450 km altitude apoapsis [9]. The required ΔV from LMO to 5-Sol orbit at the 100 km altitude is about 1.4 km/s [10]. Once all the large transfer maneuvers are complete, the other pair of external tanks will be dropped, and the final maneuvers will be completed with the internal attitude control tanks and the attitude control system. The rendezvous with the deep space transit vehicle is performed further in the 5-sol orbit, meaning the total time of flight for the MAV is estimated to be about 2.5 days before docking. Docking can take up to a few hours and the MAV may stay attached to the DST however long is needed after docking for crew and hardware transfer. Finally, the MAV will perform its end-of-mission maneuver. This is discussed further in **Section 7.3**, but once transfer is complete, the MAV will orbit Mars naturally for approximately 20 years before it deorbits onto Mars. The flight-ops can be seen in **Figure 4.5-3**.

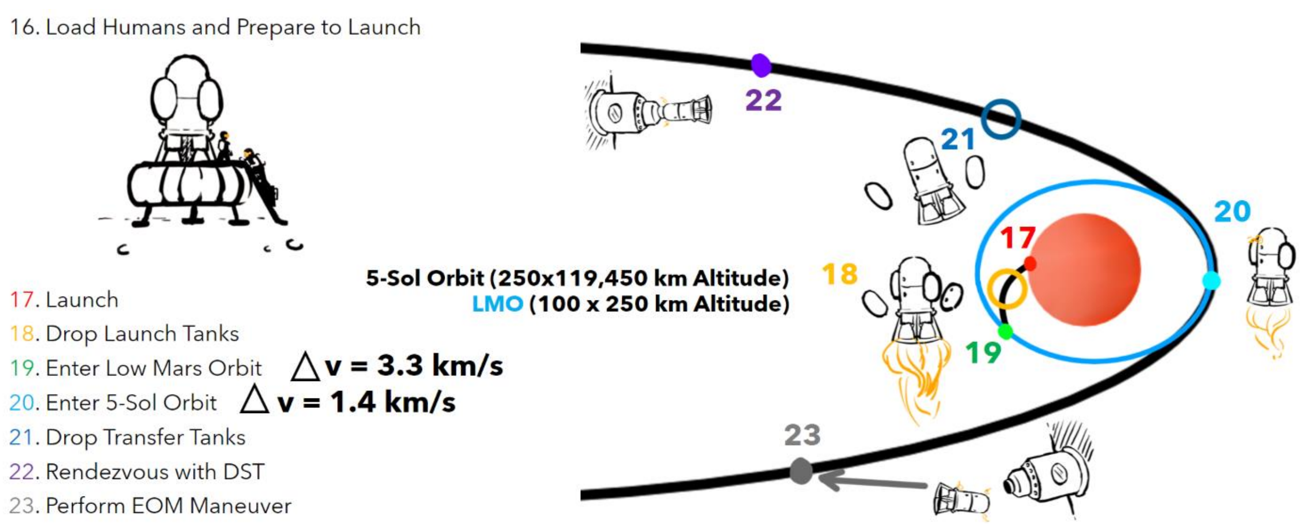


Figure 4.5-3 Flight Ops

5.0 Mars Ground Operations

The ground environment and climate of Mars present formidable challenges for the MAVERICK mission, necessitating careful consideration and robust design. The Martian soil is characterized by its unique properties, including fine-grained particles, high iron oxide content, and a low water content. The rocky terrain further complicates traversing the Martian surface, with potential obstacles and uneven terrain requiring the rover to have excellent mobility and terrain-agnostic capabilities. In addition to the physical challenges, the planet is prone to intense dust storms that can engulf its entire surface, severely impacting visibility and posing risks to the SPDR rover's sensitive instruments and solar panels.

The temperature range on Mars is extreme, with average temperatures ranging from 15 degrees Celsius to -65 degrees Celsius [11].These temperature variations have significant implications for the rover's functionality and performance. Thermal management becomes critical to protect sensitive components and maintain operational efficiency in the face of such temperature extremes. Furthermore, the rover must store nitrogen tetroxide, requiring precise temperature control to keep it below its boiling point of 21.15 C during the mission [12]. Additionally, the pressure on the Mars surface, which is around 651.8 Pa needs to be considered when designing the rover's structure and sealing mechanisms to maintain atmospheric integrity and protect sensitive equipment from the harsh external conditions [13]. Proper insulation and thermal regulation systems are essential to prevent temperature fluctuations that could jeopardize the integrity and functionality of the stored materials.

Considering the harsh Martian environment, terrain, and dust storms, designing a rover capable of effective operation requires deep integration between all the subsystems. Each aspect, from mobility and thermal management to power systems and communication infrastructure, must be integrated to ensure the rover's ability to endure the challenges and fulfill its scientific objectives on the Martian surface.

5.1 Design Overview

The refuel vehicles include the Refuel Lander and the SPDR. This section will be broken into two sub sections discussing the two. The primary purpose of the refuel lander is to store the rover and oxidizer and act as a gas station of sorts throughout the duration of ground operations. The purpose of the SPDR is to act as an autonomous propellant tankard on Mars that runs the NTO from the RFL gas station to the MAV. The reasoning for only transferring one propellant was to reduce the complexity that comes with transferring both the fuel and oxidizer. The reasoning for transferring the NTO specifically was because it was the more massive of the two propellants. This allows for the MAV to land fully loaded with MMH and have more design headroom while still fitting in the 25 metric ton payload requirement of RFP.

The Lander:

The basic dimensions of the refuel lander can be seen in **Figure 5.1-1**. The diameter of the HIAD base is 7.5 meters which is small enough to fit within the 8.4m-diameter payload fairing.

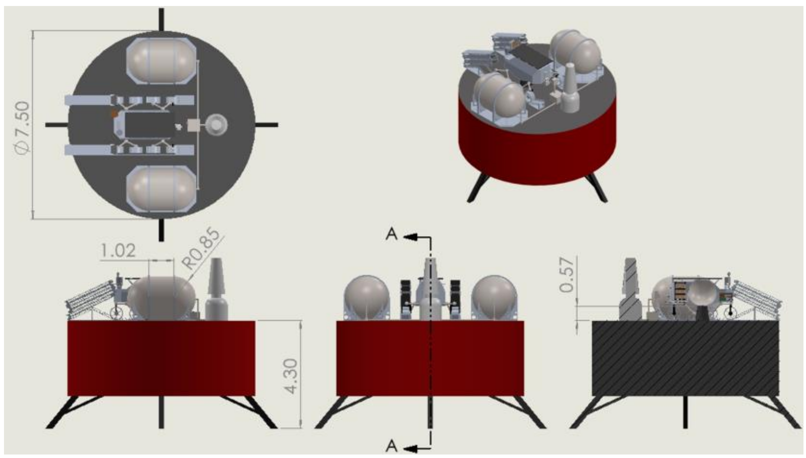


Figure 5.1-1 RFL Dimensions (Meters)

A more detailed view of the lander's stowed and mission configurations with callouts can be seen in **Figure 5.1-2.**

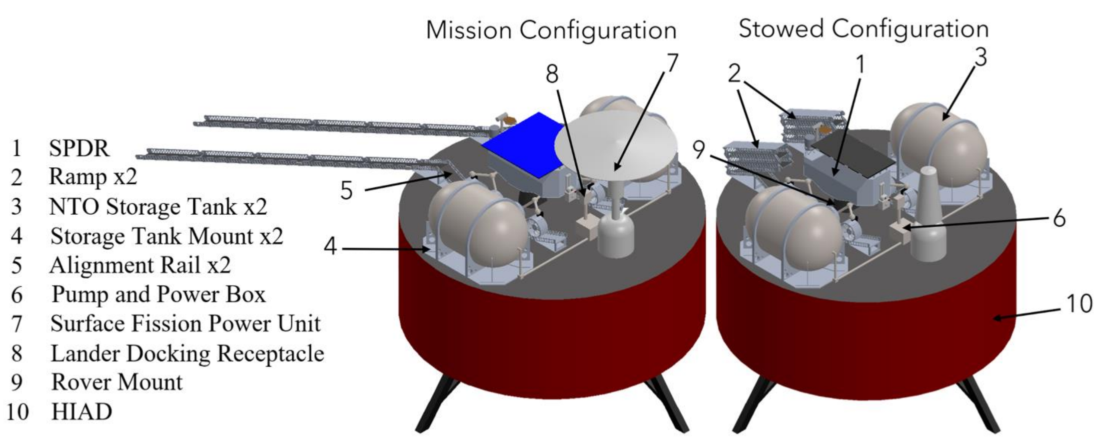


Figure 5.1-2 RFL Stowed and Mission Views

The ramp allows for the rover to climb atop and depart the RFL as needed. This particular ramp design is intended to demonstrate a feasible option for the rover to enter and depart a tall lander. Future HIAD-compatible landers may be thinner or have crouching capabilities which would reduce the length of the ramp. The refuel tanks onboard the RFL are identical to those to be seen later attached to the MAV to save on design and manufacturing costs. The tank mounts are built to withstand launch conditions (shown in **Section 5.2**) and provide space for insulation and heating around the tanks. Alignment rails are used to help guide the rover on the elevated platform and to prevent slipping in windy conditions. The pump and power box is what moves the oxidizer from the storage tanks to the rover, as well as contain the power regulation for the payload from the FSPU. The FSPU is a novel design with very little documentation. For design purposes, Mu3 assumed similar measurements to KRUSTY, which is a recent fission power unit design [14, 15, 16]. The Docking receptacle is how the rover and lander interfaces. It uses a RAFTI refueling interface for oxidizer transfer and also has a power port for rover charging [8]. The rover mount is how the SPDR is locked to the lander during transport. The rover crouches when in transit and will essentially spring upwards when it is released during system deployment. And finally, the HIAD is the heat shield of the lander. In **Figure 5.1-1** and **Figure 5.1-2** the HIAD is retracted to better visualize the size of the lander itself and the deployment of the ramp.

The lander payload is relatively balanced as seen in **Table 5.1-1** and **Figure 5.1-3**, though the center of mass is slightly off in the X and Y direction. This can be mitigated by adding ballast since we still have 4000kg of mass overhead to be within the payload requirement of the RFP. Another point to note is that the values listed in **Table 3.2-2** are for the payload only and do not include the mass of the lander itself as per mission scope.

Table 5.1-1 RFL Payload Mass Properties

Property	Stowed (Full Refuel Tanks, Dry SPDR)
Mass (kg)	20900
Center of Mass (m)	(0.44, 0.23, 0.00)
Ixx (kg×m²)	672300
Iyy (kg×m²)	1068100
Izz (kg×m²)	614100

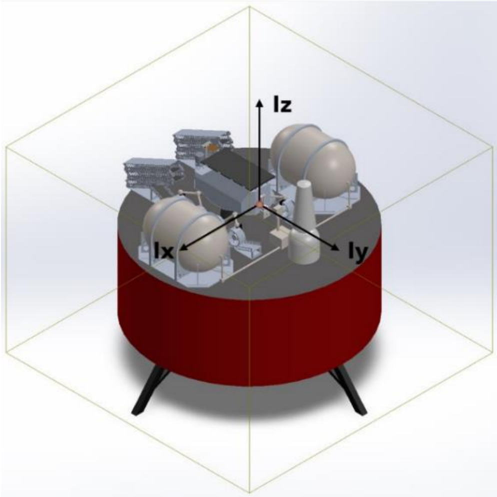


Figure 5.1-3 Payload Inertia Visualization

The SPDR:

The primary dimensions of the SPDR can be seen in **Figure 5.1-4**. The maximum rover dimensions are 2.9 meters in length, 2.2 meters in width, and 2.0 meters in height, leaving plenty of space within the payload fairing for the rest of the refuel system. A deployable solar array of approximately 4 m² would be enough to power the rover and keep the batteries charged during the day with the charging cycle discussed in **Section 5.4**. The array is initially stowed to protect the array surface and prevent excess stress on the arrays during launch and landing. The tank is sized to carry 1000 kg of NTO with a 10% ullage. The stowed and mission configurations of the SPDR can be seen in **Figure 5.1-5**.

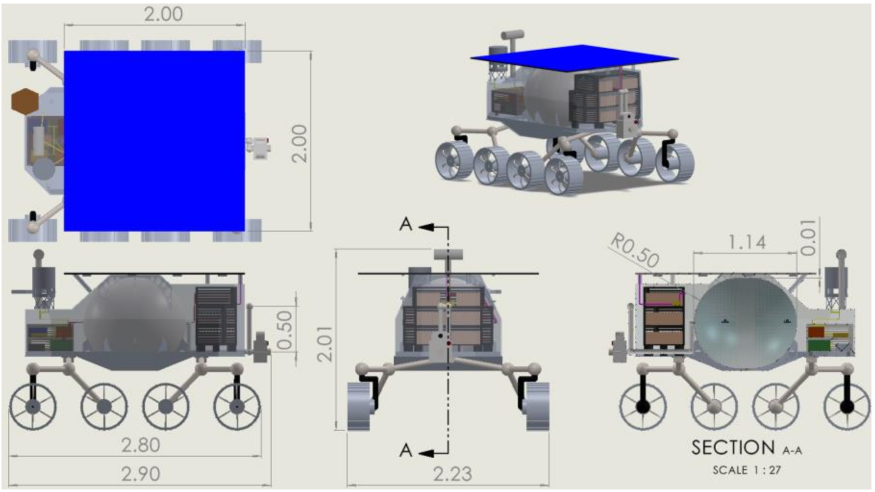
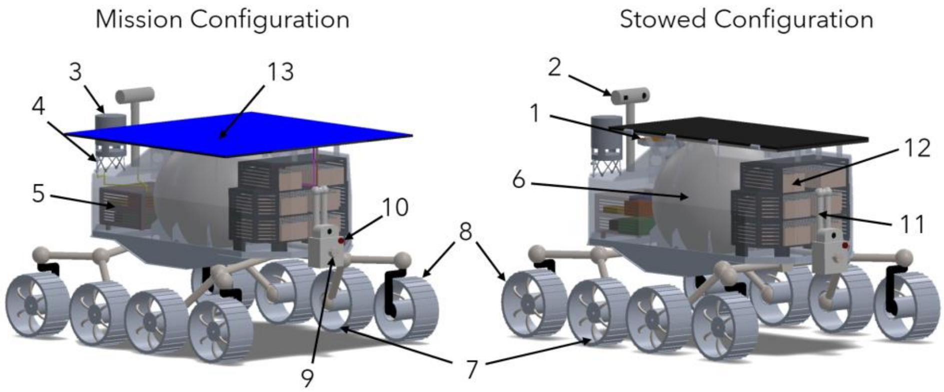


Figure 5.1-4 SPDR Dimensions (Meters)



1 High Gain Antenna
2 Mast
3 UHF Antenna
4 Low Gain Antenna
5 Electronics Box:
  Telecom Hardware
  C&DH
6 Refuel Tank
7 Drive Wheels x4
8 Drive and Steerable Wheels x4
9 Refueling Docking Port
10 Charging Port
11 Arm
12 Battery Rack
13 Solar Array

Figure 5.1-5 SPDR Stowed and Mission Views

The SPDR must be able to make navigational decisions and act independently, but also communicate with Earth to send and receive updates, including emergency software changes. The three antennas onboard the rover allow for two-way communication which will be discussed in more depth in **Section 5.6**. The mast allows the rover a larger field-of-view than strictly body mounted cameras to help the rover make more informed decisions about its pathfinding. The electronics box contains the telecommunication hardware and Command and Data Handling hardware, both of which will be discussed in their own sections later. The refuel tank is a titanium (Ti-13V-11Cr-3Al) fuel tank used to transfer NTO from the Refuel Lander to the MAV. The middle wheels are drive-only wheels used to help propel the rover. The outer steerable wheels allow the rover to turn and maneuver along its journey, as well as propel the rover forward with drive capabilities. The refueling docking port locks into the RAFTI receptacle on each of the landers to transfer the NTO and the power charging port lines up with the charging receptacle to charge the rover once docked. The arm gives the rover about one meter of reach in case the ground is uneven to ensure successful docking. The battery rack houses the battery array and power regulator before the power is sent to the electronics box and the Solar array is the primary source of rover power when it is traveling.

Figure 5.1-6 and **Table 5.1-2** show the mass and inertial properties of the SPDR. Focusing primarily on the rover masses, the dry mass of the rover is about 1,390 kg and the wet mass of the rover is about 2,390 kg. Even the empty mass of the SPDR is more massive than any other rover on Mars up to this point, making this unique mission an even greater challenge.

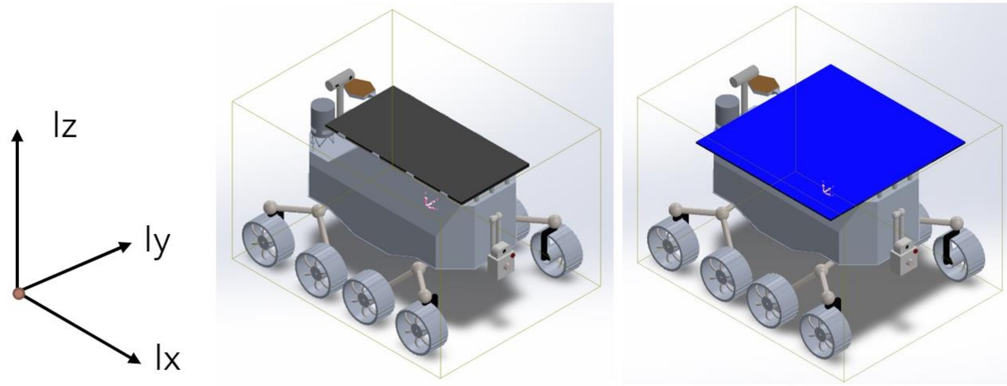


Figure 5.1-6 SPDR Inertia Visualization

Table 5.1-2 SPDR Mass Properties

Property	Stowed (Dry)	Mission (Wet)
Mass (kg)	1390	2390
Center of Mass (m)	(0.21, 0.31, 0.00)	(1.91, 2.23, 1.49)
Ixx (kg×m²)	720	15900
Iyy (kg×m²)	1170	13600
Izz (kg×m²)	1125	19270

To ensure mission success, the rover carries many onboard sensors to monitor the health of the system and to navigate the Martian terrain. **Figure 5.1-7** shows the field of views of the LiDAR, cameras, and antennas onboard. The LiDAR in red is primarily used for docking and is located near the fuel docking. The cameras are the eyes of the rover. There is a camera above the docking mechanism, under the belly to keep an eye on debris under the rover, and a mast camera primarily used for navigation. The low gain antenna is omnidirectional, the high gain antenna is on a gimble, and the ultra-high frequency antenna is not intended to communicate directly with Earth but rather to a Martian orbit, so its field of view is acceptable.

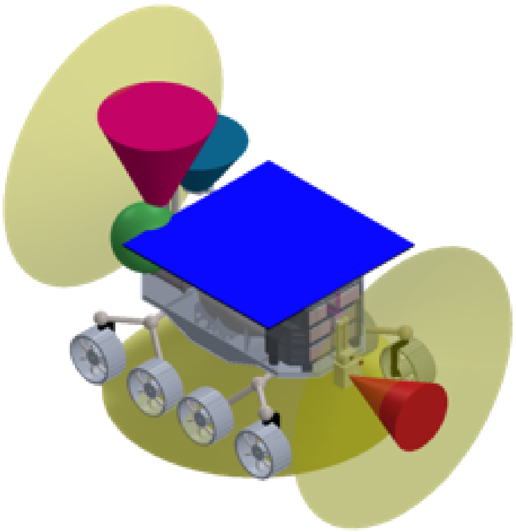


Figure 5.1-7 SPDR Field of View

Other sensors and masses can be seen listed in **Table 5.1-3**. The MEDA sensor array and REMS would be used to monitor external weather conditions to check if it is safe to travel or transfer propellant. The Sun Sensors, IMU, LiDAR, and cameras would be used for navigation to help the rover make its way to and from the landers as well as during the docking procedure. The pressure transducers, temperature sensors, and power sensors would all be used to monitor internal system health, especially that of the propellant and tank.

Table 5.1-3 Rover Sensor List

Instrument Name	Mass	Source
Air Temperature Sensors (MEDA)	6 kg	[14], [15]
Relative Humidity Sensor (MEDA)		
Pressure Sensor (MEDA)		
Infrared Sensor (MEDA)		
Wind Sensors (x2) (MEDA)		
REMS	454 g	[16]
Sun Sensors (x2)	100 g	[17], [18]
Inertial Measuring Unit	1 kg	[19]
LiDAR	12 kg	[19], [20]
Cameras (x3)	425 g	[21]
Pressure Transducer (x2)	-	[22]
Temperature Sensor (x2)	1 g	[23]
Power sensors (x2)	-	[24]
TOTALS	20 kg	-

5.2 Structures

SolidWorks was utilized to design both the system architectures and conduct structural analyses.

RFL:

Figure 5.2-1 shows the stress and displacement of the lander tank assembly loaded with about 6,000 kg of NTO per tank under 4.1g SLS launch conditions and pressurized to 850 kPa [25].

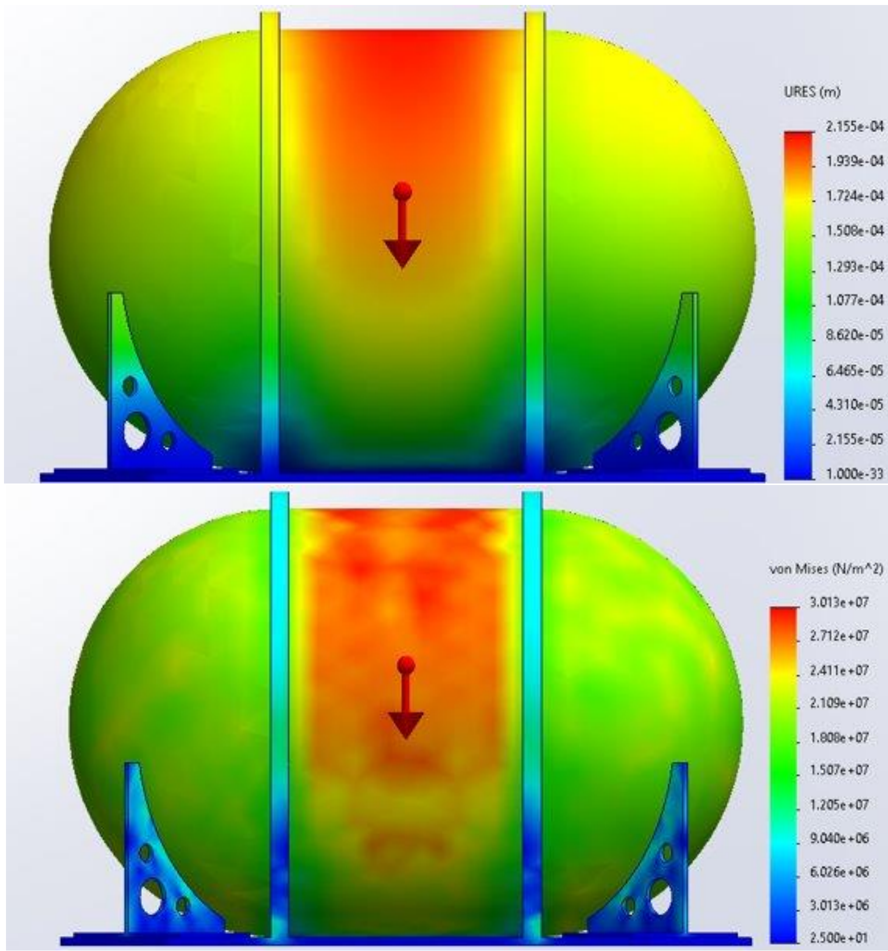


Figure 5.2-1 (a and b) Stress and Displacement of Lander Tanks in Launch Conditions

The worst-case Von Mises stress is 3.013×10^7 N/m² according to the analysis. Being as the yield stress of the materials are a magnitude $\times 10^8$ N/m², the factor of safety is well above two which allows for some wear and tear to occur on Mars over the course of the mission without tank failure. Displacement during launch is less than a millimeter, which is not a cause for concern.

Figure 5.2-2 shows the stress and displacement of the lander ramp in the stowed configuration under the same 4.1g launch conditions.

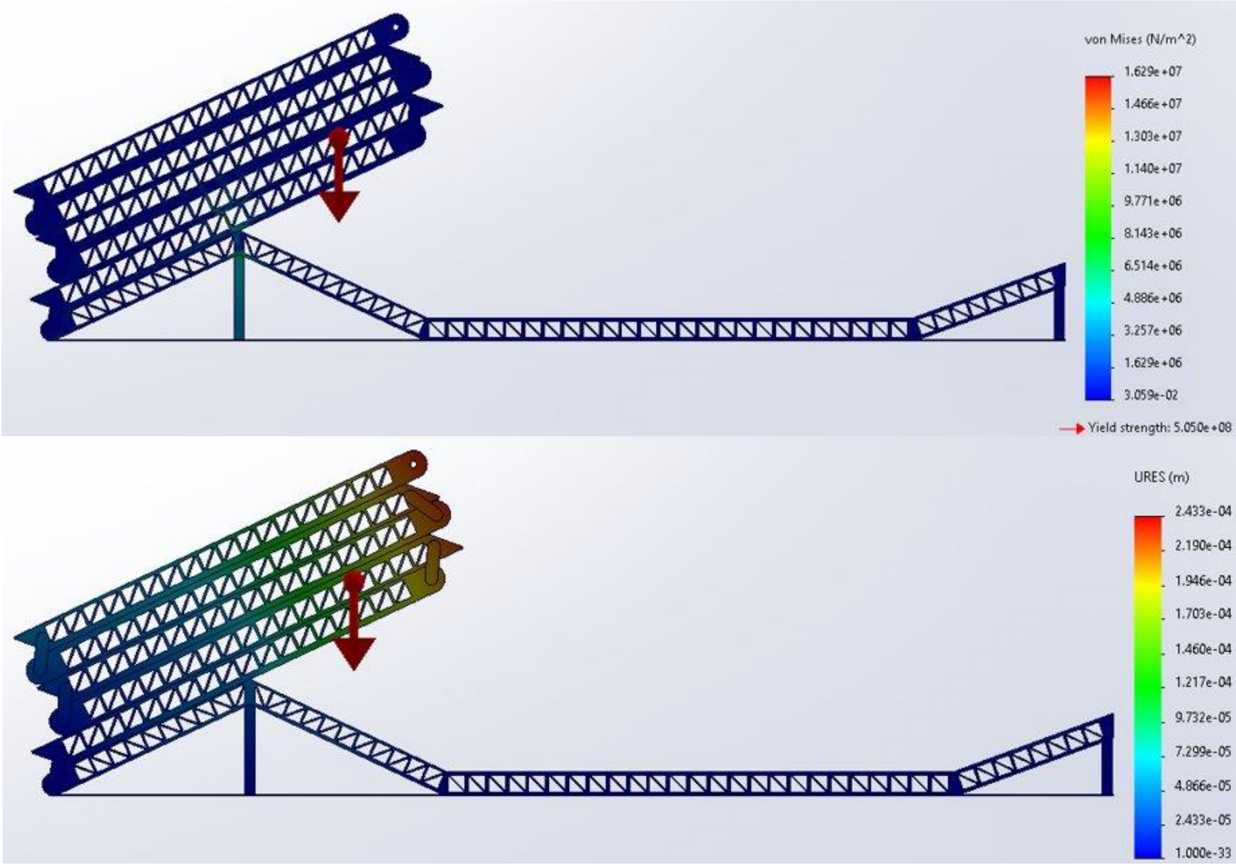


Figure 5.2-2 (a and b) Stress and Displacement of Lander Ramp in Launch Conditions

Once again, the Von Mises stress is a magnitude less than the yield stress of the aluminum 7075-O, allowing for a factor of safety much larger than 2 and a displacement less than 1 millimeter. This ramp represents a worst-case tall lander. The customer could choose a different lander with crouching capabilities or an enclosed lander with a hatch like the COBRA [26]. The analysis is mostly here to show that a long length ramp is feasible. Analysis for the ramp in operation can be found in **Appendix B-11.2.**

SPDR:

Figure 5.2-3 shows the rover empty of NTO and belly supported in launch conditions. Since the payload fairing supports the rover during launch and flight, and to increase the ease of running the simulation, the legs were omitted from this analysis.

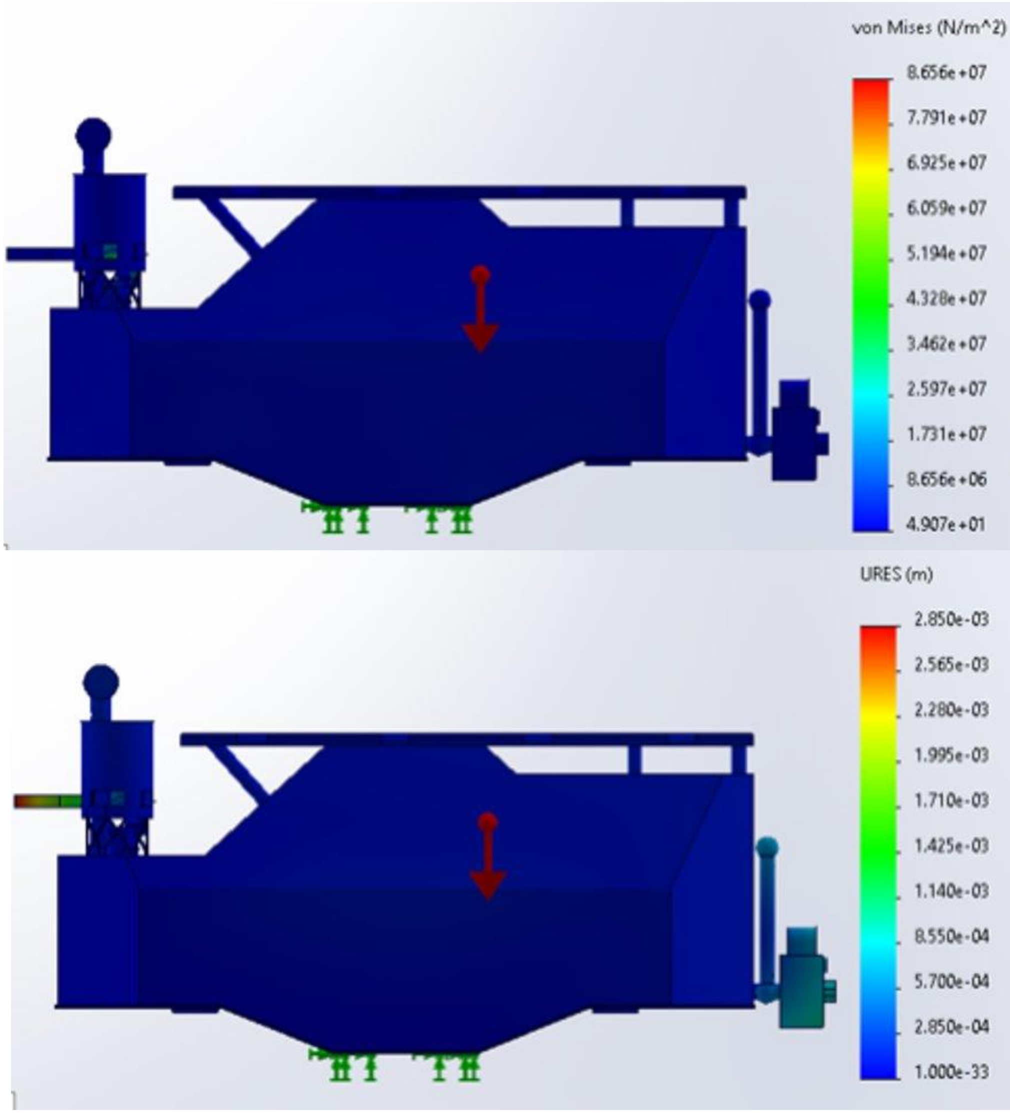


Figure 5.2-3 (a and b) Stress and Displacement of SPDR in Launch Conditions

Under 4.1g, the Von Mises stress magnitude is below $9x10^7$ N/m^2 with a material yield stress above $3x10^8$ N/m^2. The worst-case displacement is less than 3 mm which is found at the high gain antenna. The overall displacement of the SPDR is less than 1 mm.

Figure 5.2-4 shows the rover under operating conditions on Mars with Martian gravity simulated at 3.7 m/s^2 and the tank holding 1,000kg of NTO. The outer shell was hidden to show the interior stresses as the stress and displacement of the outer shell was negligible in comparison.

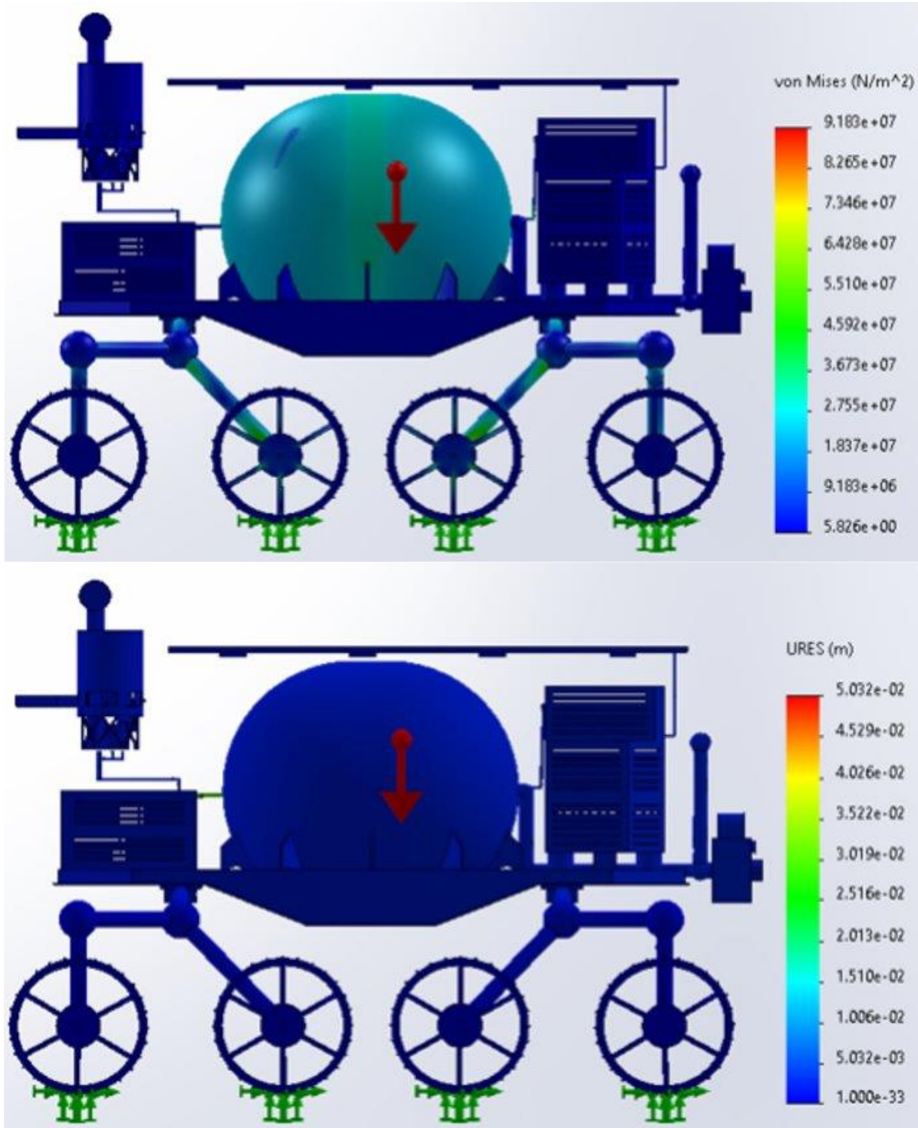


Figure 5.2-4 (a and b) Stress and Displacement of SPDR in Operational Conditions

The Von Misses stress is well within the yield strength operating limits once again and gives the rover a factor of safety well over 2. The 5 cm displacement shown in **Figure 5.2-4b** is in the cabling added to the model primarily for the mass estimate and is not a design concern.

5.3 Propulsion

In this section we will explore the different propulsion systems that were evaluated for the SPDR rover and the chosen architecture. Requirement 4.1.1.02 specifies that the refuel rover must be able to travel at least 1 km without recharging, and the Mu3 team has designed the rover to travel up to 1.1 km without recharging. The current design of the SPDR rover has an unloaded weight of 1,390 kg and a loaded weight of 2390 kg with the Nitrogen Tetroxide oxidizer. Therefore, it is essential for the propulsion system or drivetrain to provide sufficient power to enable the SPDR rover to travel the Martian terrain.

One critical design consideration was whether to use tank treads or wheels. While tank treads offer a larger surface area and increased traction, they were ultimately rejected by Mu3 due to their lower reliability, high complexity, high weight, and lack of space heritage. After extensive analysis and research, Mu3 chose wheels for the SPDR design. Wheels have space heritage, are less complex, lighter, and more maneuverable. Mu3 designed the propulsion system with 8 wheels with a custom suspension design based on the rocker-bogie design found on the Opportunity and Curiosity rovers. Each wheel measures 0.5 m in diameter and consumes about 100W of power with an output of 180.3 N-m of torque. As a result, the SPDR rover only needs 6 wheels to operate but the design includes dual wheel redundancy in the event of a failure.

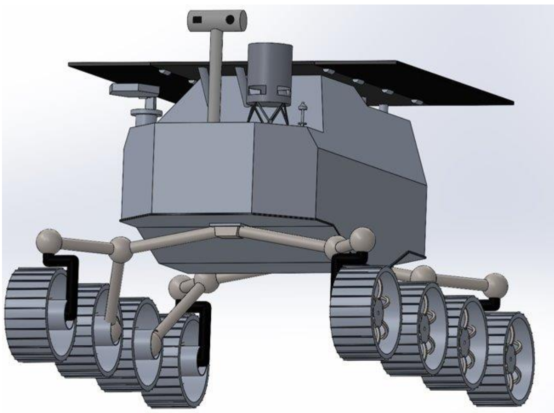


Figure 5.3-1 Drivetrain Assembly

At present, the drivetrain of the SPDR rover has a maximum speed of 47.4 cm/s although it will be driven at a speed similar to the Perseverance rover, which moves at 4.2 m/s. The limited speed is deliberate, as it helps minimize sloshing and allows the rover to navigate obstacles more comfortably. The current plan is for the SPDR rover to move for 10 seconds and then survey its environment for 20 seconds, repeating this cycle until it arrives at its destination. The approach is intended to map the terrain and avoid any obstacles that may be in the rover’s path, ensuring safety of the mission.

The rover's drivetrain will be manufactured at NASA JPL in California. NASA JPL has experience with constructing numerous Mars rovers and a variety of components are shared between existing rovers and the SPDR rover.

5.4 Power

The SPDR rover embarks on an extensive journey carrying invaluable cargo. Along the way, it must cover significant distances while maintaining stable cargo temperatures, facilitating communication with other vehicles, and surveying its surroundings. Consequently, a robust and efficient power system becomes imperative to sustain continuous power supply to its extensive subsystems.

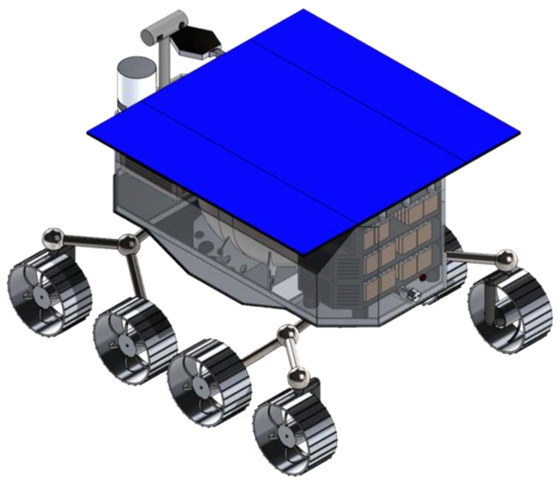


Figure 5.4-1 SPDR Power System (Batteries in Front, Solar Cells on Top)

The team extensively evaluated various power sources, including MMRTG's, batteries, fuel cells, solar cells, and the 10-kW FSP. Their objective was to identify a power solution with high energy density, substantial energy capacity, and minimal weight. After careful consideration, the team determined that batteries integrated with solar cells best fulfill these criteria, making them the chosen power supply for the SPDR rover. The batteries, 60 Ah Space Cell, are sourced from EaglePicher and offer 60% depth of discharge, an energy capacity of 256 W-hr for each cell and weigh about 1.6 kg per each cell. The batteries are configured with 22 parallel strings each with 8 cells in series giving the SPDR rover about 31,777 W-hr of energy. This is 14% more energy than needed for a trip across 1.1 km distance which provides greater redundancy. With an estimated power consumption of 100W per wheel, the SPDR's power system can supply power for an entire trip which will take about 22 hours. 3 days will cover the full travel distance of 1.1 km in 22 hours of sunlight. The rover will unload the NTO oxidizer to the MAV. The power breakdown while driving is shown in **Table 5.4-1**. From this table, the total power needed to travel 1.1 km is 27,480.8 W-hr.

Table 5.4-1 SPDR Rover Power Breakdown While Driving

Fuel Transport/ Driving	**10 seconds**		**Fuel Transport/Surveying**	**20 seconds**	
Thermal Power	117.6	W	Thermal Power	117.6	W
Power	3.2	W	Power	3.2	W
CDS	24.4	W	CDS	24.4	W
Propulsion	800	W	---	---	---
Fuel	28.7	W	Sensors	146.7	W
Total	**973.9**	**W**	**Total**	**291.9**	**W**

The rover will then recharge its batteries with solar cells supplied by IMM-alpha. With the solar cells wired in parallel, Mu3 plans to recharge the batteries at 4.1V with 228 Amps. Recharging will replenish the 27,480.8 W-hr consumed from multiple subsystems during travel. These solar cells offer 449.9 W/m^2 and weigh about 490 g/m^2.

Table 5.4-2 SPDR Rover Power Breakdown

Subsystem	**Budget, W**	**Current, W**	**Status**
Thermal	110	117.6	C
Power	3.2	3.2	E
CDS	24.4	24.4	E
Telecom	32.5	191.6	C
Propulsion	32.5	800	R
Mechanisms	16.2	16.2	E
Total	**218.8**	**1153**	
Payload	100	146.7	C
Margin	63.76	0	E
Mission Power	282.6	1299.7	

The configuration for the SPDR rover is a 4 m^2 area on top of the rover and the solar cells will unfold after the rover has successfully moved off the RFL lander. This architecture will allow the rover to charge batteries in the daytime. Research indicates that dust degradation of solar cells can reach up to 30%. With this reduction in efficiency, charging via solar cells will take about 29.3 hours. This makes up about 4 days of sunlight. From this, Mu3 allocated 15 days per round trip which breaks down into 3 days for travel, 4 days for recharging, 1 day for refueling and communications, 3 days for return travel and 4 additional days for recharging.

5.5 Command and Data Handling

The C&DH subsystem is critical to the success of the MAV and SPDR missions, serving as the central nervous system of both vehicles. The C&DH manages data input from the sensors and cameras. It then processes the data, executing commands accordingly and stores the data. It can also transmit and receive data from and to Earth. However, the harsh conditions of space, particularly on the surface of Mars, require that the C&DH subsystem be able to withstand extreme environmental conditions. Without the C&DH the MAV and SPDR will not be able to control the temperature and pressure of the fuel/oxidizer, nor control the power of the subsystems.

One of the key challenges of operating electronic components in space is the impact of electromagnetic radiation on data integrity. Data integrity is lost by the radiation flipping the bits that are stored on the memory modules. Computer systems need specific sets of instructions in order to be able to operate properly. When those instructions are tampered with it could cause the entire system to crash or change the behavior of the programs that keep the MAV and SPDR safe. To address this critical hazard, rad-hard components were selected for the CPU, RAM, and Flash memory, all of which are equipped with Error Code Correction to minimize the risk of data corruption. Flash memory is a type of non-volatile memory that can retain data even when the power is turned off. To further enhance the reliability of the C&DH subsystem, an RMU was selected as its centerpiece as seen in **Table 5.5-1**. The RMU, manufactured by MOOG, includes two parallel IAUs with triple RMUs, providing redundant computers in case of catastrophic failure, ensuring a 10–15-year mission life, and facilitating power distribution to the SPDR [27].

To ensure optimal performance, the VxWorks OS was chosen due to its flight history, low-latency, fault-tolerant file system, and high reliability. These carefully selected components and systems enable the C&DH subsystem to operate reliably in the challenging conditions of space, providing the necessary data handling and processing capabilities for a successful mission. VxWorks is an RTOS which allows it to provide deterministic performance and precise timing in applications that require it.

Table 5.5-1 Technical Specifications for SPDR C&DH Computers and Storage

MOOG	
Performance	2-IAU's, 3-RMU's
RAM	512 kb
Storage	1 – 10 TB
Operating System	VxWorks

Given the time required to send or receive a signal from Mars, which ranges from 5 to 20 minutes depending on the relative positions of Earth and Mars, automation of most tasks and processes is the best choice for the SPDR. However, the SPDR also has the capability of receiving and executing commands from Earth in case of emergency or to receive software/firmware updates. The SPDR can send information either directly to Earth or via relay connections with the MRN.

One critical function of the C&DH subsystem is to monitor and maintain the health of the SPDR and MAV. The data collected will be stored in solid-state modules and transmitted to Earth at specific intervals or as directed by NASA. These intervals will be discussed in depth in the telecommunications section. This data will also be processed so that the computer modules can take appropriate actions when necessary.

To ensure safe transportation and refueling of the SPDR, it is important to quickly detect and respond to environmental, terrain, and refueling hazards. The optimal solution is to implement Artificial Intelligence (AI), which will process data from LiDAR, image recognition software, and engineering cameras located around the SPDR. Additionally, route planning by personnel on Earth can help in analyzing the data. To achieve this, AutoNav software, currently being used on the Perseverance rover, will be implemented. AutoNav creates a 3-D map of the environment and identifies hazards so that it can plan a safe route towards the MAV or RFL. To strengthen its maneuverability, Enhanced Navigation ENav will also be used. It is a software and algorithm system that enables more accurate identification of potential hazards and is also being used on the Perseverance rover [28].

After the SPDR and MAV land on the ground, they will undergo thorough diagnostics to ensure that everything is functioning properly. These diagnostics include checking the pressure in the MAV, tanks, and rover to ensure that they are constant, indicating that the systems are properly sealed with no leakage. Additionally, the C&DH system will verify the voltages of the solar cells, batteries, and sensor voltage drops to detect any potential short circuits.

During this ground stage of the mission, the SPDR will be particularly active as it shuttles back and forth between the RFL to refuel and replenish the MAV. Meanwhile, the MAV will focus on monitoring itself and performing operations to keep itself and the fuel/oxidizer safe.

Overall, these initial diagnostics are critical to ensuring the success of the mission by verifying that all systems are functioning properly and that the necessary resources are available to continue the mission.

5.6 Telecommunications

We based our system primarily off Perseverance's telecom system. Most of the hardware is the same, including an ultra-high frequency antenna for relaying large amounts of data from Mars to Earth, an X-band high gain Antenna for direct communication to and from Earth, and an omnidirectional X-band low gain antenna for small bits of data from Earth to Mars. The transceivers, transponders and other internal hardware are also based on Perseverance, except for the inclusion of an X-band transmitter in the case we want to send more complicated data over the high-gain link. All hardware considered, this means the Telecom System is approximately 26 kilograms and would require about 192 Watts to operate all systems at once (though that would be a very atypical use case as the operation of one antenna at a time would suffice. The list of parts, masses, and power input requirements can be found in **Table 5.6-1** and the models of the hardware can be seen in **Figure 5.6-1**. Values noted with an asterisk are estimated from other similar hardware as the data desired does not seem to openly exist on the internet.

Table 5.6-1 Telecom Hardware

No.	Item	Quantity	Mass Total (kg)	Power Total (W)	Manufacturer	Source
1	UHF Antenna	1	3*	0	JPL	[29]
2	High Gain Antenna (plus Gimbal)	1	8	5*	Airbus/Space-España	[30]
3	Low Gain Antenna	1	2*	0	JPL	[30]
4	UHF Transceiver	1	3	65	L3Harris	[31], [32]
5	X-Band Transponder	2	6.4	31.6	General Dynamics	[33]
6	X-Band SS Power Amplifier	1	1.37	60	General Dynamics	[34]
7	X-Band Transmitter	1	2.5	30	L3Harris	[35]
-	Totals	-	26.3	191.6	-	

The primary way we intend to communicate with Earth for both the SPDR and MAV is first through the Mars Relay Network. It allows for a very high-speed data connection between Earth and Mars without the need for a heavy or costly telecom system within our own mission. Despite the concerns of the MRN starting to age and several of the spacecraft operating past their expected mission lifetime, past rover missions have proven how essential it is to have the relay link to push large amounts of data from Mars to Earth quickly. If not the Mars relay network as we know it, then definitely an upgraded network in the future.

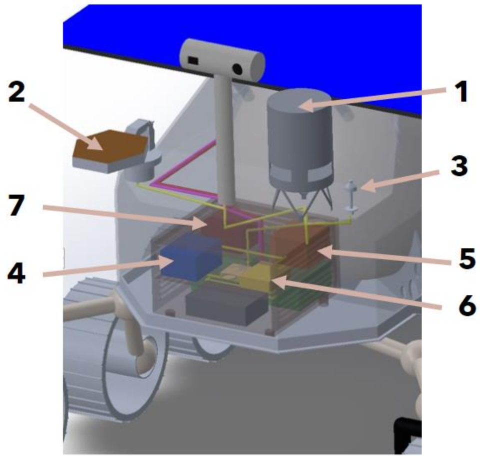


Figure 5.6-1 SPDR Telecom Callouts

We would also be using the Deep Space Network here on Earth to parse all of the Mars data. We would use both the 34 and 70m stations depending on the situation and amount of data needed to transfer. With multiple options to connect to Earth on top of the rover autonomy means that the probability of total rover telecommunications failure is very slim and not a mission-ender.

Now moving on from hardware to data transmission. **Table 5.6-2** shows the intended sensors to be included on the rover, as well as the data rates for each. When each sensor operates depends on the operational mode the rover is in. The current operating modes currently calculated for the rover include "Rover in Transport", "Rover Docking", and "Rover Transferring Propellant". For a full in-depth breakdown of the operating modes, which sensors are used, and data rates for each mode, see **Appendix B-11.3**. All data rate calculations include a max overhead of 0.1 and Convolutional Encoding. Some sensor data is reduced for scheduled transmissions to transfer the data in a timely fashion which is why some of the transmitted values are smaller than the full bit rates.

Table 5.6-2 SPDR Sensor Data Rates

SPDR				
Instrument Name	**Number of Sensors**	**Data Rate bps (each)**	**Sampling Rate Hz**	**Source**
Air Temperature Sensors (MEDA)	1	10000	1	[14], [15]
Relative Humidity Sensor (MEDA)				
Pressure Sensor (MEDA)				
Infrared Sensor (MEDA)				
Wind Sensors (MEDA)				
REMS	1	9600	50	[16]
Sun Sensors	2	9600	50	[17], [18]
Inertial Measuring Unit	1	115200	600	[19]
LiDAR	1	100000000	10	[19], [20]
Cameras	3	96000	24	[21]
Pressure Transducer	2	9600	NI	[22]
Temperature Sensor	2	9600	NI	[23]
Power sensors	2	1000	1	[24]

Data collected can be transmitted under a couple classifications: "live", long term, or general. Live data is greatly cut down with the intent of sharing the important information to Earth quickly. Although there is technically a time delay between Earth and Mars transmission, this data is as Live as can be done from Mars. Long-term data is split into long-term total and long-term nominal data. The long-term nominal data is only sending key data points after long stints of less crucial mission. All data is stored and can be accessed after the fact if any of the transmitted data looks off, which is where the long-term total data comes in (for data storage calculations, see **Appendix B-11.3**, but one terabyte of sensor storage would offer enough space to store the data of any mission leg well into the next phase of the mission before needing to be cleared for new data). General data transmission typically occurs after live data transmission for a total picture of what happened during critical parts of the mission. The exception to this would be the LiDAR data due to how large the data rate is for that sensor. Rather than transmitting all of the LiDAR data for the docking procedure, the rover would only transmit two minutes' worth of the LiDAR data.

From the operational modes, and transfer times of the transmission types, we were able to find an estimated telecom schedule for ground operations as seen in **Figure 5.6-2**. A full table of data modes, collection and transfer times, and total bits sent can be found in **Appendix B-11.3**.

The MAV mostly just sleeps and transmits sleep data while on the ground, so the focus should be on the Rover shown on the lower half of the timeline. The Rover will arrive at the MAV after about 15 days' worth of travel as a worst-case estimate. It will then transmit the data of its trip before beginning the docking operation. During docking, the rover will transmit important “live” data as it collects the total docking data. It will then take a few hours to transmit all of the docking data and about two minutes worth of LiDAR data back to Earth. Both vehicles then enter refueling mode to monitor the transfer status before each sending that data. Once finished, the SPDR will depart the MAV and arrive at the RFL 15 days later where it will perform roughly the same schedule as it did at the MAV. A noteworthy point is this does not include SPDR sleeps to wait out dust storms or other harsh weather. During these times, data collection would be minimal, and a transmission would be scheduled before proceeding with the next portion of the mission. Since the mission is supposed to be autonomous, frequent contact with Earth at this point in the mission is not required.

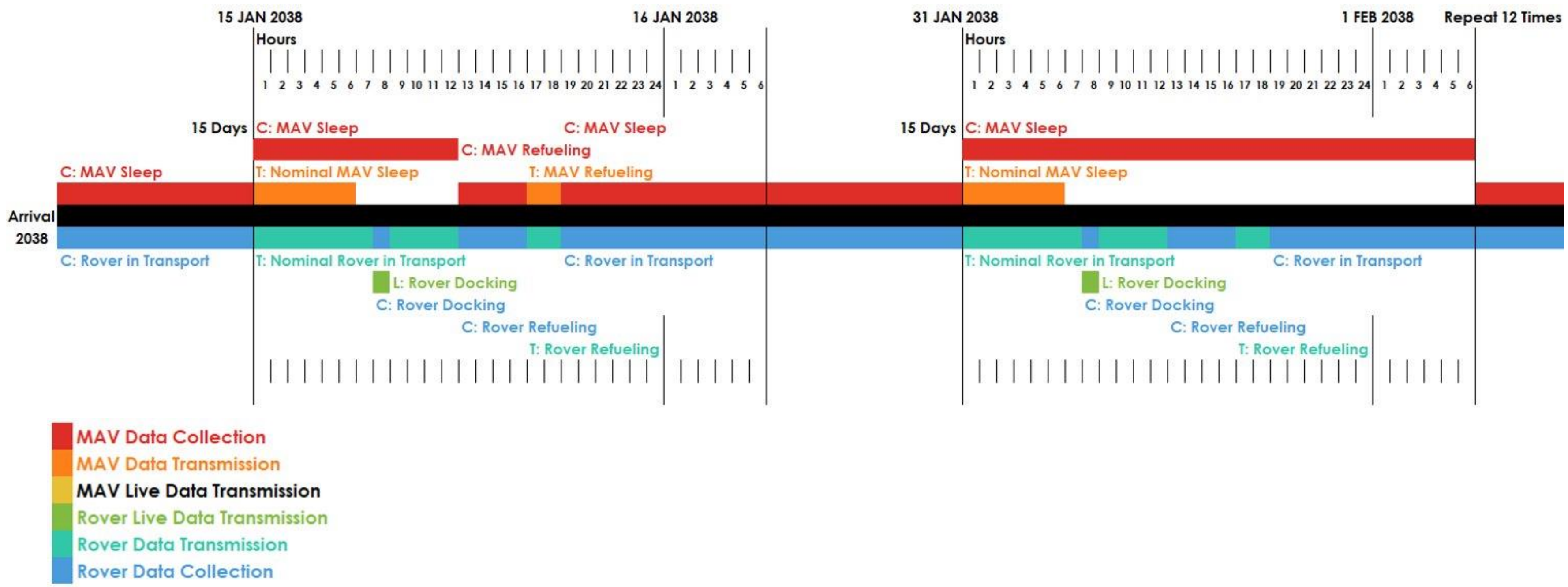


Figure 5.6-2 Example Ground Telecom Schedule

5.7 Mass and Power Statements

The final PDR-level mass estimate for the rover and fuel base station is produced from a bottoms-up estimate of using actual masses from selected components where appropriate and using as-design values from the structural model for mechanical components and fuel tanks. Maturity codes were designated for each line item based on the AIAA S-120 mass estimating standard. The required growth allowance depends on the type of component, and the maturity of the concept, ranging from estimate to as-measured existing hardware. For PDR, all components have at least a preliminary design rating, and many have an existing hardware rating due to our emphasis on high heritage components.

Table 5.7-1 includes a summary of the rover and base station wet and dry mass. In the table, CBE reflects the listed hardware mass or model design mass as appropriate. MGA is listed as a function of the S-120 maturity code. The MEV is the sum of the current best estimate and mass growth allowance. The allocation is hard upper limit for the system based on capability. Finally, total margin is calculated as the percentage that the CBE could grow while still fitting within the allocation. The rover and fuel base station have a substantial margin against the lander's 25,000 kg capability including the transported fuel. The rover is limited in dry mass based on the initial point design concept of the egress system and associated stresses. This case has an adequate margin as well and should more be required; the egress ramp could be redesigned for increased strength.

Table 5.7-1 Rover and Base Station Mass Summary

	CBE Total	MGA Total	MEV Total	Allocation	Total Margin
Landing Dry Mass	1060	14.2%	1210	1500	41.6%
Landing Wet Mass	5714	2.6%	5864	25000	337.6%

6.0 Ascent

The Mars environment poses unique challenges for a mission focused on a Mars Ascent Vehicle (MAV). With a peak ascent load of 1.3(Earth)g [36].the increased gravitational force on Mars presents a demanding physical strain on both the vehicle and its occupants. The MAV must be designed to withstand this increased load and ensure the safety and well-being of the crew during ascent.

Additionally, the maximum dynamic pressure of 540 Pa [36], during ascent further emphasizes the need for a robust and aerodynamically stable MAV. The vehicle must be engineered to withstand the forces exerted by the Martian atmosphere, ensuring structural integrity and stability throughout the ascent phase.

The direct solar flux of 590 W/m^2 [36] on Mars is another crucial factor to consider. The MAV's thermal management system must efficiently dissipate the absorbed solar energy to prevent overheating of critical components, while also providing sufficient power to sustain onboard systems and instrumentation.

Furthermore, the calculated gravity gradient torque of 2.4×10^{-3} N-m and the calculated solar radiation pressure of 2.7×10^{-5} N-m need to be accounted for in the MAV's attitude control system. These external forces can impact the vehicle's orientation and stability, necessitating precise control mechanisms to maintain the desired trajectory.

Lastly, the calculated aerodynamic torque of 6.7×10^{-1} N-m during ascent introduces additional challenges. The MAV's shape and aerodynamic design must therefore be optimized to minimize drag and maximize stability, enabling efficient maneuverability through the Martian atmosphere. This can be seen in the moments of inertia for the MAV.

6.1 Design Overview

The MAV is the ascent vehicle that will carry astronauts from the surface of Mars to a 5-sol orbit where it will rendezvous with the DST as mentioned in the concept of operations. A successful mission will help establish a human presence in the outer galaxy. The spacecraft will utilize 3 RS-72 engines manufactured by Aerojet Rocketdyne and 12 Monarc-22-6 ACS thrusters to both facilitate lift off the

Martian surface and docking with the Deep Space Transit Vehicle. This section will be split into two subsections concerning the MLV and MAV [1].

The Mars Lander Vehicle:

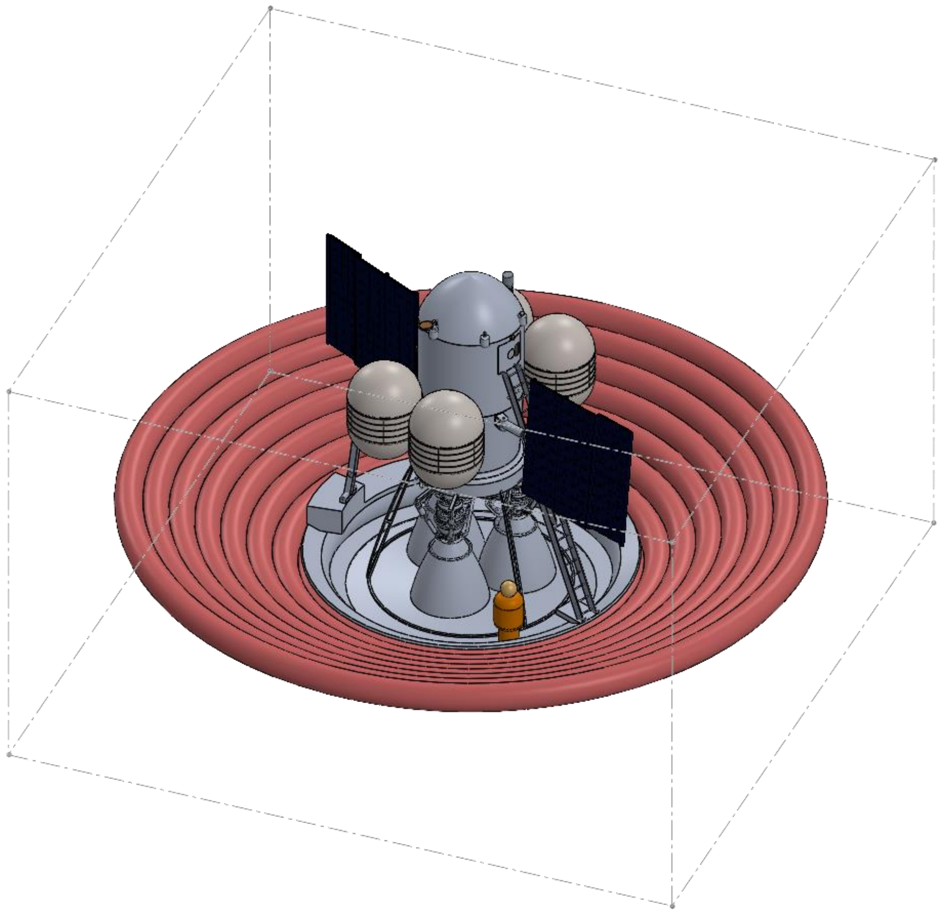


Figure 6.1-1 MAV Stowed within MLV

The MLV follows the basic dimensions shown in **Figure 6.1-2**. The overall diameter of the uninflated HIAD is 7.7 meters which falls well within the RFP's 8.4 meter diameter payload fairing requirement [1]. Both the tube angle and layout follow JPL's HIAD test demonstrator of 30 degrees. With the MAV nested atop, the overall height of the HIAD and MAV is 10.1 meters which is well within margin for the SLS Block 2's capabilities. As mentioned with the RFL in the previous section, this layout can be rearranged to fit more specific mission parameters as necessary. A detailed internal view of the MLV in stowed and mission configuration is shown in **Figure 6.1-2.** Specific callouts to key features are referenced in **Figure 6.1-3.** As mentioned previously in the concept of operations, the HIAD will deflate and retract once safely landed on the surface of Mars.

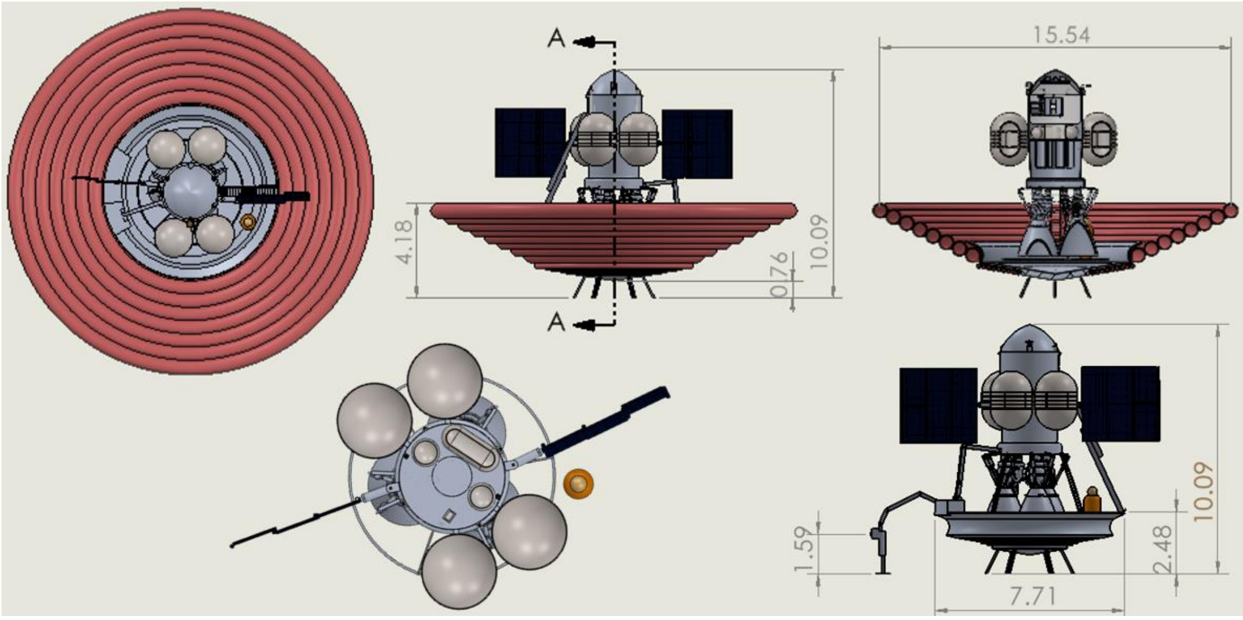


Figure 6.1-2 MLV Dimensions

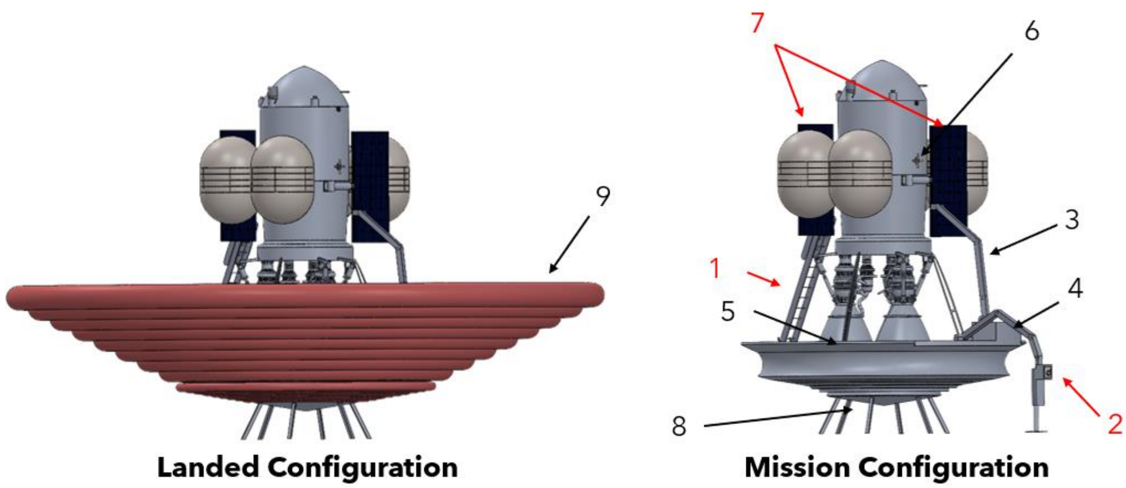


Figure 6.1-3 MAV Landed and Mission Configurations

Table 6.1-1 MAV Call MLV Callouts

1	Crew Ladder
2	RAFTI Interface
3	Fuel Transfer Tube
4	Fuel Transfer Pump
5	MAV Mounting Point
6	ACS Thrusters
7	Solar Arrays
8	HIAD Inflator Tubes
9	HIAD Base

The MLV will primarily act to safely transport the MAV from Earth to the Martian surface. Though the scope of the mission assumes that our design starts on the Martian surface, successful mission operations required a lander design to work from. As such, the MAV will remain on the MLV throughout the ground operations phase and will act as the launchpad during ascent. During all phases of the mission there is a securely latched interface between the MAV and the MLV as shown in **Figure 6.1-2**. These systems will remain latched until the astronauts begin the onboarding process. The sequence of events is important as successful detachment ensures launch readiness. Additionally, the latches are primarily hydraulically locked but include a physical redundancy to allow the crew to detach by hand if necessary.

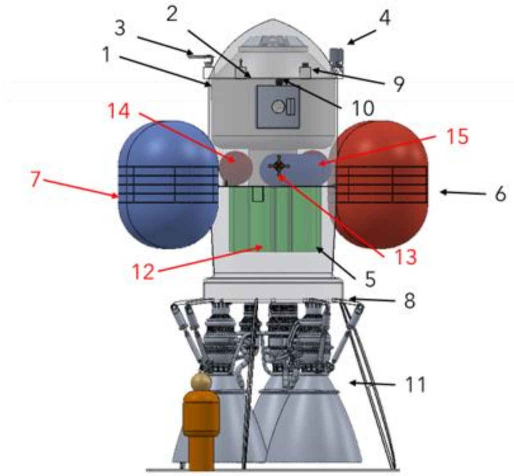
Perhaps the most important phase of the ground operations is the successful deployment of the 'refuel leg' that will hydraulically deploy from the Lander once the HIAD is successfully deflated. This leg will act as the interface between the MAV and the SPDR rover. Fuel from the SPDR will be pumped from an onboard centrifugal pump and then inlet valves feeding directly into the oxidizer tanks. Special focus was placed on material interaction to ensure the oxidizer does not materially deform the hose in material selection and design.

The MAV:

Figure 6.1-4 MAV

The ascent phase of the mission primarily concerns the MAV and as such, much analysis has been placed on ensuring mission success. The primary dimensions can be found in **Figure 6.1-6** which show an overall height of 8.4 meters and stowed diameter of 4.32 meters. During the orbital phase with all solar panels extended, the footprint diameter is 10.47 meters. Internal measurements are provided in **Figure 6.1-7** which altogether allow the crew 6 m^3 of living space. Callouts for the external and internal BUS components are provided in **Figure 6.1-5** and **Table 6.1-2**, which show design considerations and life support systems for the crew. Included are both crew seats and control systems (mirrored) and the internal ACS tanks and pressurant tank.

The crew cabin was optimized so that astronauts could complete all mission duties while not being bereft of space. To that end, the crew seating and controls center also doubles as the sleeping module once folded flat. Between both headrests is the hermetically sealed sample return container. To ensure that there is no contamination, the entire sample is first placed into a hermetically sealed container while still on the Martian surface and then the whole container is then transferred to an awaiting receptacle which is then sealed. This methodology ensures that there is no contamination between the crew cabin and the samples or vice versa by providing multiple layers of protection and additional insulation.



1	Crew Cabin
2	High Gain Antenna
3	UHF Antenna
4	Low Gain Antenna
5	Electronics Box (Telecom/CDH)
6	MMH Tanks (x2)
7	NTO Tanks (x2)
8	Environmental Sensors
9	LIDAR
10	Sun Sensors
11	RS72 Engines (x3)
12	Life Support
13	ACS Thrusters
14	ACS Tanks
15	Pressurant Tank

Figure 6.1-5 MAV Component Callouts

Callouts for components of the MAV can be seen in **Figure 6.1-5**. Of specific focus are the MMH and NTO tanks colored Red and Blue respectively. Additionally shown are the three RS-72 engines and internal pressurant and ACS tanks. For ease of viewing, the solar array has been hidden.

The overall dry weight of the MAV is 4842 kg with an overall wet mass of 22267 kg which can be seen in table alongside the respective moments of inertia.

Table 6.1-2 MAV Mass Summary

Property	**Stowed (Dry)**	**Mission (Wet)**
Mass (kg)	4842	22267
Center of Mass (m)	(0.00, -0.60, -0.05)	(0.07, 0.5, 2.45)
Ixx (kgm²)	31344	159906
Iyy (kgm²)	26035	92597
Izz (kgm²)	29667	152695

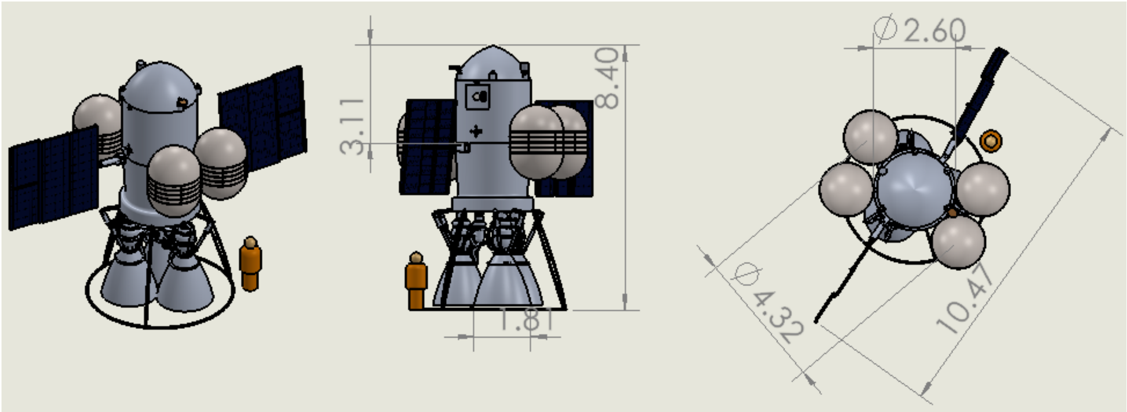


Figure 6.1-6 MAV Primary Dimensions

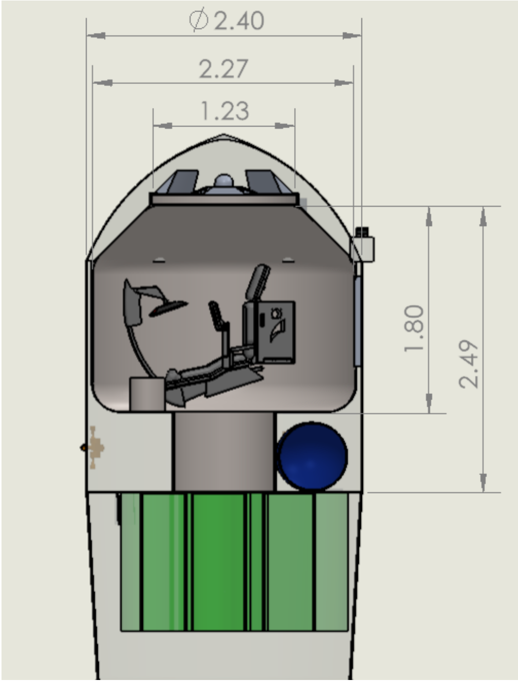
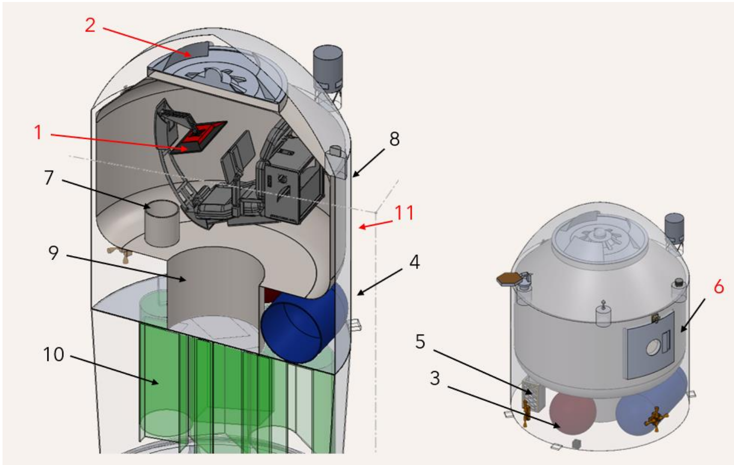


Figure 6.1-7 MAV Internal Dimensions



1	Crew Seats and Controls
2	DST Docking Interface
3	ACS Tanks (x2)
4	Pressurant Tanks
5	Batteries
6	Crew Egress/Ingress
7	Sample Storage
8	Flight Computer
9	Configurable Access (Modular)
10	ECLSS Systems/Thermals
11	Shielding and Insulation

Figure 6.1-8 MAV BUS Layout and Callouts

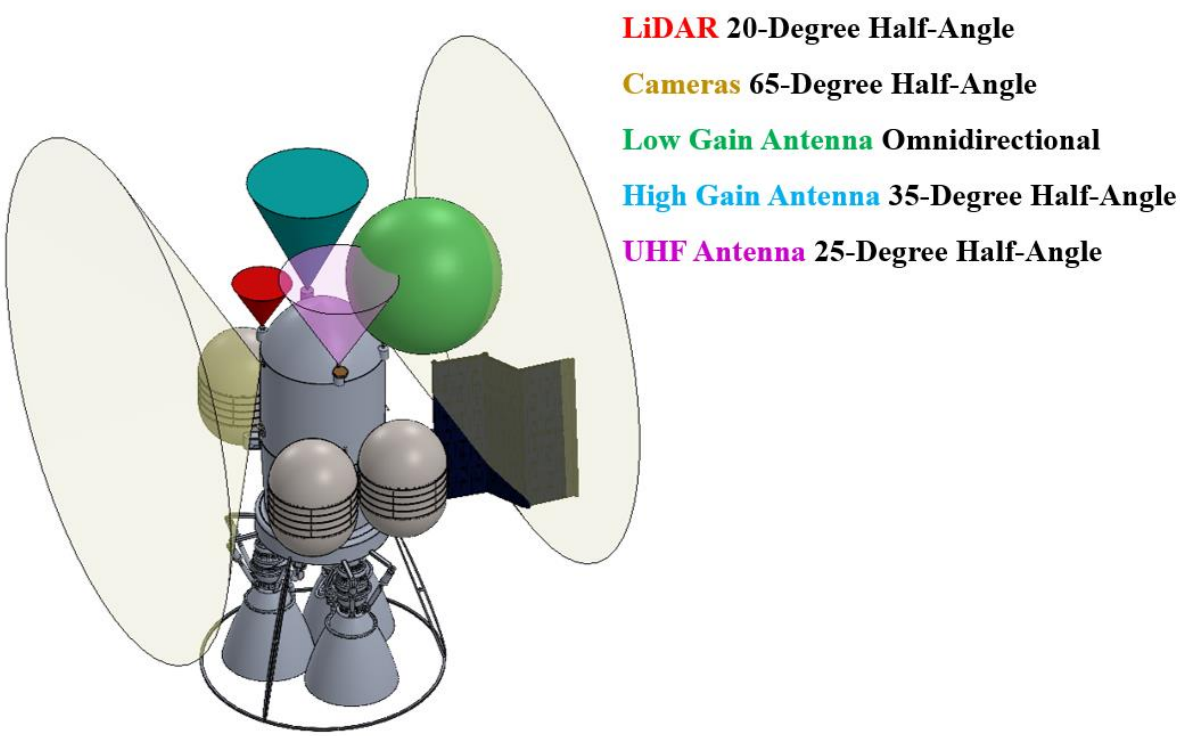


Figure 6.1-9 MAV FOV Plots

Table 6.1-3 FOV Plots and Sensor Mass List

Instrument Name	Mass	Source
Air Temperature Sensors (MEDA)	6 kg	[14], [15]
Relative Humidity Sensor (MEDA)		
Pressure Sensor (MEDA)		
Infrared Sensor (MEDA)		
Wind Sensors (x2) (MEDA)		
REMS	454 g	[16]
Sun Sensors (x8)	100 g	[17], [18]
Inertial Measuring Unit	1 kg	[19]
LIDAR	12 kg	[19], [20]
Cameras (x2)	425 g	[21]
Pressure Transducer (x2)	-	[22]
Temperature Sensor (x2)	0.35 g	[23]
Power sensors (x2)	-	[24]
Star Tracker (x2)	50 g	[37]
LAMS	2 kg	[38]
TOTALS	23.0 kg	-

Additional analysis was conducted to show the Field of View plots of various systems seen in **Figure 6.1-9**. This is to ensure communication with Earth, the SPDR, and the DST as necessary. As denoted by the colored legend, the 2 cameras and LiDAR are primarily used to assist in docking with the DST as high precision and rapid update rates are required. Additional sensors include the star trackers which assist with station keeping and the MEDA sensor array which are used to ensure nominal ground conditions. This is important as the successful landing of the MAV will signal to Earth-based crews that it is safe to launch the RFL portion of the mission.

6.2 Thermal

Based on the SolidWorks CAD model, the worst-case cold and hot temperatures that the MAV spacecraft may encounter while in operation have been determined and documented in **Table 6.2-1**. Calculation of the worst-case hot and cold scenarios has helped to determine the equilibrium temperature required to maintain the spacecraft's effective operation. This temperature is crucial to prevent overheating or freezing of the spacecraft's components, which could result in malfunctions or permanent damage. To maintain the equilibrium temperature, an active control system has been selected as detailed in **Table 6.2-2.** The control system will continuously monitor the temperature of the spacecraft's components and adjust the thermal control mechanisms accordingly to ensure that the equilibrium temperature is maintained. The active control system will play a critical role in ensuring that the spacecraft operates effectively in various environments and conditions.

Table 6.2-1 Worst Case Hot and Cold

System State for MAV	**Temp**	**Unit**
Worst case hot	89.4	(°C)
Worst case cold	-162.7	(°C)

Table 6.2-2 Thermal Mases and Volumes

Item	Mass (kg)	Volume (m^3)
Radiator	58	0.4
Multi-Layer	210	1.5
Heater	14	-
Total	282	2,2
Spacecraft temperature at thermal equilibrium		156.1

6.3 Structures

Structures play a crucial role in the overall system as they serve as the foundation that connects every subsystem. The success of the mission, spanning from Earth launch to Mars landing, ascent, and docking, relies heavily on the proper coordination and interaction of all subsystems during each mission phase. In line with this, Mu3 has conducted a comprehensive analysis of every aspect of the structures subsystem to ensure a factor of safety of at least 2 for all components. Mission-critical components, such as the crew cabin and propellant tanks, have been designed with a factor of safety exceeding 4.

Considering that the MAV experiences maximum load during Earth launch, we conducted a thorough structural analysis under these conditions with an applied gravity load of 4.1g. For ease of viewing and simplified meshing, the internal components are hidden but the same weight of the entire wet mass system is applied. As seen in **Figure 6.3-1**, the maximum stress the structure experiences during launch is significantly lower than the yield stress.

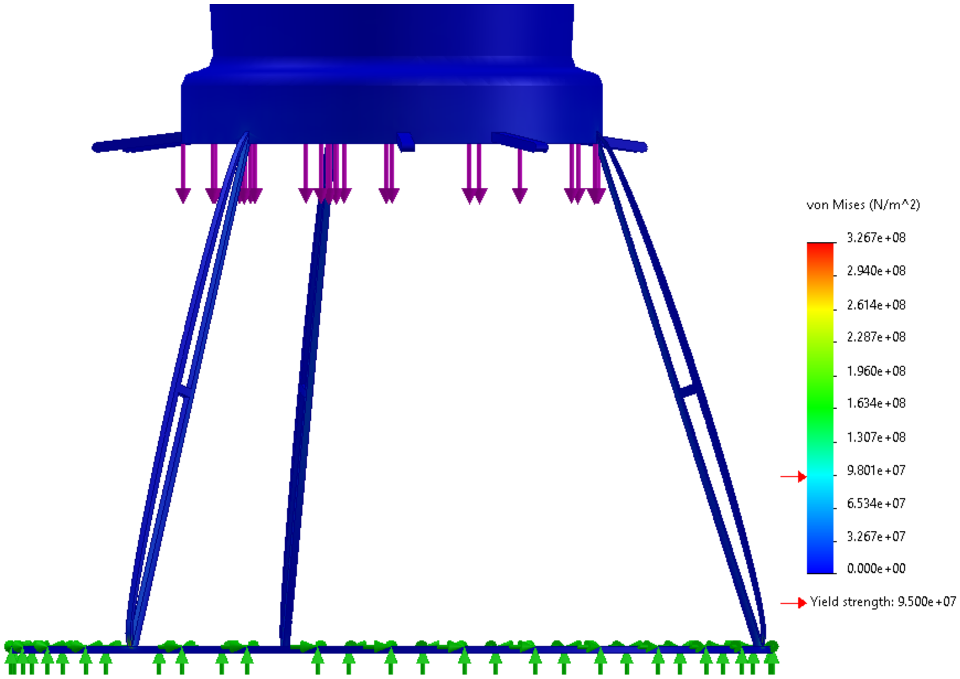


Figure 6.3-1 External Shell Stress During Launch

By utilizing an aluminum alloy (7075-O) as the external structural material, we have achieved a maximum deformation of less than 0.5 mm as seen in **Figure 6.3-2** and a maximum stress of under 64 mPa. This indicates that even under worst-case scenarios with full payload, our structure remains resilient and capable of safely transporting the MAV.

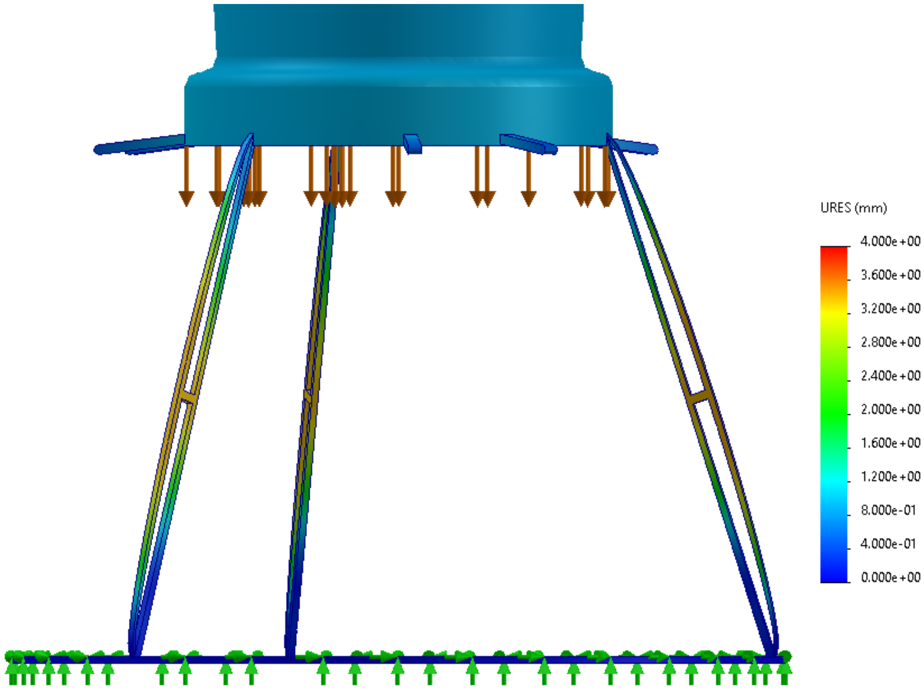


Figure 6.3-2 External Shell Displacement During Launch

As the MAV utilizes a dual-shell design with an internal crew cabin and the above external shell, it was imperative to design a crew cabin that could both withstand launch loads but also internal atmospheric pressure (101.325 kPa) for astronaut survival. Analysis shown in **Figure 6.3-3** illustrates the maximum stress distribution which is indicative of an exceptionally strong design. The crew cabin is manufactured from the same titanium alloy Ti-13V-11Cr-3Al as the fuel tanks due to both the high yield stress and effectiveness at holding pressure that this titanium alloy provides. The cabin's walls are three millimeters thick. As previously mentioned, Multi Layer Insulation and resistive heaters between the crew capsule and external shell will provide thermal protection as well as heating during the appropriate mission phases. The combined thickness of the crew cabin, insulation, stringers, and external shell is 5 centimeters.

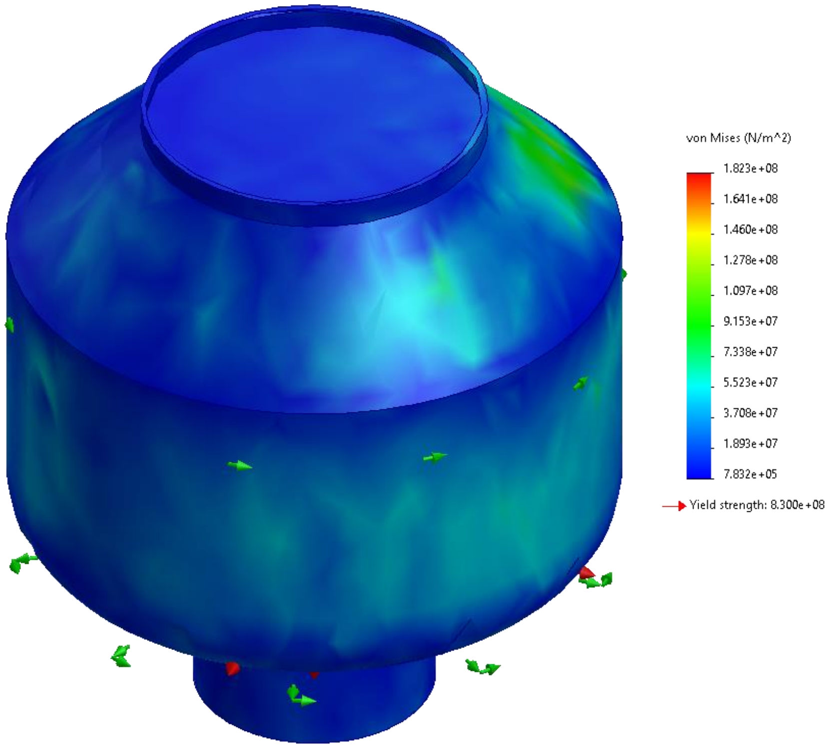


Figure 6.3-3 Crew Cabin Stress Distribution

As described in the concept of operations, the rover will connect to the MAV using an RAFTI (Rapidly Attachable Fluid Transfer Interface) adapter, which is manufactured by Orbit Fab. This open-source adapter serves the purpose of transferring fluids, such as propellants, by both filling and draining the system. The RAFTI adapter offers versatile functionality, including fluid transfer, utility, and docking, as outlined in the RAFTI user guide [8].

To establish a secure connection, the RAFTI adapter features multiple 'grapples' on its external housing [8]. These grapples actively center and grip the receiving receptacle, ensuring a positive mate as seen in **Figure 6.3-4** [8].

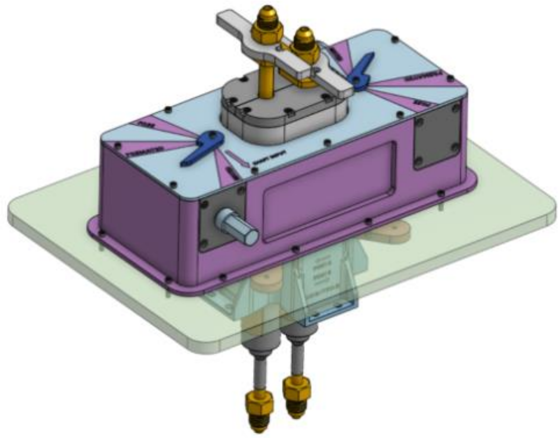


Figure 6.3-4 RAFTI Interface Mounted with Receptacle

In situations where the terrain is uneven, sinking, or exhibits different topography, the leg of the rover is equipped with hydraulic capabilities, allowing for over 2 meters of longitudinal travel and 2 meters of variable height shown in **Figure 6.3-5.** This hydraulic leg enhances the confidence of successful fuel transfer by accommodating ground obstructions and maintaining stability. The decision to utilize a hydraulic leg over an electronic system was based on several factors. The hydraulic leg offers a simpler design and brings added durability and fault-tolerance to the system. Additional analysis was conducted to show this hydraulic leg could be utilized as a backup 'steppingstone' in case the primary mode of ingress - the hydraulic ladder- were to fail.

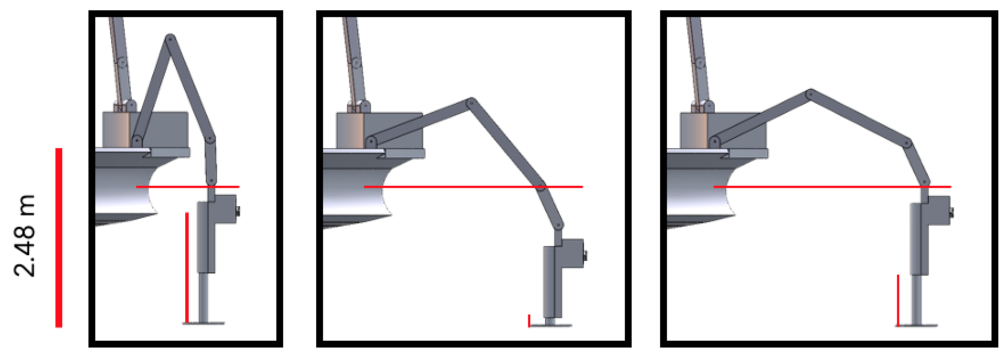


Figure 6.3-5 Three Different Possible Leg Configurations

The primary mode of ingress onto the HIAD and eventually the MAV is through the use of a hydraulically hinged extending ladder which follows OHSA 29 CFR 1910.23 [39] requirements for ladder design. **Figure 6.3-6**Figure shows the stowed, lowered, and raised ladder. In the raised position, astronauts will be able to extend the ladder and hook it onto locks beneath the crew hatch door. Though intended to be actuated primarily from handheld remote controls worn by the astronauts, there is also a redundant design feature allowing astronauts to raise and lower the ladder manually.

Mu3 will utilize a similar unified hatch as the Orion capsule with the interior shown in **Figure 6.3-7** [40]. This was a design decision following well established space design and ease of initial entry and closing of the hatch. It will use a unified hatch interior with 17 interior latches linked together and a Honeybee Robotics multi-stage gear system to allow crews to "actuate the latch trains from inside and outside the Crew Module" [40]. Additional screw jacks are included to allow latching even in the case of thermal disfigurement. The overall weight is 152 kg with an overall thickness of 6.6 cm as designed in SolidWorks. Following NASA requirements there is an additional multi-layer window made of polycarbonate and synthetic sapphire. Synthetic sapphire is an advancement of traditional glass technology and was selected for its higher hardness and clarity. This is an overall improvement in the design owing to the harsher Martian environment.

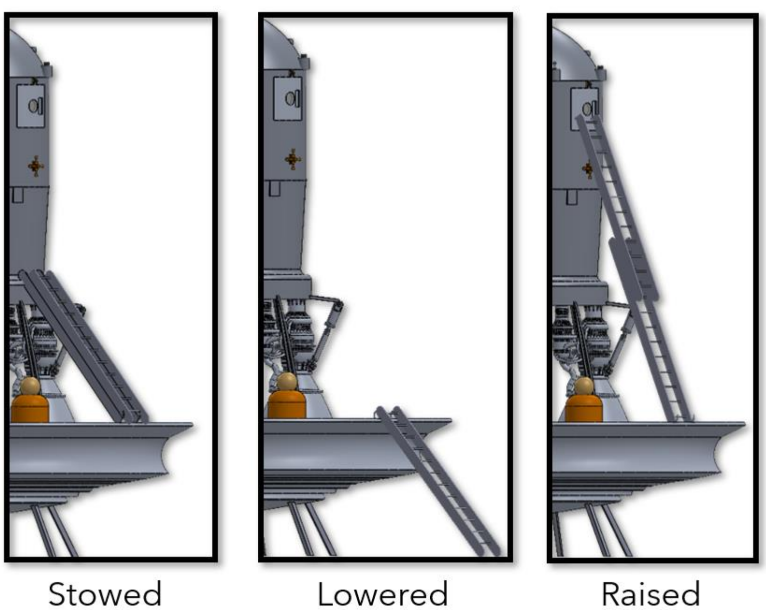


Figure 6.3-6 Stowed, Lowered, and Raised Ladder Capabilities

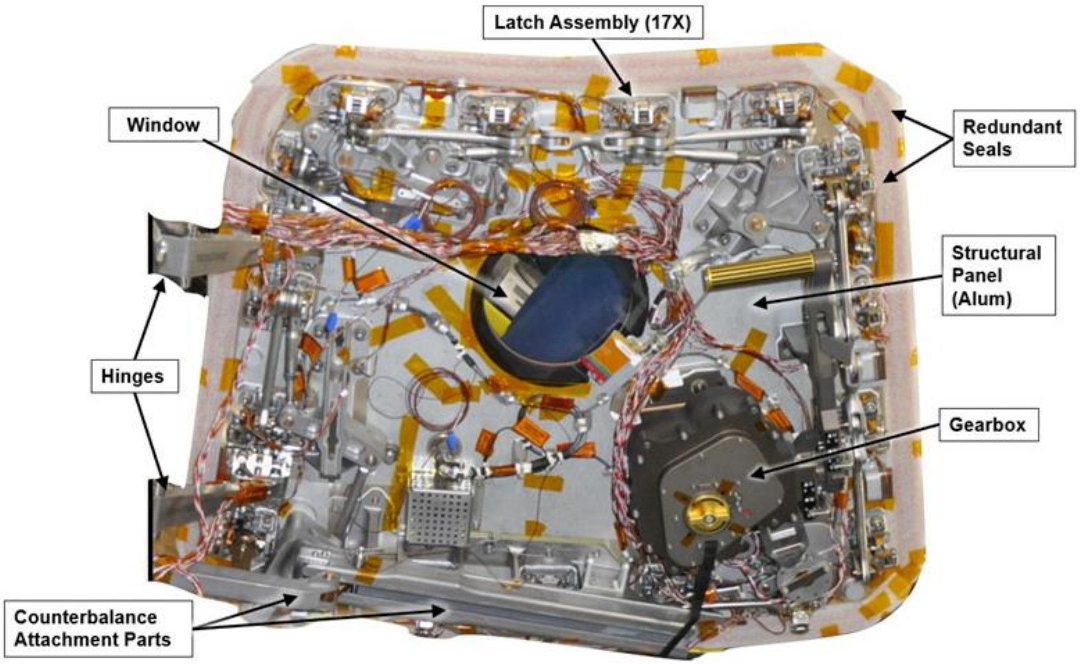


Figure 6.3-7 Orion Hatch

At the topmost of the MAV is the ISS docking hatch which follows dimensions from the International Docking System Standard [41]. This standard ensures interoperability with the DST and any future missions.

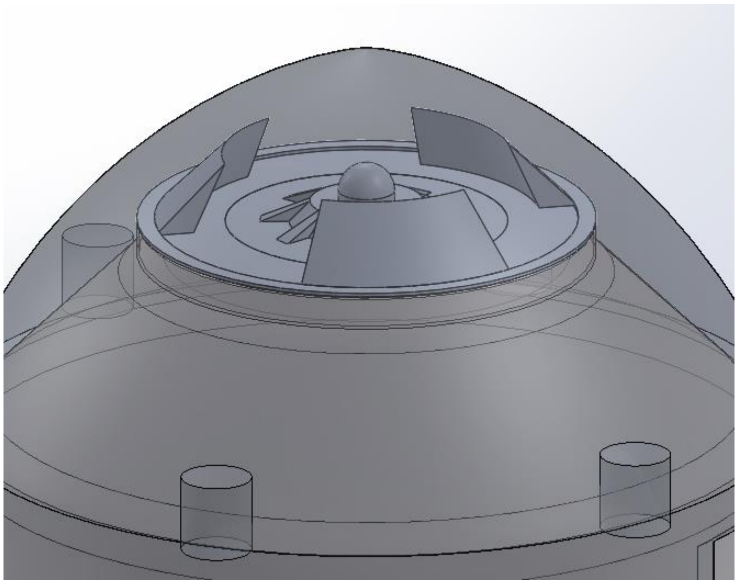


Figure 6.3-8 MAV DST Docking Hatch

By ensuring the integrity and robustness of the structural components, Mu3 has taken a critical step in guaranteeing the overall reliability and safety of the mission. The structural analysis provides confidence that the system can withstand the demanding forces and conditions encountered throughout the mission, reinforcing our commitment to mission success and the well-being of the astronauts involved.

6.4 Propulsion

The capacity to carry the MAV to our transfer orbit is of utmost importance for the health and safety of the crew and mission success. The main engine used for MAV orbit entry is the RS-72 [3]. For spacecraft attitude control, the MAV will also be equipped with 12 MONARC-22-6 thrusters [4]. A full trade study for engines and thrusters can be found in the **Appendix B-11.1**. The properties for each propulsion system are summarized in **Table 6.4-1**.

Table 6.4-1 MAV Engine and ACS Thruster Specifications

Characteristic	**RS-72 (main engine)** [3]	**Monarc-22** [4]
Propellant	MMH/NTO	MMH/NTO
Impulse	340 s	230 s
Mass (ea.)	138 Kg	0.7 Kg
Quantity	3	12
Purpose	Main Ascent Engine	Attitude control

Propellant mass is sized from the ΔV requirements laid out in **Table 6.4-2**. Our total propellant load is 19740kg. All propellants are stored in titanium alloy (Ti-13V-11Cr-3l) tanks as shown in **Figure 6.4-1**.

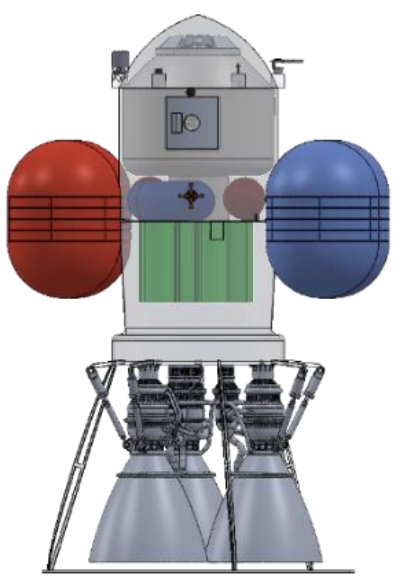


Figure 6.4-1 MAV with Propellant Tanks

Table 6.4-2 ΔV and ISP

Maneuver	ΔV(km/s)	ISP (s)
Ascent	3.3	350
5-sol	1.4	350

Structural analysis was conducted to show that all tanks could withstand worst case launch loads as shown in **Figure 6.4-2.** Steel stringers around the circumference of the tanks add increased rigidity and mounting points for access to the MAV. They also add contact points of the spring mechanism to allow for jettison of the tanks as mentioned in the concept of operations. As the ACS thrusters are monopropellants, their propellant is housed separately in the unpressurized section within the MAV immediately beneath the crew cabin. They are made of the same titanium alloy as the larger tanks. Additionally, each propellant and oxidizer tank were designed to carry similar weights of propellant to ensure a central MCG (mass center of gravity) and to reduce manufacturing costs by following a 'bulk-production' manufacturing process.

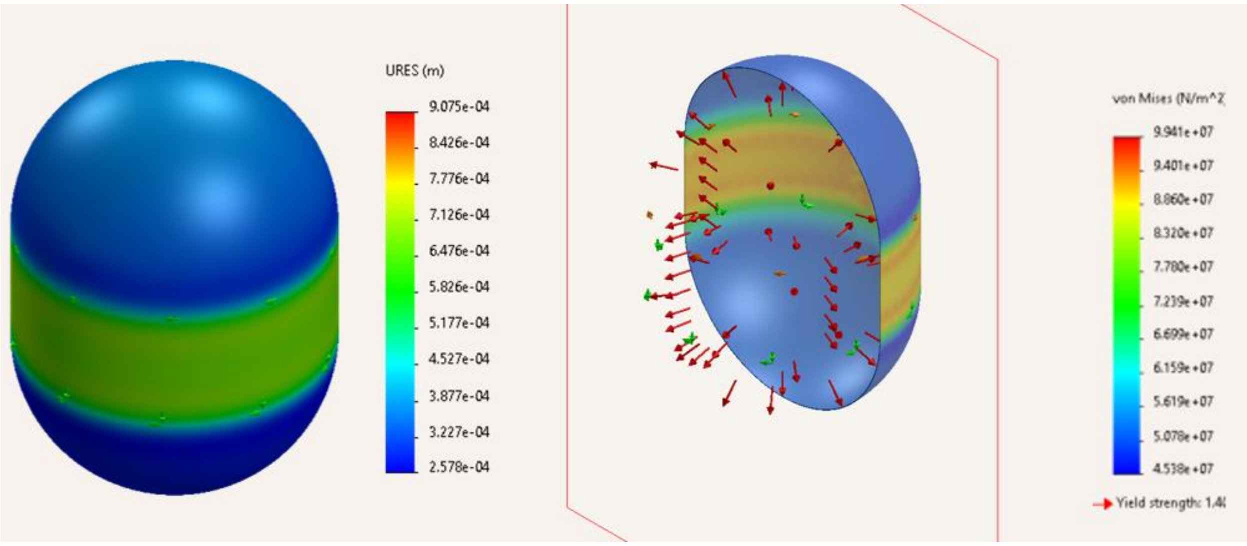


Figure 6.4-2 Tank Analysis

6.5 Power

Producing electrical power on the surface of Mars is incredibly difficult. This section covers the power system selection for the MAV. For this mission, the RFL lander brings the 10-kiloWatt Fission Surface Power Unit to the surface of Mars. The FSP is not well documented, so Mu3 decided to use other power sources alongside this technology. The power system design was developed from past missions to identify systems with flight heritage power systems. Some systems researched include the Apollo Landers, the Orion Capsule, and the Dragon Capsule. These systems all have solar cells and high efficiency batteries with redundancy measures. From this observation, the design uses solar cells and batteries due to their energy density and relatively low mass.

The MAV will carry both solar cells and batteries to conduct the mission. Currently the MAV houses fourteen VES-16 batteries and a 17.6 m^2 extendable and folding solar array from IMM-alpha. Each battery has 4 parallel strings with 8 cells in series for each string. Each battery provides 512 W-hr of energy and each battery has a depth of discharge of 80%. 14 batteries provide the MAV with 7168 W-hr of energy to keep the MAV operational during ground operations, ascent, and orbit. Currently, the projected power budget and timeline estimates for power consumption follow *Updated Human Mars Ascent Vehicle Concept in Support of NASA's Strategic Analysis Cycle 2021* [10].

Table 6.5-1 Power Phases for MAV

On Mars Surface		**Powered Ascent**		**Coast/Phasing**		**Coast to Apoapsis**		**Rendezvous**	
10.25 Hr		**0.174 Hr**		**10 Hr**		**60 Hr**		**0.33 Hr**	
1897	W	4642	W	**4767**	W	**4767**	W	5034	W

The most power-intensive phases in are transfer orbit and waiting for rendezvous with the Deep Space Transit Vehicle. During this period the crew will be coasting to the rendezvous point and consuming power throughout the entire duration. During this phase, the MAV will be using 260,035 W-hr of energy powering subsystems including ECLSS, ACS, Power Control, Command and Data Systems, Communications, etc. This phase is planned to last about 60 hours with a power usage of about 4,767.3 Watts. From the MAV's orbit trajectory, the expected time in sunlight is 66.0 minutes while the time in eclipse is 42.8 minutes. It is important to note that during sunlight, the solar cells will supply power to the MAV to recharge batteries and to operate systems. When the MAV is in an eclipse, it will only consume electrical power stored in its batteries. Only 7 batteries are required to meet the power requirement for one eclipse period, but redundancy was added to ensure there is a reserve of battery power. So far, the power system has 14 batteries that are recharged by solar cells with an area of 17.6 m^2 without packing. The total area of the solar cells increases to 19.6 m^2 with packing and drive mechanisms.

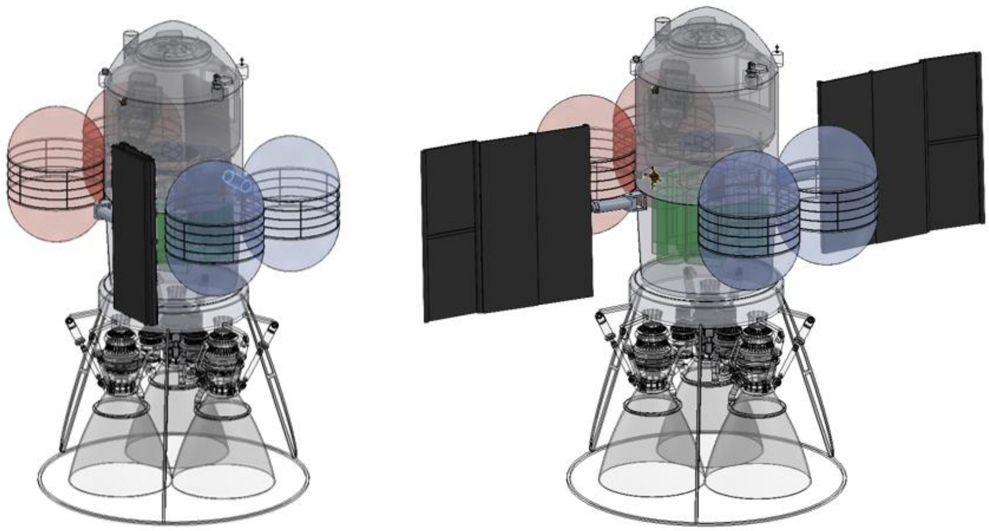


Figure 6.5-1 MAV with Solar Arrays Stowed and Extended

This is rather large for this class of spacecraft however Mars has surface dust storms that have shown to degrade solar cell performance up to 30%. [insert source here] Due to this reduction in performance, larger solar arrays are needed to ensure that power requirements are met to keep systems nominal. This large solar array accounts for these losses and with gimbaling, the solar cells can supply power to the MAV while simultaneously charging all batteries under 66 minutes.

6.6 Command and Data Handling

The MAV is a critical component of the Mars mission, and its reliability is of utmost importance for the success of the mission. To address the potential for system failures and manufacturing defects, the MAV is equipped with redundant components. Specifically, the MAV incorporates two separate OBCs, Solid-State Recorders, and Operating Systems. This approach provides an additional layer of protection against system failures, ensuring the MAV can continue to function properly even if one of the components fails. In such a scenario, the backup component will seamlessly take over to maintain the MAV's vital functions. This redundancy also enables the MAV to continue taking measurements from its sensors and cameras, even if one of the components malfunctions. By ensuring the reliability of the MAV through redundant components, the mission can continue to operate smoothly and achieve its objectives. The primary OBC, manufactured by BAE Systems, boasts an impressive performance of 3.7 GFLOPS, and comes equipped with 1 Gigabyte of Flash memory [42]. This allows for a lightweight operating system, such as Linux, to be installed. Additionally, the storage capacity of this system is modular and provided by Airbus, allowing it to be scaled up from 8 to 32 TB, as shown in **Table 6.6-1** [30].

The secondary OBC, developed by MOOG, is even faster than the first, capable of performing at a rate of 150 GFLOPS [43]. Its flash memory can be used as a tertiary storage unit in the event of malfunctions or memory corruption in the other two storage devices. For this computer, the VxWorks OS was selected, along with a modular storage unit that ranges from 1 to 10 TB [44]. The trade study can be found in **Appendix B-11.1**.

By incorporating redundant OBCs and Solid-State Recorders with different operating systems and storage capabilities, the MAV is able to operate reliably and efficiently even in the face of potential system failures. This helps to ensure the success of the mission by providing critical data handling and processing capabilities in the challenging environment of Mars.

Table 6.6-1 Technical Specifications for MAV C&DH Computers and Storage

BAE Systems/Airbus Combination	
Performance	3.7 GFLOPS
RAM	4 GB w/ ECC
Flash Memory	1 GB w/ ECC
Storage	8 - 32 TB
Operating System	Linux
MOOG	
Performance	150 GFLOPS
RAM	24 GB w/ ECC
Flash Memory	48 GB w/ ECC
Storage	1 – 10 TB
Operating System	VxWorks

Before the ascent, the MAV performs a comprehensive system diagnostic to check the fuel and oxidizer levels. The ECLSS then makes the MAV habitable for the astronauts. The MAV has two OBCs and Solid-State Recorders, ensuring redundancy and reliability. The primary OBC, manufactured by BAE Systems, has a performance of 3.7 GFLOPS, 1 GB of Flash memory, and an Airbus modular storage capacity of 8 to 32 TB. The secondary OBC, made by MOOG, has a higher performance rate of 150 GFLOPS and can be used as tertiary storage. The C&DH subsystem constantly monitors the health of the MAV and the SPDR.

The MAV is equipped with LiDAR and cameras that will facilitate the astronauts to rendezvous with the DST. The MAV can execute commands from Earth, send information directly to Earth, or via the MRN.

When the astronauts enter the MAV, they initiate the launch sequence, and the OBC takes over, igniting the rocket engines. The OBC then initiates the tank separation procedure, and the MAV enters a LMO, aligning itself with the DST. To ensure a precise rendezvous with the DST, the MAV uses Star Trackers, LiDAR, and cameras to align and orient itself.

During the ascent phase, the MAV continues to monitor and maintain its systems to ensure their health and reliability. The OBC executes automated commands and procedures for a smooth ascent and rendezvous with the DST. Once the MAV successfully docks with the DST, the astronauts transfer to the next stage of the mission. Thorough diagnostics are performed constantly to ensure that all systems are functioning correctly.

6.7 Telecommunications

The telecommunications system of the MAV is also based on Perseverance hardware and uses the MRN and DST like the SPDR. The callouts in **Figure 6.7-1** lists the same hardware as **Table 5.6-1** in the SPDR Telecommunications section. It is printed again here for convenience in referencing the callouts in **Figure 6.7-1**. Refer to **Section 5.6** for more details on the hardware, relay stations, and ground stations.

No.	Item
1	UHF Antenna
2	High Gain Antenna (plus Gimbal)
3	Low Gain Antenna
4	UHF Transceiver
5	X-Band Transponder
6	X-Band SS Power Amplifier
7	X-Band Transmitter

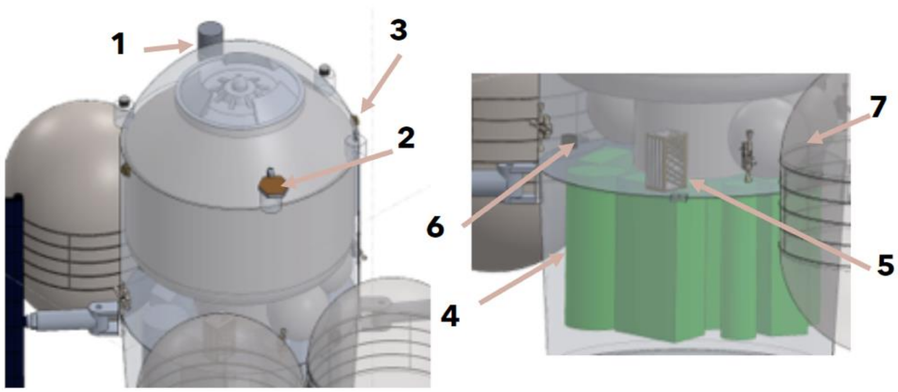


Figure 6.7-1 MAV Telecom Hardware and Callouts

By utilizing the same robust telecommunications systems on both the MAV and SPDR, manufacturing and design costs are kept at a minimum. An additional benefit is that in the case of long-range transmission, the SPDR and MAV can act as communication relays which adds another layer of redundancy.

Table 6.7-1 shows the sensors and bit rates intended to be used on the MAV. Like the SPDR, the MAV will also use different sensors during different operational modes. These modes include "MAV Sleep on Surface", "MAV Refueling", "MAV Launch and Occupied", "MAV In Flight and Occupied", and "MAV Docking and Occupied". Again, for a full in-depth breakdown of the operating modes, which sensors are used, and data rates for each mode, see **Appendix B-11.3**.

Table 6.7-1 MAV Sensor Data Rates

MAV				
Instrument Name	**Number of Sensors**	**Data Rate bps (each)**	**Sampling Rate Hz**	**Sources**
Air Temperature Sensors (MEDA)	1	10000	1	[14], [15]
Relative Humidity Sensor (MEDA)				
Pressure Sensor (MEDA)				
Infrared Sensor (MEDA)				
Wind Sensors (MEDA)				
MSL RAD	1	8000	NA	[45]
REMS	1	9600	50	[16]
Sun Sensors (x8)	8	9600	50	[20]. [21]
Star Tracker	2	9600	50	[40]
Inertial Measuring Unit	1	115200	600	[22]
LIDAR	1	100000000	10	[22], [23]
Altimeter	1	1200	NA	[25]
Cameras	3	96000	24	[24]
Pressure Transducer	8	9600	NA	[25]
Temperature Sensor	6	9600	NA	[26]
Power Sensors	2	1000	1	[27]
Life Support				
LAMS		10000	40	[38]
Cabin Pressure Sensors	2	1400	NA	[46]
Air Quality Sensors	2	10000	40	[47]
Oxygen Management	1	1500	40	[48]
Waste Management	1	10000	40	[48]
Climate Control	1	750000	80	[48]
Audio Relay	1	9600	NA	[49]

Like the SPDR, the MAV uses the same transmission classifications of “live”, long term, or general. It would also need about a terabyte of dedicated sensor storage to keep old data for emergency transmission before being deleted to make new space. For more information on the storage and transmitted data calculations, see **Appendix B-11.3.**

Once again, from the operational modes, and transfer times of the transmission types, we were able to find an estimated telecom schedule for flight-ops as seen in **Figure 6.7-2**.

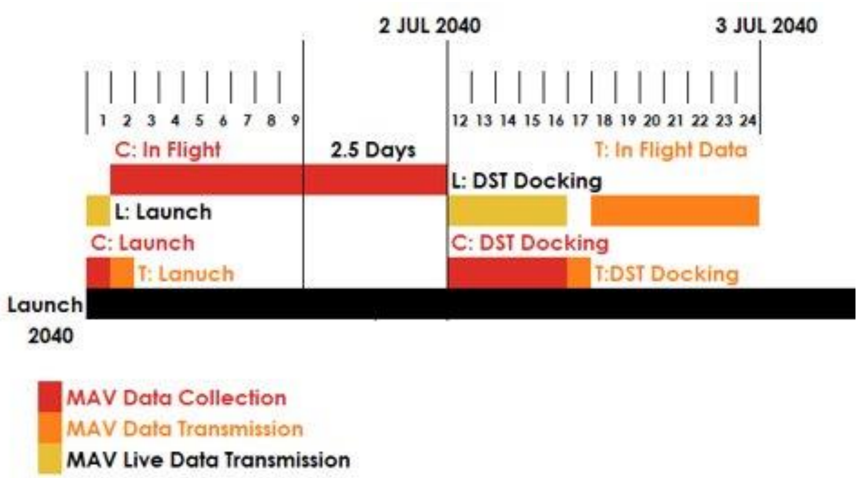


Figure 6.7-2 Example Flight Telecom Schedule

At launch, the MAV will send "live" data while it is possible to do so, as well as collect data to transmit after the launch sequence. In flight, the current plan is to collect data but not transmit it until after docking. There can still be smaller communications with Earth but not the full data from flight. When it is time to rendezvous, the MAV will transmit live docking data then send the rest of the saved data over a few 10-hour days after human transfer to the DST and well before the end-of-mission protocol for the MAV.

6.8 Life Support Systems

During the crew’s surface mission, life support will be provided by a third-party vehicle not represented within the scope of our mission. The MAV supports the crew for a short duration prior to launch, and its primary mission is to support during ascent and during the phasing, rendezvous, and docking portion of the mission. The MAV will inject into an orbit with a period of 5 sols. The MAV launch will be timed so that it takes half a rotation or less to phase with the DST. The MAV life support is sized to support the crew for 5 sols, which is twice the amount of time needed to reach the DST.

There is a short duration mission and analogous to space shuttle examples as described in Human Space Mission Analysis and Design [48]. This source was drawn upon for completing life support technology trade studies and baselining the current MAV life support design as summarized in **Table 6.8-1.** The main functions bookkept under "life support" are crew water, food, crew cargo, atmospheric regulation, and thermal temperature control. A unique aspect of this mission is that the life support systems will be in use for a short duration, but they must survive and be ready for use for several years in a standby state.

Water is recycled by a multi-filtration system to reduce the total amount of stored liquid that is required to be brought from Earth and maintained prior to use. A small reservoir provides make-up water for drinking and food rehydration, but the majority is recycled using similar technology to what is used today on the International Space Station.

Food and cargo are bookkept as inert mass that is present when the vehicle launches from Earth. Shelf-stable freeze-dried food is used for this duration of the mission to provide maximum robustness. Cargo includes a small medical kit, shirt-sleeve environment uniforms, and other necessities. There is also a volume and mass allocation for storing the crew's spacesuits. Related to this, a vacuum cleaning system is included to mitigate the impacts of dust and debris from the Martian regolith.

A trade study was conducted for atmospheric regulation to find the minimal mass and power solution. Options considered but ultimately rejected included a Sabatier reactor and a catalytic bed similar to that employed by the ISS. Ultimately, because of the short duration, lithium hydroxide (LiOH) canisters were deemed the best solution for CO_2 removal. Small tanks of gaseous oxygen and nitrogen provide make-up gas for maintaining pressurization of the cabin in a breathable ratio.

A broader discussion of the mission's thermal design is included in **Section 6.2**. Prior to being inhabited, the interior of the MAV is maintained at 5°C to prevent the stored water from freezing, but to conserve power. The albedo and emissivity of the crew cabin surface coating is tuned so that the spacecraft is cold biased and in the worst-case hot scenario, very little heater power is required to maintain the cabin in the desired crew temperature configuration. For the cold case, additional heater power is necessary. This greatly simplifies the thermal design with the only active components being patch heaters that can turn on and off. This design choice also minimizes radiator area for the size and mass constrained spacecraft.

Table 6.8-1 Life Support Summary

Parameter	Description	Mass [kg]	Volume [m^3]	Power [W]
Water	Multi-filtration water recycling	20	0.	80
Food, Crew Cargo, Accommodations, Spacesuits, Equipment	Freeze-dried food; shuttle-like minimal amenities for short duration mission	726	5.5	489
Atmosphere	Lithium Hydroxide Canisters (remove CO2) + Stored O2 (make-up gas) + Trace contaminant control system	76.5	0.4	112
Thermal	Worst-case-cold power to keep crew cabin warm during eclipse (will be a short duration and could run on batteries, which can be charge the rest of the time)	10	0.01	2667
Crew	2 crew members	190	6	--
Samples	Required Mars Rocks per RFP	50	0.03	--
Totals	totals not including power	1073	11.9	-
Worst Case Cold Total	Totals for MAV in eclipse (short duration)	-	-	3349
Worst Case Hot Total	Totals for MAV in the sunlight, no heaters needed	-	-	681

6.9 Mass and Power Statements

Table 6.9-1 is the current power budget per subsystem for the MAV. Mu3 started this power budget by using reference [2] and researching similar class spacecraft such as Orion, Dragon, and Apollo. The table went through an evolutionary process as Mu3 developed each subsection. Once a subsection had a more detailed design, Mu3 selected hardware.

Table 6.9-1 MAV Power Statements

	MAV POWER STATEMENT			
Subsystem	**Budget, W**	**Margin, %**	**Current, W**	**Status**
Thermal	1763.41	37.1	1108.4	C
ACS	587.80	38.8	360.0	C
Power	106.87	0	106.9	E
CDS	801.55	79.6	163.2	C
Communications	1603.10	89.0	175.8	C
Propulsion	213.75	0	213.8	E
Mechanisms	267.18	0	267.2	E
ECLSS	3348.54	0	3348.5	C
Budget	8692.22	33.9	5743.8	
Payload	600.43	2.0	612.8	C
Margin	956.14	-	0.00	E
MISSION POWER	10248.79	40	6356.6	

The table went through an evolutionary process as Mu3 developed the design for each subsystem. Once a subsection had a more detailed design with hardware, Mu3 updates the power statement to reflect the design. The subsystem consuming the most power is the ECLSS which will house the crew. The thermal subsystem consumes over 1100 W of power to cool the fuel and oxidizer tanks as well as other components on the MAV. This subsystem consumes a large amount of power due to the temperature controls of the fuel and oxidizer. Mu3 was able to reduce initial power requirements using insulation for the fuel and oxidizer tanks. Mu3 was able to reduce power requirements for the CDS and telecommunications subsystems by selecting telecommunications hardware from the SPDR rover.

Currently Mu3 has a 40% margin should extra power be required for operation. This power margin allows Mu3 to have space for additional hardware to mitigate potential issues such as power loss or power system malfunction.

The final PDR-level mass estimate for the MAV is produced from a bottoms-up estimate of using actual masses from selected components where appropriate and using as-design values from the structural model for mechanical components and fuel tanks. Maturity codes were designated for each line item based on the AIAA S-120 mass estimating standard. The required growth allowance depends on the type of component, and the maturity of the concept, ranging from estimate to as-measured existing hardware. For PDR, all components have at least a preliminary design rating, and many have an existing hardware rating due to our emphasis on high heritage components. Additionally, no growth allowance is applied to GFE, which in this case includes the large fission reactor unit on descent, and the samples on ascent.

In addition to a growth allowance based on maturity, there is also a determined allocation for both ascent and descent. For descent during EDL, the total mass is limited by the 25,000 kg capability of the landing vehicle. This is measured against a half-full wet configuration that includes the dry mass of the lander and one of the propellants, with the other propellant to be later delivered by the rover. This case has a high mass margin against the total capability.

For ascent, the critical value to control was the dry mass of the system. This was the basis from which all ΔV and propellant mass calculations were performed. Some margin was included during propulsion system sizing to preserve AIAA S-120 guidelines for how much margin to carry at the PDR stage. The system was designed around a 5000 kg mass to orbit capability. Currently the vehicle's estimated dry mass is 4368 kg including samples and crew, which provides some room for growth during the critical design and build stages.

Table 6.9-2 includes a summary of the different MAV configurations, with dry and wet masses listed for ascent and descent. The margin is shown against the relevant limiting allocation in each case. In the table, CBE reflects the listed hardware mass or model design mass as appropriate. MGA is listed as a function of the S-120 maturity code. The MEV is the sum of the current best estimate and mass growth allowance. The allocation is hard upper limit for the system based on capability. Finally, total margin is calculated as the percentage that the CBE could grow while still fitting within the allocation. For both critical phases, the MAV is currently showing healthy margins.

Table 6.9-2 MAV Mass Summary Table

	CBE Total	**MGA Total**	**MEV Total**	**Allocation**	**Total Margin**
Landing Dry Mass	9228	2.6%	9467	-	-
Landing Wet Mass	13882	1.7%	14121	25000	80.1%
MAV Takeoff Dry Mass	4368	5.5%	4608	5000	14.5%
MAV Takeoff Wet Mass	17864	1.3%	18104	-	-

6.10 Maintenance

As mentioned earlier in **Section 5.1.** SPDR is designed to be fully autonomous, and the MAV must be fully refueled when the astronauts reach the surface of Mars. As such, there will be no humans on the surface of Mars to maintain the rover. However, our telecoms schedule has the capability to support software updates. The software update would be sent by JPL, to the DSN, which will then be relayed by the MRN. Depending on the size of the files, software updates take anywhere from three to four days. An example software that can be implemented is Wheel Speed Algorithm. The Wheel Speed Algorithm will adjust the wheel speed to reduce pressure on the wheels. This is an algorithm already has heritage in Mars Rovers, from which our current wheel designs are inspired from the Perseverance Rover [50]. Another form of maintenance would be decreasing the maximum capacity that the refuel tank can carry. This would decrease the stress on the wheels as they traverse the one-kilometer distance between the landers.

The maintenance of the MAV will be defined by the time of maintenance during the mission, and it will affect the crew functions. The following table describes the time of scheduled maintenance that should be expected per subsystem, the time of unscheduled maintenance, and repairs should be scheduled for a successful mission. It should be noted that this table is for maintenance when humans are present on the surface of Mars, which will be from mid-2040 to July 1st, 2040.

Table 6.10-1 Maintenance During Overall Mission

Key Subsystems during Overall Mission 35 days	Scheduled Maintenance (min avg/day)	Unscheduled Maintenance (min)(% of total time)	Repair time (min) (% of total time)	Total Time: Scheduled, Unscheduled, Repair (min avg/day)
Life support	33.7	4.3 (12.88%)	4.0 (11.73%)	42.0
Propulsion	13.7	1.1 (8.12%)	1.8 (12.86%)	16.6
Data management	3.1	1.4 (44.26%)	.9 (29.58%)	5.5
Structural	12.0	.03 (.27%)	.1 (.72%)	12.1
Electrical	9.4	.4 (4.15%)	.5 (5.2%)	10.3

From NASA's *Maintainability of Manned Spacecraft for Long-Duration Flights* [51] we see that the maintenance is calculated using the occurrence of maintenance spanning from 1, 3, 7, 21, 30 days each with an estimated amount of maintenance time per subsystem. The percentages were optimized using Boeing's Maintainability and Reliability Cost Effectiveness Program which considers parallel redundancy, standby redundancy, and spares redundancy.

Table 6.10-2 Maintenance During Ground Operations

Key Subsystems During Ground Operations 30 days	**Scheduled Maintenance (min avg/day)**	**Unscheduled Maintenance (min) (% of total time)**	**Repair time (min) (% of total time)**	**Total Time: Scheduled, Unscheduled, Repair. (min avg/day)**
Crew System	49.3	.1 (.14%)	.03 (.06%)	49.4
Communications	51.0	1.9 (3.76%)	3.5 (6.92%)	56.5
Mechanical	44.3	-----	10.8 (24.4%)	55.2
Key Subsystems During Ascent 5 days				
In-flight Test System	10.0	.2 (11.94%)	.1 (6.16%)	10.3
Guidance and Navigation	12.0	.9 (7.16%)	2.0 (16.57%)	14.9

From ground mission landing to arrival to the DST, an allotted daily average of 4.5 HRS should be planned for. There should be 2.7 HRS daily average dedicated solely to ground operations alone and .4 HRS daily average during accent mission. The higher of the total min/day average and total time allotted are which are the inflight test systems, life support, mechanical and crew system indicate that they are the most important to ensure the safety of the crew there by requiring the most attention during the mission. The mission specific subsystems were selected due to their use during the overall mission. The scheduled maintenance would be defined as maintenance on a regular cycle- while the unscheduled maintenance- which would take priority- is designed as random failures, human error, and environmental impact on the spacecraft. The repair confidence has been attributed to and embedded in the calculations to simulate an accurate repair time with confidence. It is important to note that training for Spacecraft maintenance and use of tools will be provided on Earth and specific tasks will be delegated to the repair-experienced crew members for ease of function without disruption of the mission goal.

7.0 Mission Lifetime Assessment

7.1 Planetary Protection

According to the Office of Safety & Mission Assurance, both the MAV and SPDR architectures are Category IV under the PPP. The reasoning behind this decision is that both the MAV and SPDR will not be returning to Earth and will remain on Mars after mission completion. It is also imperative to limit the contamination of Mars from these architectures. The required return samples are classified as Category V since they will be transferred to the DST. Key details in the samples handling will be discussed later in this section.

Both the MAV and SPDR will need to be manufactured in a minimum ISO Class 8 Cleanroom. For the MAV and SPDR, backwards contamination will be as limited as possible, and the full end of mission and disposal of the two architectures will be discussed later in **Section 7.3.**

The Martian samples will be transported with the crew within the MAV as mentioned in **Section 5.1**. The samples will be held to PPP standards as well as the COSPAR policies and the SSAP. For conciseness, **Table 7.1-1** shows key requirements that will affect our design and treatment of the samples. It should be reiterated that the extraction and selection of the samples is out of the scope of our mission. The MAV will have the capability to hold and transfer the samples to the DST.

Table 7.1-1 Sample Return Requirements

Relevant Policies	Req. Description
COSPAR("Committee on Space Research")	The samples shall be treated as though they hold Martian life
Sample Safety Assessment Protocol (SSAP)	No samples shall be released during hold
	Sample safety shall be a dynamic process
	Every sample tube shall be considered a separate sample
	Every sample shall be contained in a "multi-layer" containment system
	Samples shall be hermetically sealed

7.2 Fault and Risk Analysis

Since this is a crewed mission, our fault and risk analysis will focus on human design considerations. Starting with Fault Analysis, below in **Figure 7.2-1**, a fault tree is presented with the "Loss of Human Life". For this paper, the focus will be on the "Loss of ECLSS Functionality" branch. This branch is further subdivided into three more sections based on power, waste management, and atmosphere regulation respectively.

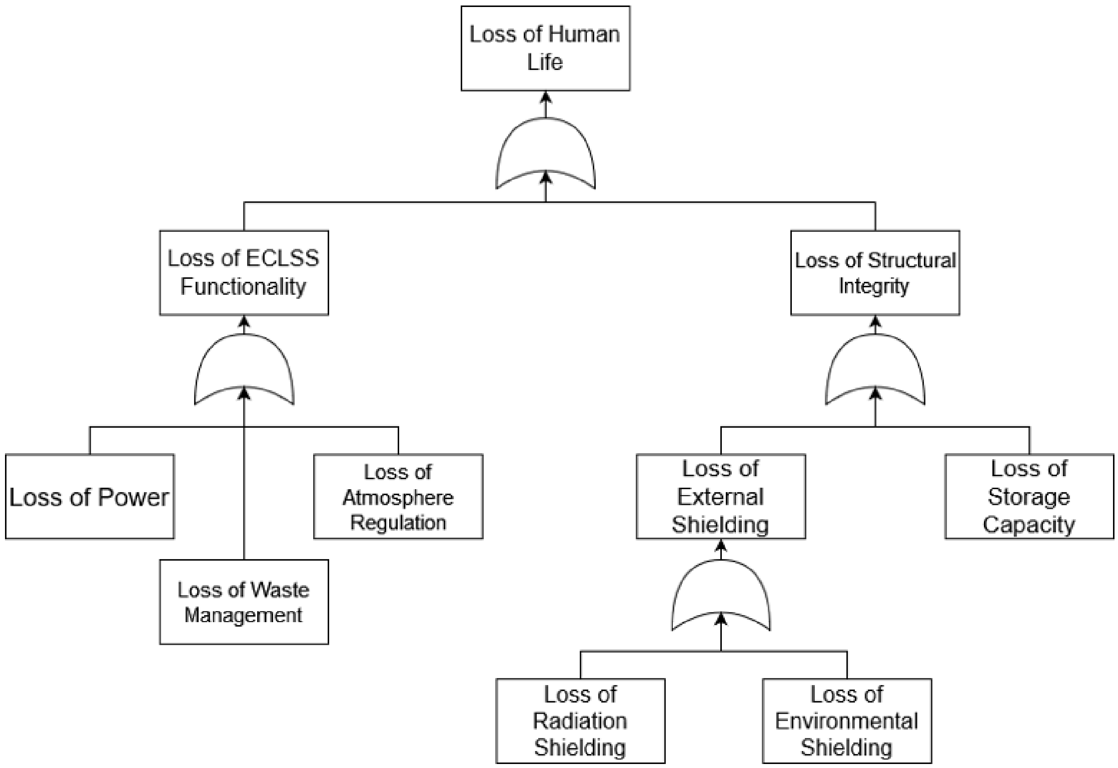


Figure 7.2-1 Fault Tree

Based on the fault tree presented above, risks were derived. The following **Figure 7.2-2** is a risk cube, where likelihood is on the vertical axis, while consequence is on the vertical axis.

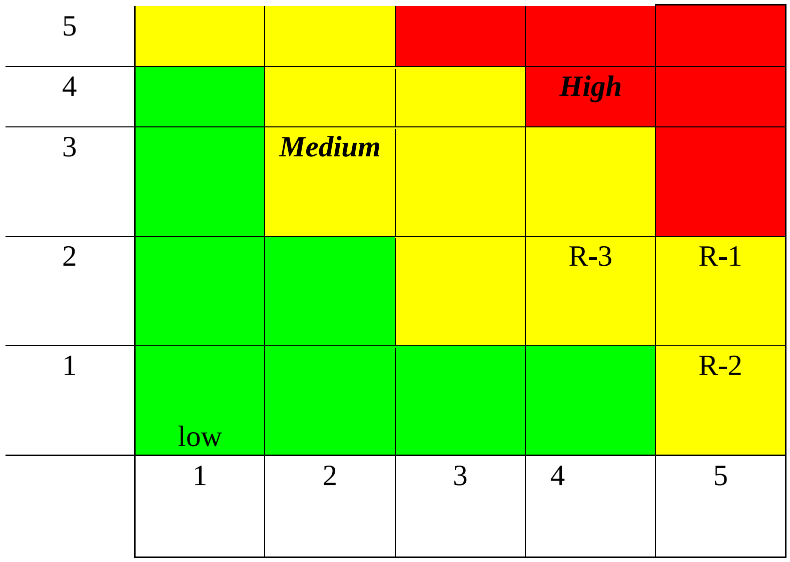


Figure 7.2-2 Risk Cube

Situated on the cube itself are Risks R 1-3, which are expanded upon below in **Table 7.2-1 Risks**.

Table 7.2-1 Risks

Number	Risk
R-1	If the main power fails, due to a shortage, then ECLSS could fail.
R-2	If there is a defective LiOH, due to manufacturing processes, then CO2 may build up in cabin.
R-3	If crew members produce more waste, then there may not be enough filters to remove waste from water.

Note that while the likelihood of the risks is relatively low, the consequences of them are level four or higher. This is since humans will be impacted if the risks in the design are presented. R-1 in particular deals with the design of the power system of the ECLSS. The rest of the risks are associated with the length of the mission, and the associated supplies available on board. **Figure 7.2-3** to **Figure 7.2-5** are the mitigation waterfalls to address the presented risks.

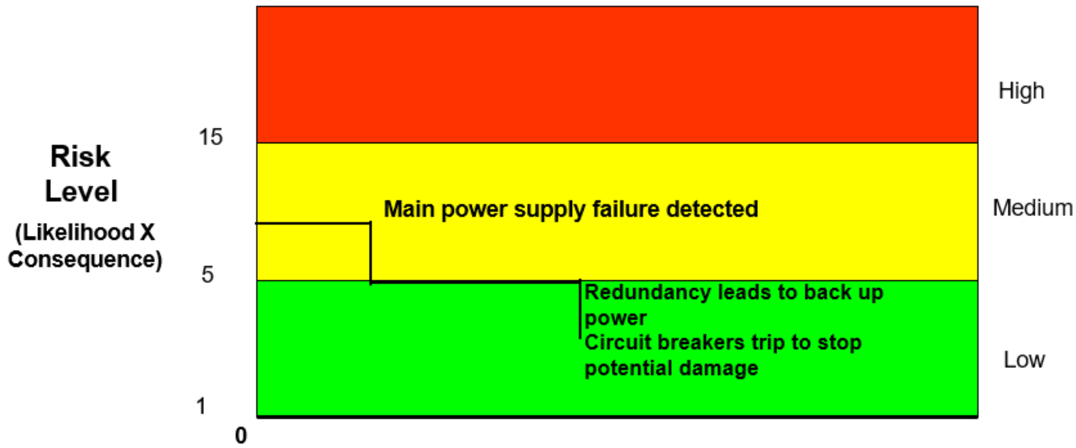


Figure 7.2-3 Mitigation Waterfall

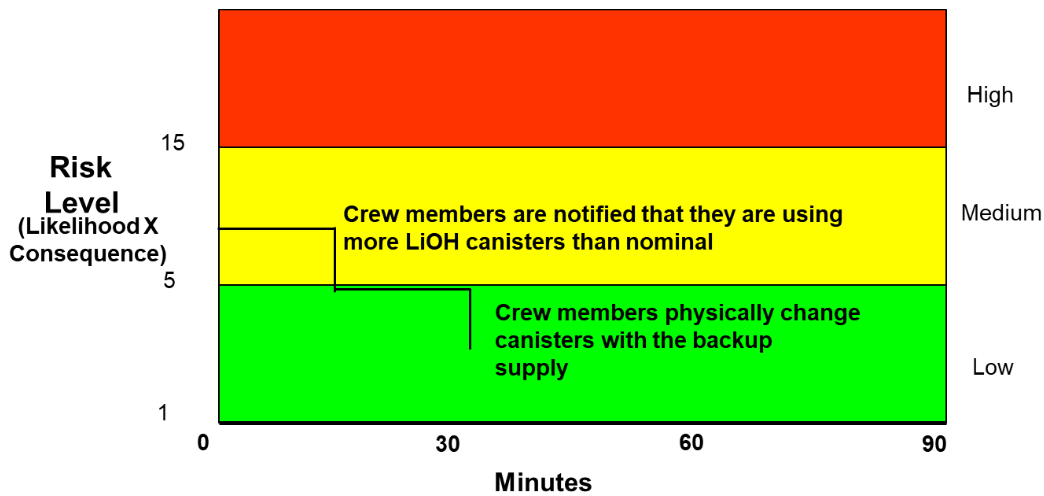


Figure 7.2-4 Mitigation Waterfall

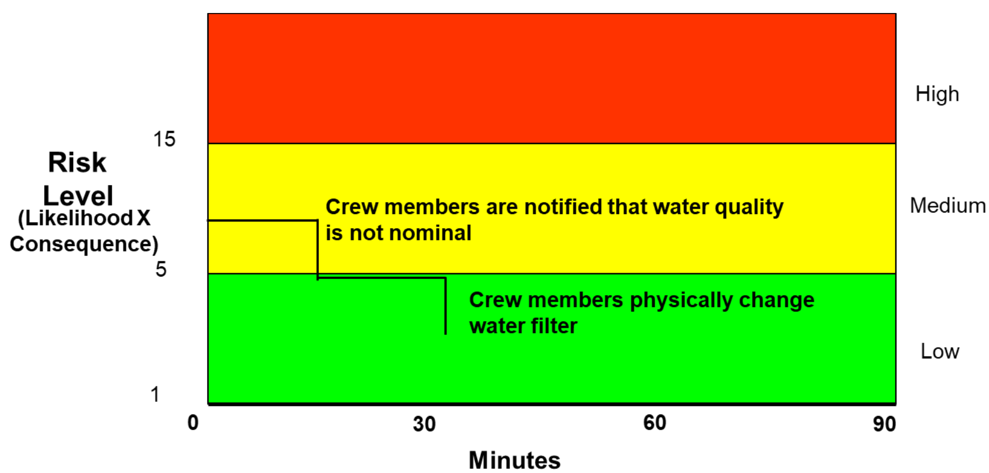


Figure 7.2-5 Mitigation Waterfall

As discussed earlier, though our sources state that the duration of ascent to docking with the DST will only take 2.5 days, our mission has the capability to support the two crew members for a total if five days.

7.3 End of Mission and Disposal

Brough up earlier in **Section 7.1**, PPP states to limit backwards contamination as much as possible. Thus, for the EOM, both the MAV and SPDR will remain within the Mars system.

The SPDR itself will remain on the surface of Mars. After the refueling mission is complete, the SPDR will drive away from the MAV, so as not to interfere with ascent operations. Extra fuel, either left in the RFL or SPDR propellant tanks, will remain in the tanks. However, the remaining pressure will be vented. Without proper temperature regulation, the NTO will freeze, and remain in the tanks. The titanium alloy (Ti-13V-11Cr-3Al) tanks will not rust under the harsh Martian environment, and they will resist corrosion. Since the SPDR is a fully autonomous rover, and was manufactured and stored in a clean room, the probability of contaminating the surface of Mars with Earth related microbes is minimal.

The End of Mission for the MAV occurs after the crew members are safely transferred to the DST, as well as the samples. Following this process, the MAV will undock with the DST. Unlike the SPDR, the MAV will have human related contaminations, and therefore needs to be disposed of carefully. The MAV will remain in the 5-sol rendezvous orbit, until natural decay, and will eventually deorbit. Due to the limitations of cleaning methods in a Martian Orbital environment, the MAV will not be cleaned after use. Instead, a simulation of the MAV in the 5-sol orbit shows that it will remain in orbit for over twenty years. The output can be seen in **Appendix B-11.4**. During these years, there will be no life support, and thus the MAV will be more of an orbiter. We expect that the microbes and contamination left by the astronauts will be gone, after spending twenty years subjected to the Mars orbital environment.

7.4 Cost

The NASA PCEC software was used to estimate cost of each element in both architectures [52]. Some inputs to the model include mass, number of components per vehicle, and mission risk class. Due to the highly critical human safety aspect of the mission, it is rated as a Class A, directed mission. The cost also includes 15% management reserve. Because Mu3 is developing vehicles for NASA, the "Contractor PM, Industry build" option was selected. Some additional assumptions in the use of FY2022 dollars as a basis of estimate for the cost, and the fact that the landers (included the rover egress system) are provided separately and not included in this cost estimate.

While the MAV is a complex, high-mass vehicle, most components have high heritage. The focused scope of integrating the existing components without new development or extensive scientific instruments limits the opportunity for cost risk. The rover, again while larger, is a straightforward development that can leverage heritage from other Mars rover designs such as Curiosity and Perseverance, with the primary changes being structural and the addition of a fuel tank and transfer arm. No scientific payloads are included other than what is needed to navigate, and this reduces integration complexity. While the PCEC tool depends primarily on mass and power as inputs for cost estimation, the above design choices support the credibility of its outputs and limit the risk of cost increases throughout the course of development. This analysis shows that the architecture proposed meets RFP Requirement 0.01 that the cost shall not exceed $4.0B. **Table 7.4-1** summarizes the total cost of both elements, including a 15% management reserve in each. **Table 7.4-1** and **Table 7.4-2** show detailed cost estimates for the MAV and Rover, respectively. These two tables are sourced from the PCEC tool summarized with respective WBS references. The full table can be found in **Appendix B-11.5.**

Table 7.4-1 Architecture Cost Estimate

Element	Cost [$B, FY2022]	Source
MAV	2.1	NASA PCEC
SPDR	1.8	NASA PCEC
TOTAL	**3.9**	**NASA PCEC**

Table 7.4-2 MAV Cost Details Summarized with WBS

MAV

FY2022 $M

WBS #	Line Item Name/Description	DDT&E	Design & Development	System Test Hardware	Flight Unit	Production	Total
	System Name	**$ 1,670.6**	**$ 1,548.2**	**$ 122.6**	**$ 124.2**	**$ 124.2**	**$ 1,816.1**
1.0	Project Management	**$ 111.4**	$ 111.4	-	$ 12.8	**$ 12.8**	**$ 124.2**
2.0	Systems Engineering	**$ 173.0**	$ 173.0	-	$ 17.3	**$ 17.3**	**$ 190.4**
3.0	Safety/Mission Assurance	**$ 163.1**	$ 163.1	-	-	**-**	**$ 184.0**
4.0	Payload	**$ 518.2**	$ 430.1	$ 88.1	$ 67.7	**$ 67.7**	**$ 585.9**
5.0	Spacecraft	**$ 356.9**	$ 322.6	$ 34.5	$ 26.4	**$ 26.4**	**$ 383.3**
6.0	Manufacturing	**$ 348.0**	$ 348.0	-	-	**-**	**$ 348.0**

	Total w/ Reserves
Reserves	**$ 2,088.5**

Table 7.4-3 Rover Fuel and Depot Cost Details Summarized with WBS

SPDR

FY2022 $M

WBS #	Line Item Name/Description	DDT&E	Design & Development	System Test Hardware	Flight Unit	Production	Total
	System Name	**$ 1,473.6**	**$ 1,369.5**	**$ 104.0**	**$ 125.5**	**$ 125.5**	**$ 1,599.0**
1.0	Project Management	**$ 104.4**	$ 104.4	-	$ 11.5	**$ 11.5**	**$ 115.9**
2.0	Systems Engineering	**$ 152.7**	$ 152.7	-	$ 15.4	**$ 15.4**	**$ 168.1**
3.0	Safety/Mission Assurance	**$ 143.4**	$ 143.4	$ -	$ 18.5	**$ 18.5**	**$ 161.9**
4.0	Payload	**$ 47.0**	$ 34.3	$ 12.7	$ 9.8	**$ 9.8**	**$ 56.8**
5.0	Spacecraft	**$ 734.1**	$ 642.7	$ 91.3	$ 70.3	**$ 70.3**	**$ 804.5**
6.0	Manufacturing	**$ 292.0**	$ 292.0	$ -	$ -	**$ -**	**$ 292.0**

	Total w/ Reserves
Reserves	**$ 1,838.9**

8.0 Conclusion

In conclusion Mu3 and the MAVERICK program will represent a significant paradigm shift in human space exploration. Driven by well-defined design drivers including cost, size constraints, planetary protection, and launch readiness, Mu3's design is the culmination of significant development and research with its focus on developing the necessary architectures and technologies, MAVERICK aims to ensure the secure return of astronauts from Mars to an awaiting Deep Space Transit Vehicle in a 5-sol orbit.

Though ambitious, MAVERICK necessitates the use of a dual lander ascent vehicle system composed of the MAV and the SPDR. The overall mission can be divided into two distinct phases: the Ground Phase and the Ascent Phase. During the Ground Phase, autonomous propellant transfer occurs between the RFL and the MAV. In the Ascent Phase, the MAV launches, ascends, and docks with the orbiting DST.

Following the manufacturing engineering principles of 'first-time-right' and concurrent development, the overall cost of the mission as defined by the mission scope falls beneath the $4 billion cost constraint. Additionally, as shown and elaborated on in their specific sections, Mu3 has met every requirement provided by the AIAA.

Mu3 will play a vital role in bringing humans back from Mars and in the process, help bring humanity closer to the future. Indeed, in the age of emerging technologies, successfully returning humans to Earth will provide everlasting proof of humanity's ingenuity.

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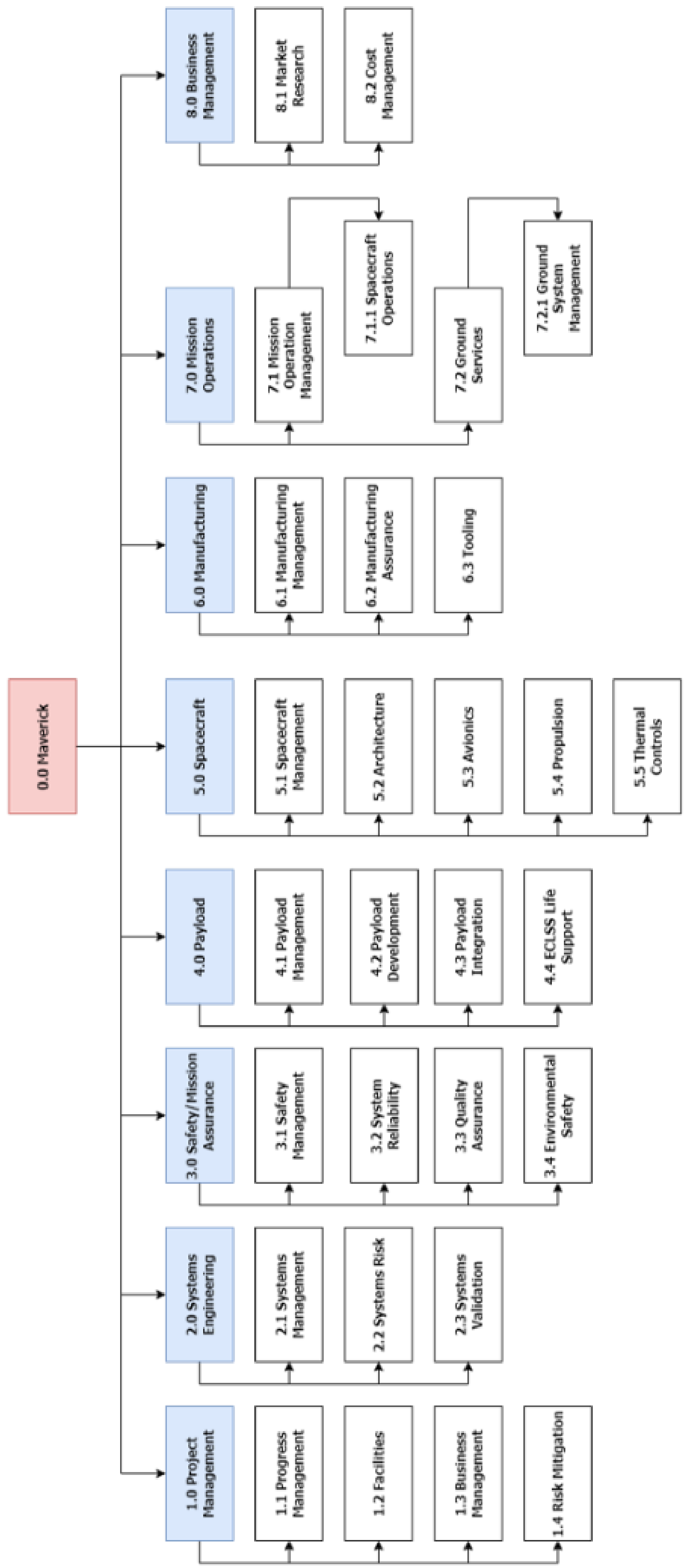
10.0 Appendix A: Work Break Down Structure



11.0 Appendix B: Additional Work

11.1 Trade Studies

MAV Computer Trade Sturdy

Manufacturer	MOOG – 150 GFLOP		Airbus – ICDE-NG		BAE Systems – RAD 5545	
	Score	Wt.	Score	Wt.	Score	Wt.
Performance	3	3	1	3	2	3
RAM	3	2	1	2	2	2
Flash	3	2	---	2	2	2
Total	21		5		14	

Main Engine Trade Study

Main Engine											
FOM	WF	Req. Value	Liquid Monopropellant Engine (MR-80B)			Liquid Bi-Propellant Engine (RS-72)			Electronic Propulsion System (NSTAR)		
			Value	Score	Tot. Wt.	Value	Score	Tot. Wt.	Value	Score	Tot. Wt.
ISP	2	> 300 s	225 s	3	6	340 s	3	6	1814 – 3000s	1	2
Mass	3	< 200 kg	170 kg	1	3	138 kg	3	9	8.2 kg	3	9
Cost	3	Low Cost	----	3	9	~ $8 M	2	6	~ $50 M	1	3
Propellant	2	Req. Prop	Hydrazine Hypergolic mixture	1	2	MMH & NTO	3	6	Xenon	3	6
Total			20			27			20		

MAV ACS Trade Study

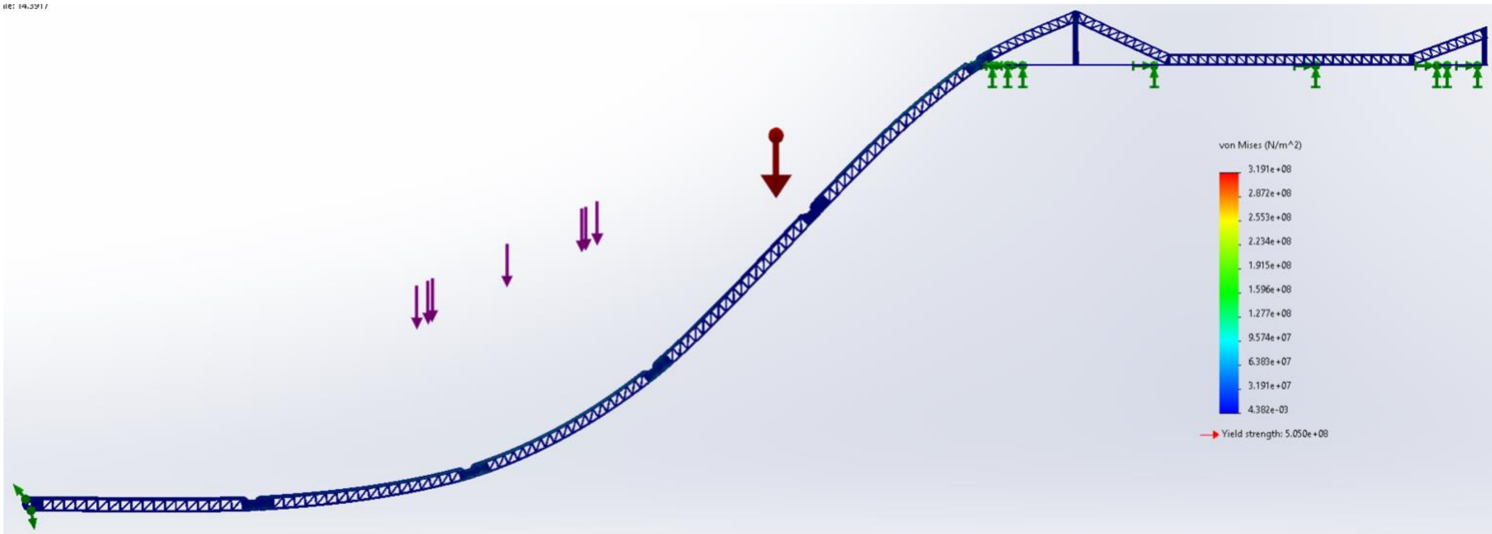
MAV ACS											
FOM	WF	Req. Value	L400 N Hydrazine Thruster			Monarc-445			Monarc-22-6		
			Value	Score	Tot. Wt.	Value	Score	Tot. Wt.	Value	Score	Tot. Wt.
ISP	2	> 200 s	220 s	1	2	234 s	1	2	230 s	3	6
Mass	3	< 3 kg	3.8	1	3	1.6 kg	2	6	0.72 kg	3	9
Min Impulse	2	< 10 N-s	9 N-s	1	2	11.5 N-s	1	2	0.312 N-s	3	4
Thruster	2	< 20 N	120 – 400 N-s	1	2	445 N	3	6	22 s	1	2
Total			9			16			21		

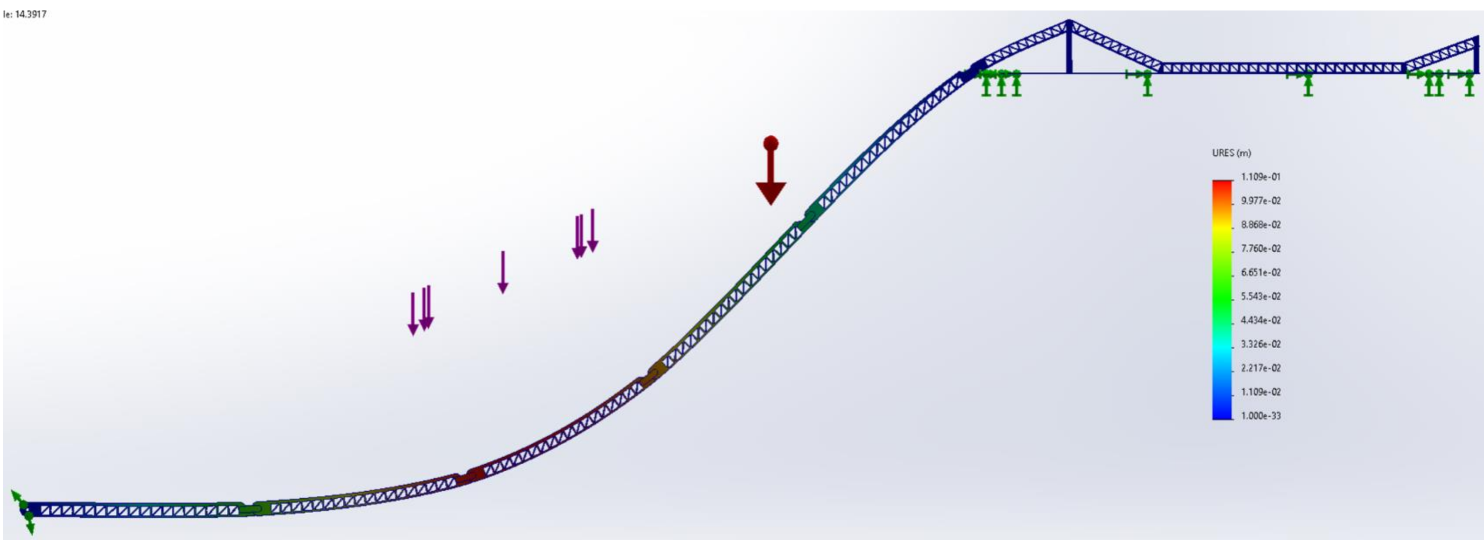
11.2 Additional Structural Analysis Information

RFL Ramp in Operating Conditions

Ramp In Operating Conditions

Mass of rover Wet (kg)=	3000
Gravity (m/s^2) =	3.721
Weight of rover (N) =	11163
Weight of rover per ramp (N)=	5581.5





11.3 Additional Telecommunications Information

Operational Modes and Data Rates

Rover in Transport				
Sensor	Full rate (bps)	Transmitted Data Rate (bps)	Data Rate w/ Max Overhead (bps)	Symbol Rate (bps)
MEDA	10000	667	741	1481
REMS	9600	640	711	1422
Sun Sensors (x2)	19200	640	711	1422
Inertial Measuring Unit (x1)	115200	7680	8533	17067
Cameras (x3)	288000	6000	6667	13333
Pressure Transducer (x2)	19200	640	711	1422
Temperature Sensor (x2)	19200	640	711	1422
Power sensors (x2)	2000	67	74	148
Total	482400	16973	18859	37719

Rover Docking				
Sensor	Full rate (bps)	Transmitted Data Rate (bps)	Data Rate w/ Max Overhead (bps)	Symbol Rate (bps)
MEDA	10000	10000	11111	22222
REMS	9600	9600	10667	21333
Sun Sensors (x5)	19200	19200	21333	42667
LIDAR	100000000	10000000	11111111	22222222
Cameras (x3)	288000	288000	320000	640000
Pressure Transducer (x2)	19200	19200	21333	42667
Temperature Sensor (x2)	19200	19200	21333	42667
Power sensors (x2)	2000	2000	2222	4444
Total	100367200	367200	408000	816000

Rover Transferring Propellant				
Sensor	Full rate (bps)	Transmitted Data Rate (bps)	Data Rate w/ Max Overhead (bps)	Symbol Rate (bps)
MEDA	10000	10000	11111	22222
REMS	9600	9600	10667	21333
Sun Sensors (x5)	19200	19200	21333	42667
Cameras (x3)	288000	288000	320000	640000
Pressure Transducer (x2)	9600	9600	10667	21333
Temperature Sensor (x2)	9600	9600	10667	21333
Power sensors (x2)	2000	2000	2222	4444
Total	348000	348000	386667	773333

MAV Sleep on Surface				
Sensor	Full rate (bps)	Transmitted Data Rate (bps)	Data Rate w/ Max Overhead (bps)	Symbol Rate (bps)
MEDA	10000	666.6666667	741	1481
Cameras (x3)	288000	12000	13333	26667
Pressure Transducer (x4)	19200	1280	1422	2844
Temperature Sensor (x3)	28800	1920	2133	4267
Power sensors (x2)	2000	133.3333333	148	296
Total	348000	16000	17778	35556

Operational Modes and Data Rates Continued

MAV Refueling				
Sensor	Full rate (bps)	Transmitted Data Rate (bps)	Data Rate w/ Max Overhead (bps)	Symbol Rate (bps)
MEDA	10000	10000	11111	22222
MSL RAD	8000	8000	8889	17778
REMS	9600	9600	10667	21333
Sun Sensors (x8)	9600	9600	10667	21333
Cameras (x3)	288000	288000	320000	640000
Pressure Transducer (x8)	76800	76800	85333	170667
Temperature Sensor (x6)	9600	9601	10668	21336
Power sensors (x2)	2000	2000	2222	4444
Total	413600	413601	459557	919113

MAV Launch and Occupied				
Sensor	Full rate (bps)	Transmitted Data Rate (bps)	Data Rate w/ Max Overhead (bps)	Symbol Rate (bps)
MEDA	10000	10000	11111	22222
MSL RAD	8000	8000	8889	17778
REMS	9600	9600	10667	21333
Inertial Measuring Unit	115200	384	427	853
Altimeter	1200	1200	1333	2667
Sun Sensors (x8)	76800	76800	85333	170667
Star Tracker (x2)	19200	9600	10667	21333
Cameras (x3)	288000	144000	160000	320000
Pressure Transducer (x8)	76800	2560	2844	5689
Temperature Sensor (x6)	57600	1920	2133	4267
Power sensors (x2)	2000	2000	2222	4444
LAMS	10000	250	278	556
Cabin Pressure Sensors (x2)	2800	2800	3111	6222
Air Quality Sensors (x2)	20000	500	556	1111
Oxygen Management	1500	37.5	42	83
Waste Management	10000	250	278	556
Climate Control	750000	9375	10417	20833
Audio Relay	9600	9600	10667	21333
Total	1468300	288877	320974	641948

MAV In flight and Occupied				
Sensor	Full rate (bps)	Transmitted Data Rate (bps)	Data Rate w/ Max Overhead (bps)	Symbol Rate (bps)
MSL RAD	8000	8000	8889	17778
REMS	9600	9600	10667	21333
Inertial Measuring Unit	115200	384	427	853
Altimeter	1200	1200	1333	2667
Sun Sensors (x8)	76800	76800	85333	170667
Star Tracker (x2)	19200	9600	10667	21333
Cameras (x3)	288000	48000	53333	106667
Pressure Transducer (x8)	76800	2560	2844	5689
Temperature Sensor (x6)	57600	1920	2133	4267
Power sensors (x2)	2000	2000	2222	4444
LAMS	10000	250	278	556
Cabin Pressure Sensors (x2)	2800	2800	3111	6222
Air Quality Sensors (x2)	20000	500	556	1111
Oxygen Management	1500	37.5	42	83
Waste Management	10000	250	278	556
Climate Control	750000	9375	10417	20833
Audio Relay	9600	9600	10667	21333
Total	1458300	91438	101598	203196 *

Operational Modes and Data Rates Continued

MAV Docking and Occupied				
Sensor	Full rate (bps)	Transmitted Data Rate (bps)	Data Rate w/ Max Overhead (bps)	Symbol Rate (bps)
MSL RAD	8000	8000	8889	17778
REMS	9600	9600	10667	21333
Inertial Measuring Unit	115200	384	427	853
LIDAR	100000000	10000000	11111111	22222222
Sun Sensors (x8)	76800	76800	85333	170667
Star Tracker (x2)	19200	9600	10667	21333
Cameras (x3)	288000	144000	160000	320000
Pressure Transducer (x8)	76800	2560	2844	5689
Temperature Sensor (x6)	57600	1920	2133	4267
Power sensors (x2)	2000	2000	2222	4444
LAMS	10000	250	278	556
Cabin Pressure Sensors (x2)	2800	2800	3111	6222
Air Quality Sensors (x2)	20000	500	556	1111
Oxygen Management	1500	38	42	83
Waste Management	10000	250	278	556
Climate Control	750000	9375	10417	20833
Audio Relay	9600	9600	10667	21333
Total	101457100	277677	308529	617059

Symbol Rates and Transmission Types

	Total Sensor Datarate (bps)	With Overhead (bps)	Total Symbol Rate (bps)	UHF Live/ Long Term Rate (bps)	Total Symbol Rate (Tbps)	UHF Live Rate (Tbps)
Rover in Transport	482400	536000	1072000	37719	1.07E-06	3.77E-08
Rover Docking	100367200	111519111	223038222	816000	2.23E-04	8.16E-07
Rover Transferring Propellant	348000	386667	773333	773333	7.73E-07	7.73E-07
MAV Sleep on Surface	348000	386667	773333	35556	7.73E-07	3.56E-08
MAV Refueling	413600	459556	919111	919113	9.19E-07	9.19E-07
MAV Launch and Occupied	1468300	1631444	3262889	641948	3.26E-06	6.42E-07
MAV In flight and Occupied	1458300	1620333	3240667	203196	3.24E-06	2.03E-07
MAV Docking and Occupied	101457100	112730111	225460222	617059	2.25E-04	6.17E-07

Storage Calculations

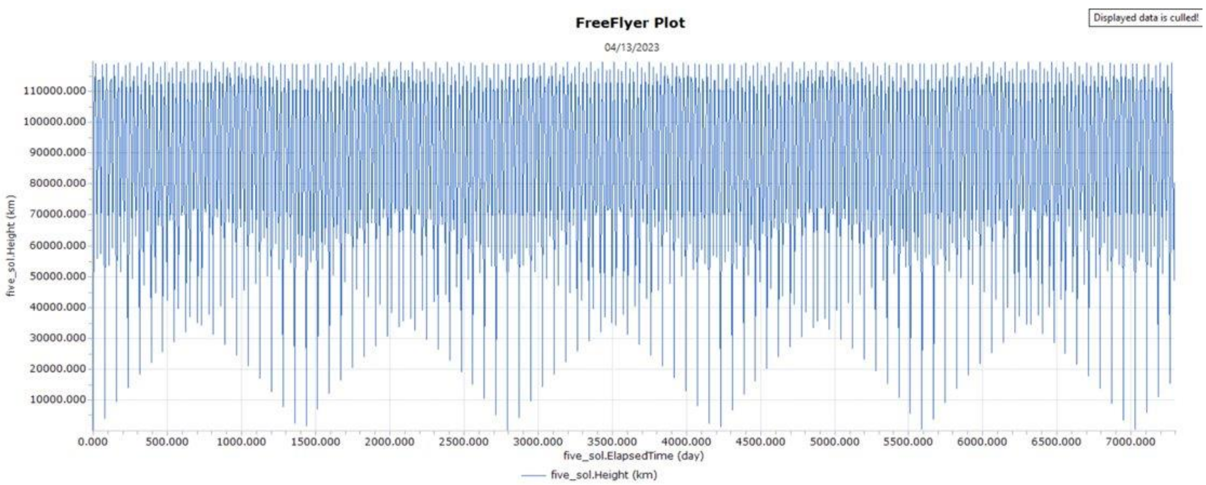
	Storage Capacity (Tb)				
	8	12	16	24	32
Seconds to Full Saturation					
Rover in Transport	7462687	11194030	14925373	22388060	29850746
Rover Docking	35868	53802	71737	107605	143473
Rover Transferring Propellant	10344828	15517241	20689655	31034483	41379310
MAV Sleep on Surface	10344828	15517241	20689655	31034483	41379310
MAV Refueling	8704062	13056093	17408124	26112186	34816248
MAV Launch and Occupied	2451815	3677723	4903630	7355445	9807260
MAV In flight and Occupied	2468628	3702942	4937256	7405884	9874511
MAV Docking and Occupied	35483	53224	70966	106449	141932
Hours to Full Saturation					
Rover in Transport	2073.0	3109.5	4145.9	6218.9	8291.9
Rover Docking	10.0	14.9	19.9	29.9	39.9
Rover Transferring Propellant	2873.6	4310.3	5747.1	8620.7	11494.3
MAV Sleep on Surface	2873.6	4310.3	5747.1	8620.7	11494.3
MAV Refueling	2417.8	3626.7	4835.6	7253.4	9671.2
MAV Launch and Occupied	681.1	1021.6	1362.1	2043.2	2724.2
MAV In flight and Occupied	685.7	1028.6	1371.5	2057.2	2742.9
MAV Docking and Occupied	9.9	14.8	19.7	29.6	39.4
Earth Days to Full Saturation					
Rover in Transport	86.61	129.92	173.22	259.83	346.44
Rover Docking	0.42	0.62	0.83	1.25	1.67
Rover Transferring Propellant	120.06	180.09	240.12	360.18	480.24
MAV Sleep on Surface	120.06	180.09	240.12	360.18	480.24
MAV Refueling	101.02	151.53	202.03	303.05	404.07
MAV Launch and Occupied	28.46	42.68	56.91	85.37	113.82
MAV In flight and Occupied	28.65	42.98	57.30	85.95	114.60
MAV Docking and Occupied	0.41	0.62	0.82	1.24	1.65

Data Modes, Collection Time, Sent Bits, and Transfer Times

Live
Long-Term Nominal
Long-Term Total

Data Modes	Collection Time (hr)	Data Sent (bits)	Transfer Time (s)	Transfer Time (hr)	Transfer Time (10-hour Days)	Transmitted Symbol Rate (bps)
Rover in Transport	359.0	1.39E+12	6.93E+05	192.43	19.24	2000000
Rover in Transport	359.0	4.87E+10	2.44E+04	6.77	0.68	2000000
Rover Docking Data	1.0	0	0	0	0	816000
Rover Docking (no LIDAR)	1.0	2.94E+09	1.47E+03	0.41	0.04	2000000
Rover 2 Minute Lidar Data	0.0	2.67E+10	1.33E+04	3.70	0.37	2000000
Rover MAV Refueling	4.0	1.11E+10	5.57E+03	1.55	0.15	2000000
MAV Sleep	359.0	1.00E+12	5.00E+05	138.82	13.88	2000000
MAV Sleep	359.0	4.60E+10	2.30E+04	6.38	0.64	2000000
MAV Rover Refueling	4.0	1.32E+10	6.62E+03	1.84	0.18	2000000
MAV Launch Data	0.5	0	0	0	0	641948
MAV Launch	0.5	5.87E+09	2.94E+03	0.82	0.08	2000000
MAV In Flight	71.8	8.38E+11	4.19E+05	116.35	11.63	2000000
MAV In Flight	71.8	5.25E+10	2.63E+04	7.30	0.73	2000000
MAV DST Docking Data	5.0	0	0	0	0	617059
MAV DST Docking (no Lidar)	5.0	5.83E+10	2.91E+04	8.10	0.81	2000000
MAV 2 Minute LIDAR Data	0.0	2.67E+10	1.33E+04	3.70	0.37	2000000

11.4 Additional End of Mission Information



11.5 NASA PCEC Tables

FY2022 $M			Inflation Factor:	1.134				
WBS #	**Level**	**Line Item Name/Description**	**DDT&E**	**Design & Development**	**System Test Hardware**	**Flight Unit**	**Production**	**TOTAL**
0	**1**	**System Name**	**$ 1,670.9**	**$ 1,548.4**	**$ 122.5**	**$ 145.1**	**$ 145.1**	**$ 1,816.1**
6.0	2	Flight System \ Spacecraft	**$ 1,670.9**	$ 1,548.4	$ 122.5	$ 145.1	**$ 145.1**	**$ 1,816.1**
6.01	3	Crewed Vehicle Management	**$ 111.4**	$ 111.4	$ -	$ 12.8	**$ 12.8**	**$ 124.2**
6.02	3	Crewed Vehicle Systems Engineering	**$ 173.0**	$ 173.0	$ -	$ 17.3	**$ 17.3**	**$ 190.4**
6.10	3	Crewed Vehicle	**$ 875.3**	$ 752.8	$ 122.5	$ 94.2	**$ 94.2**	**$ 969.5**
--	4	Primary Crew Structures	**$ 385.5**	$ 350.6	$ 34.9	$ 26.8	**$ 26.8**	**$ 412.3**
--	5	Fuselage/Body	**$ 184.7**	$ 168.5	$ 16.2	$ 12.4	**$ 12.4**	**$ 197.1**
--	5	Capsule Structures	**$ 200.8**	$ 182.1	$ 18.7	$ 14.4	**$ 14.4**	**$ 215.2**
--	4	Thrust Structure	**$ 9.0**	$ 7.5	$ 1.6	$ 1.2	**$ 1.2**	**$ 10.2**
--	4	Secondary Structures	**$ 6.8**	$ 4.5	$ 2.4	$ 1.8	**$ 1.8**	**$ 8.6**
--	4	Tanks	**$ 47.1**	$ 34.3	$ 12.8	$ 9.8	**$ 9.8**	**$ 56.9**
--	5	Fuel Tank	**$ 23.6**	$ 17.2	$ 6.4	$ 4.9	**$ 4.9**	**$ 28.5**
--	5	Oxidizer Tank	**$ 23.6**	$ 17.2	$ 6.4	$ 4.9	**$ 4.9**	**$ 28.5**
--	4	Mechanisms	**$ 116.0**	$ 110.4	$ 5.6	$ 4.3	**$ 4.3**	**$ 120.3**
--	5	Separation	**$ 33.8**	$ 32.1	$ 1.7	$ 1.3	**$ 1.3**	**$ 35.1**
--	5	Recovery	**$ 82.2**	$ 78.2	$ 3.9	$ 3.0	**$ 3.0**	**$ 85.2**
--	4	Propulsion	**$ 2.5**	$ 2.1	$ 0.4	$ 0.3	**$ 0.3**	**$ 2.8**
--	5	Reaction Control/Orb Maneuv Sys	**$ 2.5**	$ 2.1	$ 0.4	$ 0.3	**$ 0.3**	**$ 2.8**
--	4	Avionics	**$ 15.2**	$ 14.0	$ 1.2	$ 0.9	**$ 0.9**	**$ 16.1**
--	5	Range Safety	**$ 15.2**	$ 14.0	$ 1.2	$ 0.9	**$ 0.9**	**$ 16.1**
--	4	Electric Power	**$ 141.1**	$ 130.6	$ 10.5	$ 8.1	**$ 8.1**	**$ 149.2**
--	4	Crew Systems	**$ 132.7**	$ 79.5	$ 53.2	$ 40.9	**$ 40.9**	**$ 173.6**
--	4	Software	**$ 19.2**	$ 19.2	$ -	$ -	**$ -**	**$ 19.2**
--	5	Flight Software	**$ 12.8**	$ 12.8	$ -	$ -	**$ -**	**$ 12.8**
--	5	Ground Software	**$ 6.4**	$ 6.4	$ -	$ -	**$ -**	**$ 6.4**
6.60	3	Integration, Assembly, Checkout	**$ 24.8**	$ 24.8	$ -	$ 20.8	**$ 20.8**	**$ 45.7**
6.70	3	System Test Operations	**$ 138.3**	$ 138.3	$ -	$ -	**$ -**	**$ 138.3**
6.80	3	Ground Segment	**$ 348.0**	$ 348.0	$ -	$ -	**$ -**	**$ 348.0**
6.80.01	4	Ground/Test Support Equip	**$ 272.1**	$ 272.1	$ -	$ -	**$ -**	**$ 272.1**
6.80.02	4	Tooling	**$ 76.0**	$ 76.0	$ -	$ -	**$ -**	**$ 76.0**

Figure 11.5-1 Full MAV PCEC Table

FY2022 $M		Inflation Factor: 1.134						
WBS #	Level	Line Item Name/Description	DDT&E	Design & Development	System Test Hardware	Flight Unit	Production	TOTAL
0	**1**	**System Name**	**$ 1,473.6**	**$ 1,369.5**	**$ 104.1**	**$ 125.5**	**$ 125.5**	**$ 1,599.0**
6.0	2	Flight System \ Spacecraft	**$ 1,473.6**	$ 1,369.5	$ 104.1	$ 125.5	**$ 125.5**	**$ 1,599.0**
6.01	3	Vehicle Management	**$ 104.4**	$ 104.4	$ -	$ 11.5	**$ 11.5**	**$ 115.9**
6.02	3	Vehicle Systems Engineering	**$ 152.7**	$ 152.7	$ -	$ 15.4	**$ 15.4**	**$ 168.1**
6.10	3	Vehicle	**$ 781.1**	$ 677.0	$ 104.1	$ 80.1	**$ 80.1**	**$ 861.2**
--	4	Primary Structures	**$ 352.9**	$ 303.6	$ 49.2	$ 37.9	**$ 37.9**	**$ 390.8**
--	4	Tanks	**$ 47.0**	$ 34.3	$ 12.7	$ 9.8	**$ 9.8**	**$ 56.8**
--	4	Mechanisms	**$ 256.7**	$ 222.0	$ 34.7	$ 26.7	**$ 26.7**	**$ 283.5**
--	4	Avionics	**$ 15.2**	$ 14.0	$ 1.2	$ 0.9	**$ 0.9**	**$ 16.1**
--	5	Range Safety	**$ 15.2**	$ 14.0	$ 1.2	$ 0.9	**$ 0.9**	**$ 16.1**
--	4	Electric Power	**$ 90.1**	$ 83.9	$ 6.2	$ 4.8	**$ 4.8**	**$ 94.9**
--	4	Software	**$ 19.2**	$ 19.2	$ -	$ -	**$ -**	**$ 19.2**
--	5	Flight Software	**$ 12.8**	$ 12.8	$ -	$ -	**$ -**	**$ 12.8**
--	5	Ground Software	**$ 6.4**	$ 6.4	$ -	$ -	**$ -**	**$ 6.4**
6.60	3	Integration, Assembly, Checkout	**$ 22.9**	$ 22.9	$ -	$ 18.5	**$ 18.5**	**$ 41.4**
6.70	3	System Test Operations	**$ 120.5**	$ 120.5	$ -	$ -	**$ -**	**$ 120.5**
6.80	3	Ground Segment	**$ 291.9**	$ 291.9	$ -	$ -	**$ -**	**$ 291.9**
6.80.01	4	Ground/Test Support Equip	**$ 248.0**	$ 248.0	$ -	$ -	**$ -**	**$ 248.0**
6.80.02	4	Tooling	**$ 44.0**	$ 44.0	$ -	$ -	**$ -**	**$ 44.0**

Figure 11.5-2 Full SPDR PCEC Table