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Design of Dual Mars Ascent Vehicle MAVERICK

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Advancements in technology and growing interest in human exploration of Mars has raised growing technical challenges including the safe return of crewed missions. Mu3 presents a Dual Mars Ascent Vehicle design in response to the 2023 AIAA Space Design Competition to safely return humans from Mars to Earth. The purpose of this mission is to prove the feasibility to further human exploration in the solar system and expand on current technology readiness levels. The entire mission, known as MAVERICK, will comprise of two vehicles: the Mars Ascent Vehicle (MAV) and the Smart Propellant Delivery Rover (SPDR). Due to current technical constraints, the 'Dual-Lander System' concept will have the MAV land on Mars without the propellant necessary for ascent while the SPDR will land on a separate lander and autonomously transfer propellant from the SPDR's Refuel Lander (RFL) to the MAV's Mars Lander Vehicle (MLV) over a period of 2 years while awaiting astronaut arrival. As per request for proposal, mission design includes all portions of the mission between lander descent, fuel transfer, ascent, crew transfer to the awaiting Deep Space Transport vehicle, and end of mission concerns.

I. Introduction

Transporting humans from Mars to Earth 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.

Given the unique challenges, NASA has determined a dual-lander ascent vehicle as 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 (DST) in a 5-sol orbit [1].

As per the Request for Proposal (RFP), in a dual-lander system one spacecraft will be used for crew transport and the other will be used for purposes of storing fuel as a sort of space gas station [2]. The mission, itself, can be characterized by two separate but equally important parts: the Ground phase and the Ascent phase. The Ground phase concerns itself with autonomous propellant transfer between the Mars Ascent Vehicle (MAV) and Refuel Lander (RFL) while the ascent phase includes the MAV launch, ascent, and docking. The development of this project requires the collaboration of multiple foci including propulsion, life support, structures, thermal management, and communications; all of which are connected using top-down systems engineering principles. However, human landing and their prospective ground operations are outside the scope of our design

A successful mission is defined as the completion of objectives as identified during development, including adherence to requirements provided by the AIAA. Requirements which include 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) which does not include the design of the landers. 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 15% 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.

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.

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A. Requirements

Following a systems flow down approach, Table 1 details requirements directly provided by the RFP. Numbering of each requirement adheres to NASA's Work Breakdown Structure (WBS) system. A comprehensive overview of the WBS for systems architectures can be found in Appendix A.A.

Table 1 AIAA System Level Requirements

Req. #	Req. Description
0.01	The cost for both vehicles shall be less than $4 Billion US Dollars (FY22)
0.02	Both landers shall arrive on Mars no later than July 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 10 kW Fission Surface Power Unit with a control mass of 5 metric tons
0.05	MAV shall return 50kg of Martian samples
0.06	Each lander shall fit within an allocated 8.4 m diameter payload fairing
0.07	Each lander shall have a landed payload capacity of 25 metric tons
0.08	The MAV shall transport 2 crew members during ascent to 5-sol orbit
0.09	An autonomous robotic system shall be used for propellant transfer

Derived requirements presented in Table 2 relate to either specifically the Smart Propellant Delivery Rover (SPDR) architecture or common design requirements between both architectures. For example, due to a given requirement of landing on Mars no later than 2038, Req. #6.1.02 stipulates a minimum Technology Readiness Level (TRL) of 6. Even though the journey from Earth to Mars is outside the scope of our design as per RFP, the launch vehicle and its associated loads are considered throughout. For instance, both Req. #5.1.01 and Req. #5.2.4.04 deal with the NASA SLS launch interfaces to ensure compatibility.

Table 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 MAV and SPDR shall have the capability to communicate with the Mars Relay Network (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 a Margin of Safety of 2 or higher
5.2.04	Both the MAV and SPDR shall survive the launch load of 4.1g from Earth
5.5.01	The SPDR shall keep the Nitrogen Tetroxide (NTO) at a stable temperature (-5 to 15 C) for transfer

Due to the added design complexity of the MAV as a manned craft, specific design considerations must be followed to ensure astronaut survivability. Specific MAV derived requirements are provided in Appendix A.A. For conciseness, requirements from multiple subsystems are presented within the same table. Further design drivers for the human factors including life support will be discussed in Analysis III.C.

B. Concept of Operations

As per RFP, the MAVERICK mission, as designed, begins on the Martian surface. Trajectory launch analysis has determined that the Mars Lander Vehicle (MLV) will launch from Earth by June 26, 2035. After ensuring its safe transit and landing on Mars, the RFL will subsequently be launched approximately 5 months later. The RFL will arrive on MARS by approximately June 26, 2037. Current planning has identified the HIAD system from NASA to be the best option for reentry [3]. Literature review and analysis of both the scientific goals of this mission have identified the Meridiani Planum as the primary landing site. Secondary landing sites of Holden Crater and the Melas Chasma were also identified. Key phases of the mission that are in common between the MAV and SPDR are illustrated in Figure 1.

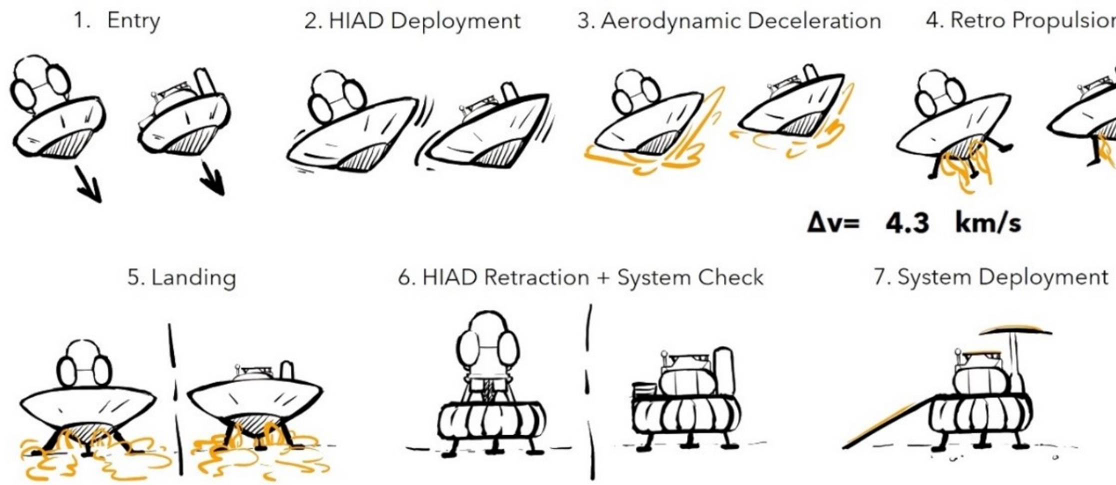


Fig. 1 Shared Concept of Operations

Due to both the weight of the craft and the reduced atmosphere of Mars, it was determined that parachutes would be insufficient for the task. The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) has therefore been selected as the most feasible primary system to facilitate safe Martian entry of both landers. The HIAD, as illustrated in Figure 10 will inflate upon entering the Martian atmosphere. This greater surface area of the inflated system will slow down the craft and provide thermal protection. Final descent will be slowed by retro-propulsion stowed within the landers themselves.

The descent of the craft will take approximately 8 minutes. Upon landing, the HIAD will deflate and retract while the respective craft will perform a systems check to ensure safe and nominal landing. Systems checks includes ensuring safe landing, nominal life support systems, and successful communication between the craft and Earth. After ensuring all systems are nominal, Earth-based crews will prepare the Refuel Lander (RFL) for launch. The primary purpose of the RFL is to store the SPDR rover and oxidizer and act as a gas station of sorts throughout the duration of ground operations, as the SPDR rover transfers oxidizer to the MAV. Once systems have been checked and deployed, the surface portion of the mission will occur as illustrated in Figure 2.

The SPDR rover will first take 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 (Rapidly Attachable Fluid Transfer Interface) [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. 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 the oxidizer required for launch. The SPDR returning to the RFL is only repeated 12 times as the rover does not need to make a final trip to the RFL and instead will be used as a camera to allow Earth crews monitor the MAV. To finish 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

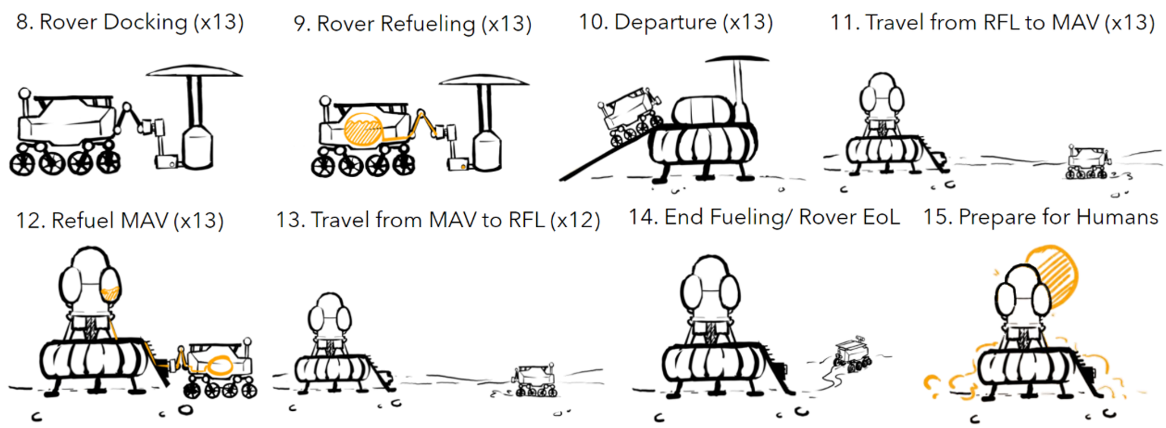


Fig. 2 Ground Concept of Operations

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.

As per RFP, the MAV must be ready for launch with humans aboard no later than July 1, 2040. Upon launch, the MLV base, RFL, and SPDR will be left on the Martian surface. Ascent will be plotted and planned based on real-time weather conditions by the crew and mission control. Under a lost-contact situation, the crew will be able to utilize surface readings to plot and plan their own course with assistance of the onboard computer. Figure 3 illustrates the ascent and flight ops portion of the mission.

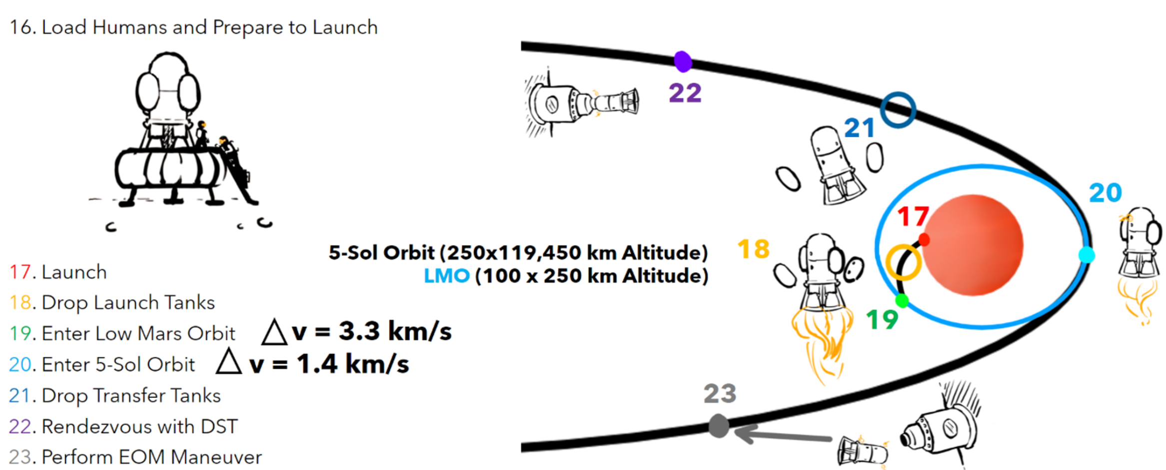


Fig. 3 Ascent Concept of Operations

Once flight preparations are complete the MAV, with astronauts onboard, will launch off the Martian surface. Once the propellants are depleted in the first two tanks, they will be dropped to decrease flight mass in a launch sequence estimated to take about 30 minutes. The MAV will then enter Low Mars Orbit (LMO). The LMO for this mission is an elliptical orbit with a 100 km altitude periapsis and 250 km apoapsis [5]. The required ΔV from launch to apoapsis is 3.3 km/s [6]. 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 [5]. The required ΔV from LMO to 5-Sol orbit at the 100 km altitude is about 1.4 km/s [6]. 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. Upon docking and safe transfer of astronauts to the Deep Space Transport (DST) vehicle, the MAV will remain in the 5-sol rendezvous orbit, until natural decay, and will eventually deorbit. Simulations show a deorbit timeline of 20 years. Further end of mission concerns and disposal are addressed in Section V.

II. SPDR Mission Architecture

Figure 4 illustrates how a ground-refuelling operation may potentially look. On the left-hand side of the image, the SPDR can be seen transferring fuel to the MLV lander on the right through the refuel port. The mechanics of this transfer are elaborated on in Section III.A. Atop the MLV is the MAV lander with its retracted solar panels. Additionally, a small 'astronaut' analogue is depicted in orange near the base of the MAV to provide a sense of scale between a human-sized figure and the overall craft.

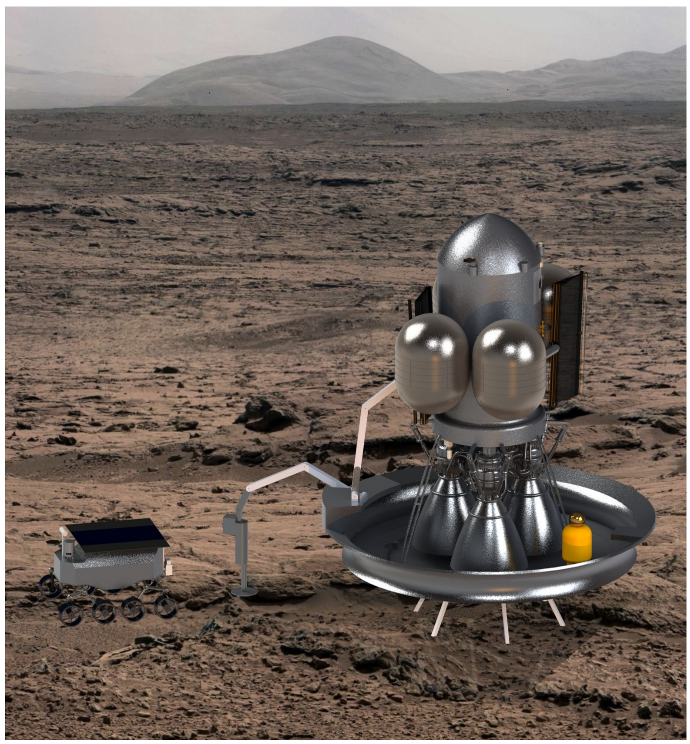


Fig. 4 Render of Mission Architectures during Ground Operations

A. SPDR Stowed Design

The primary purpose of the refuel lander is to store the SPDR rover and oxidizer and act as a gas station throughout ground operations. The purpose of the SPDR is to act as an autonomous propellant tankard on Mars that transfers the NTO from the RFL gas station to the MAV. The reason for transferring only one propellant was to reduce the complexity of transferring both the fuel and oxidizer. Specifically, NTO was chosen because it was the more massive of the two propellants. This allows for the MAV to land fully loaded with Monomethylhydrazine (MMH) and have more design headroom while still fitting in the 25 metric ton payload requirement of RFP.

Considering the harsh Martian environment, terrain, and dust storms, designing architectures 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 mission's ability to endure the challenges and fulfill its scientific objectives on the Martian surface. Detailed callouts are provided in Figure 5. As shown, the ramp will allow the SPDR to climb atop and depart the RFL as necessary. The refuel tanks onboard the RFL are identical in design to those attached to MAV to save on design and manufacturing costs, and are constructed from titanium (Ti-13V-11Cr-3Al). The tank mounts are built to withstand launch conditions and provide space for insulation and heating around the tanks as shown in Analysis III.C. The pump and power box are responsible for transferring oxidizer from the storage tanks to the SPDR rover as well as containing the power regulation for the payload from the aforementioned Fission Surface Power Unit (FSPU). The FSPU included in the RFP is not physically described beyond its mass and the visualization is estimated. The FSPU will be the primary source of power keeping the NTO within the storage tanks at optimal temperature. The RAFTI docking receptacle will be how the SPDR and RFL physically interface as the RFL transfers both oxidizer and power to the SPDR.

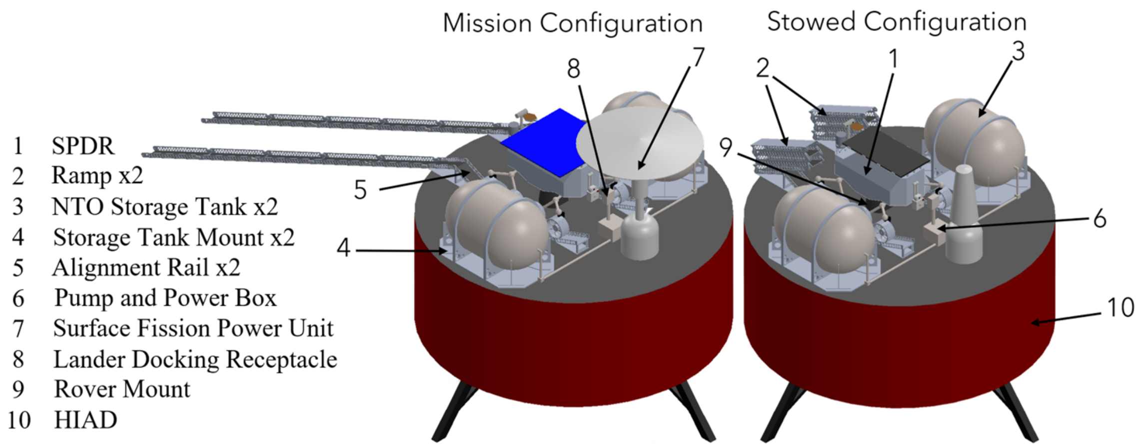


Fig. 5 SPDR Stowed Callouts

B. SPDR Design

The primary dimensions of the SPDR can be seen in Figure 5.14. The maximum rover dimensions are 2.9 m in length, 2.2 m in width, and 2.0 m in height, leaving plenty of space within the payload fairing for the rest of the refuel system. A deployable solar array of approximately 4 m^2 would be enough to power the rover and keep the batteries charged during the day with the charging cycle discussed further in this section. Dimensions of the SPDR Rover are provided in 6.

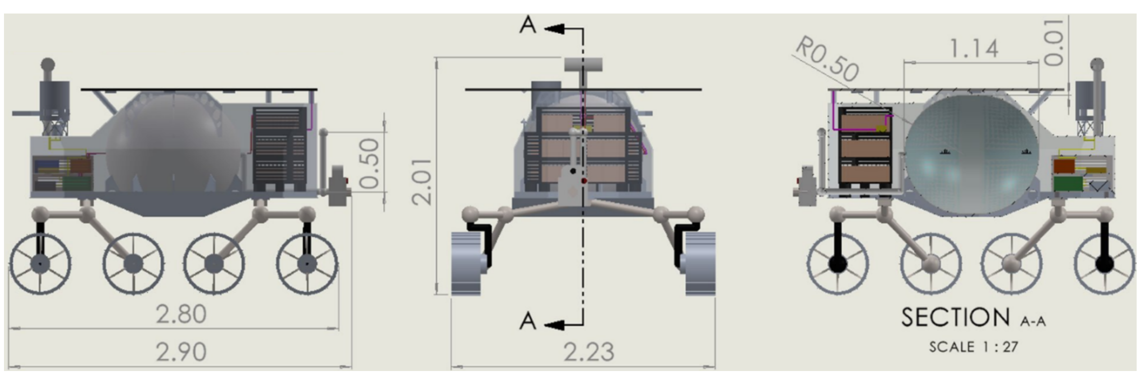
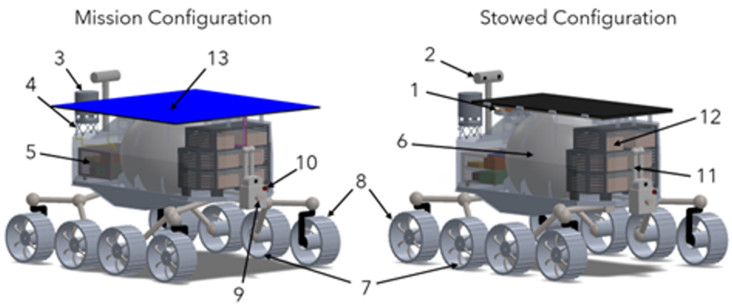


Fig. 6 SPDR Rover Dimensions

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 7.

Improving upon Req. #4.1.1.02, Mu3 has designed the SPDR to travel 1.1 km without recharging. Its unloaded weight is 1,390 kg while its loaded weight is 2,390 kg when loaded with Nitrogen Tetroxide. To support propulsion requirements, Mu3 has selected an 8-wheel propulsion system based on the rocker-bogie design found on both 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.



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

Fig. 7 SPDR Rover Callouts

Current speed estimates average at 47.4 cm/s while mission planning has indicated a 'stop-and-survey' approach to be best. The SPDR rover will 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. In accordance with Req. #0.09, the SPDR rover must be capable of autonomous navigational decisions and independent action. Further design accordance with Req. #5.2.2.03 facilitates Earth-Architecture communications. Design callouts to specific sensors for navigation and communication are provided in 8 alongside the rover's Field of View (FOV) plot of the Light Detection and Ranging (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 gimbal, 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. The Mars Environmental Dynamics Analyzer (MEDA) and Rover Environmental Monitoring Station (REMS) alongside the pressure transducers, temperature sensors, and power sensors will all be used to monitor internal system health, especially that of the propellant and tank.

To further 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 which a software and algorithm system that enables more accurate identification of potential hazards that is also being used on the Perseverance rover.

Instrument Name	Mass
Air Temperature Sensors (MEDA)	6 kg
Relative Humidity Sensor (MEDA)	
Pressure Sensor (MEDA)	
Infrared Sensor (MEDA)	
Wind Sensors (x2) (MEDA)	
REMS	424 g
Sun Sensor (x2)	100 g
Inertial Measuring Unit	1 kg
LiDAR	12 kg
Cameras (x3)	425 g
Pressure Transducer (x2)	-
Temperature Sensor (x2)	1 g
Power Sensors (x2)	-
Total	20kg

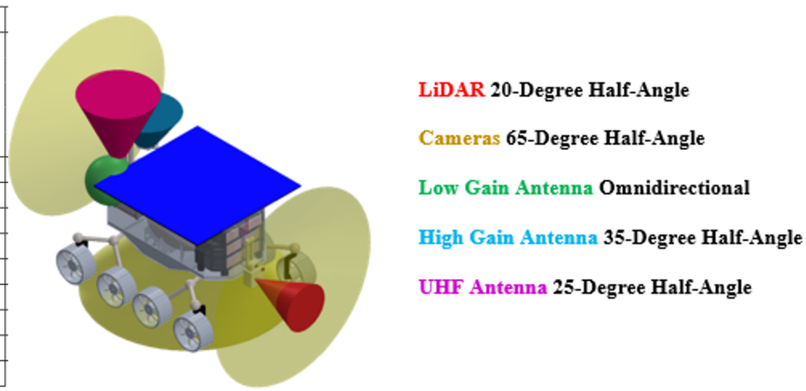


Fig. 8 SPDR FOV Plot and Rover Sensor List

As the SPDR rover covers vast swaths of terrain, it must also carry mission-critical cargo and maintain communication with other vehicles while also surveying its surroundings. As a consequence, much research was conducted on identifying a robust and efficient power system. Analysis and trade studies have determined that batteries integrated with solar cells to be the most pragmatic power solution. The 60 A-h space cells from EaglePicher offer 60% depth of discharge and energy capacity of 256 W-hr per cell. 22 parallel strings with 8 cells in series provide approximately 31,780 W-hr of energy. This provides 14% more energy than necessary for a 1.1 km distance. One 1.1 km trip is anticipated to take 3 days. When not travelling, 4 m^2 solar cells atop the SPDR supplied by IMM-α will recharge the rover. These solar cells are rated to 449.9 W/m^2 and will unfold when charging. In consideration of the harsh Martian environment, 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.

III. MAV Mission Architecture

A. MAV Stowed Design

The MLV will primarily serve to safely transport the MAV from Earth to the Martian surface. While the mission's scope assumes our design begins on the Martian surface, successful mission operations necessitate a lander design to operate from. Therefore, the MAV will remain on the MLV throughout the ground operations phase, acting as the launchpad during ascent. The MLV follows the basic dimensions shown in Figure 9. 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 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.

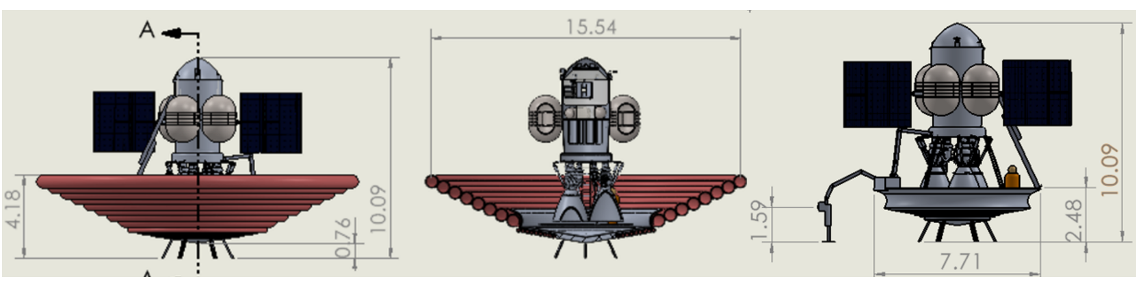


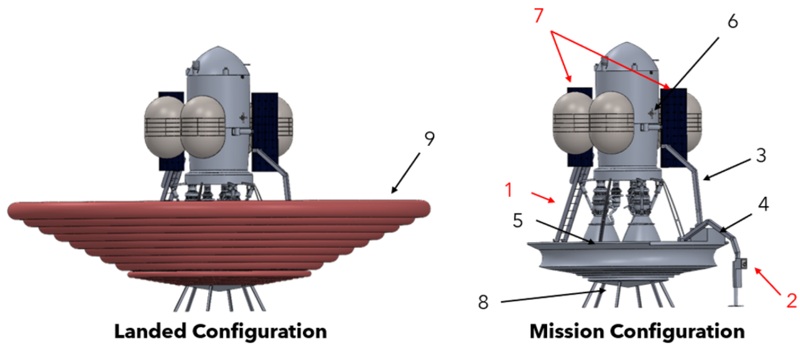
Fig. 9 MAV Stowed within MLV Dimensions

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. Specific callouts to key features of the MLV, including crew ladder and the fuel transfer system, are referenced in Figure 10. 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 requirements for ladder design. The ladder will unlatch upon final launch preparations and has a redundant manual extension capability.

As described in the concept of operations, the SPDR will connect to the MLV by way of the Orbit Fab RAFTI adapter which is attached to the hydraulic refuel leg. This leg is capable of 2 meters longitudinal travel and 2 meters of variable height which better accommodates uneven terrain or ground obstructions.

B. MAV Design

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 are an overall height of 8.4 m and stowed diameter of 4.32 m. During the



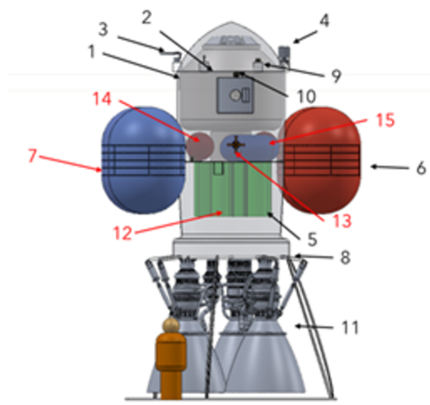
1	Crew Ladder
2	RAFTI Interface
3	Fuel Transfer Tube
4	Fuel Transfer Pump
5	MAV Mounting Point
6	ACS Thrusters
7	Solar Arrays
8	HIAD Inflator Tubes
9	HIAD Base

Fig. 10 MLV Callout

orbital phase with all solar panels extended, the footprint diameter is 10.47 m which altogether allow the crew 6 m^3 of living space.

Callouts for the external and internal BUS components are provided in Figure 11, which show design considerations and life support systems for the crew. 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.

Trade analyses identified Nitrogen Tetroxide and Monomethylhydrazine (MMH) as the ideal propellants due to their storable nature and longer flight heritage. Further criteria including thrust, specific impulse, and size show three Aestus RS-72 engines to be sufficient and will provide 130 kN of thrust with a thrust-to-weight ratio of 2 at Mars liftoff. Furthermore, all 3 engines are throttleable and gimbaled allowing for more precise maneuverability.



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

Fig. 11 MAV Dimensions

To further aid in the more precise maneuvers, especially during docking, Mu3 has selected the Moog Monarc-22-6 thrusters to provide attitude control [5]. 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 the RS-72 engines. As with the RS-72, helium will be used as pressurant.

The 19,740 kg of 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 [3]. Further design considerations are discussed in Analysis III.C

C. MAV Analysis

The MAV's overall dry mass is 4,842 kg. When fully loaded with propellant and preparing final launch preparations, it will weigh 22,267 kg. SolidWorks analysis shows a worst case hot temperature of 89.4 °C while also showing a worst case cold of -162.7 °C. As such, active and passive thermal control are important in ensuring equilibrium temperature is maintained. To that end, radiators, multi-layer insulation, and heaters will be utilized.

To ensure the MAV could survive launch and support humans, a robust structural analysis was necessary. Figure 12 shows structural analysis of both the MAV base structure during launch loads and the crew cabin under pressure. Adhering to human launch requirements, a minimum factor of safety of at least 2 was applied to all subsystems during the design process. Mission-critical components including the crew cabin and propellant tanks were designed with a factor of safety exceeding 4.

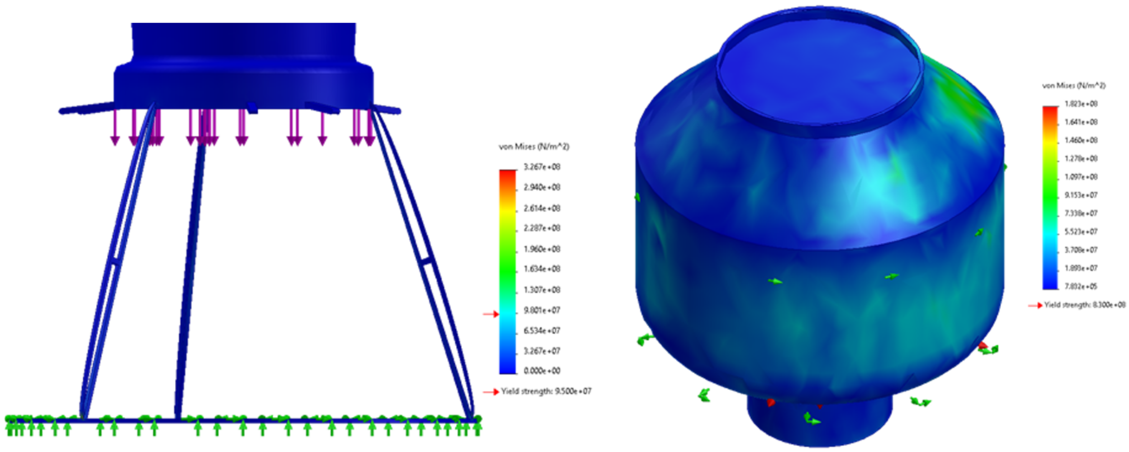


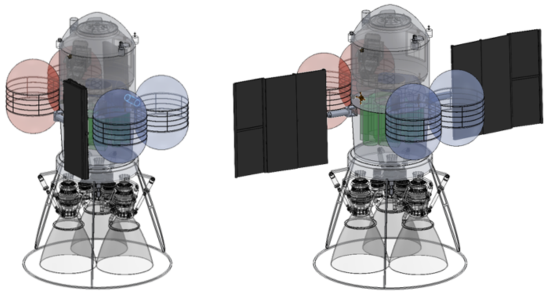
Fig. 12 MAV Structure and Crew Cabin Structural Stress Analysis

In regards to the main MAV structure, the worst-case launch loads are experienced during Earth launch. Structural analysis was conducted with an applied gravity load of 4.1 Gs. For simplified meshing and analysis, internal components are hidden from view but the same representative weight is applied in the analysis. As seen in Figure 12, the maximum stress the structure experiences during launch is significantly lower than the yield stress. Utilizing aluminum alloy 7075-O achieves a material deformation of less than 0.5 mm. Further analysis indicates that even under worst-case scenarios with full payload, our structure remains resilient and capable of safely transporting the MAV.

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 of the crew cabin on the right side of the image in Figure 12 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 internal wall is 3 mm 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.

D. Power and Life Support

As mentioned previously, the RFL will carry the 10 kW FSPU power supply while the MAV will instead carry both solar cells and batteries to conduct its mission. Current designs utilize 14 VES-16 batteries that provide 7168 W-hr of total energy while recharging is provided by 17.62 m^2 of total solar array area as seen in Figure 13. The most power-intensive phase of the mission is during transfer orbit with the DST as the crew and MAV will be consuming power the entire time across subsystems including ECLSS, ACS, Power Control, Command and Data Systems, and Communications. This phase is anticipated to last approximately 60 hours with a power usage of about 4,770 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. Figure 13 shows the power breakdown across the various MAV subsystems including the life support ECLSS system. The 'budget' column is based on percentages from Brown's analysis on previous missions while 'current' denotes current budget estimates [7]. The 'Status' column denotes current compliance where 'C' is compliance while 'E' denotes additional investigation required.



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	

Fig. 13 MAV with Extended Solar Arrays and Power Statement

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. Water will be recycled through a multi-filtration system to reduce the total stored liquid required to be brought from Earth. Shelf-stable freeze-dried foods are the primary foodstuff due to both the duration of the mission and their robustness. Other cargo includes medical kits, 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. Trade studies have further identified Lithium Hydroxide (LiOH) as 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.

IV. Telecommunications and Command & Data Handling

Telecommunications of both architectures are primarily based off the Perseverance rover's. Communication with Earth for both SPDR and MAV will be facilitated through the Mars Relay Network which allows high-speed data communications between Earth and Mars as an existing system which greatly simplifies design and cost considerations. Similarly, the Deep Space Network on Earth will be used to parse all communications.

Data collected and transferred from the SPDR depends on what operation the rover is performing. The operating modes currently calculated for the rover include "Rover in Transport", "Rover Docking", and "Rover Transferring Propellant". All data rate calculations used 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.

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. Long-term data is split into long-term total and long-term nominal data. The long-term nominal data is only sent during extended periods between less crucial missions, providing key data points. 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. General data transmission typically occurs after live data transmission to provide a comprehensive overview of critical mission phases. An exception to this practice is the LiDAR data, which has a high data rate, necessitating a different approach. Rather than transmitting all the LiDAR data for the docking procedure, the rover would only transmit two minutes' worth of data. From the operational modes and transfer times of the transmission types, an estimated telecom schedule for ground operations can be found in Figure 14.

To address critical hazards, 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. To further enhance the reliability of the C&DH subsystem, a Redundancy Management Unit (RMU) was selected as its centerpiece. The RMU, manufactured by MOOG, includes two parallel Integrated Avionics Unit 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. For optimal performance, VxWorks, a real-time Operating System (OS) renowned for its deterministic performance and precise timing in demanding applications, was selected. This choice is attributed to its proven flight history, low-latency capabilities, robust fault-tolerant file system, and high reliability.

To address the potential for system failures and manufacturing defects, the MAV is equipped with redundant

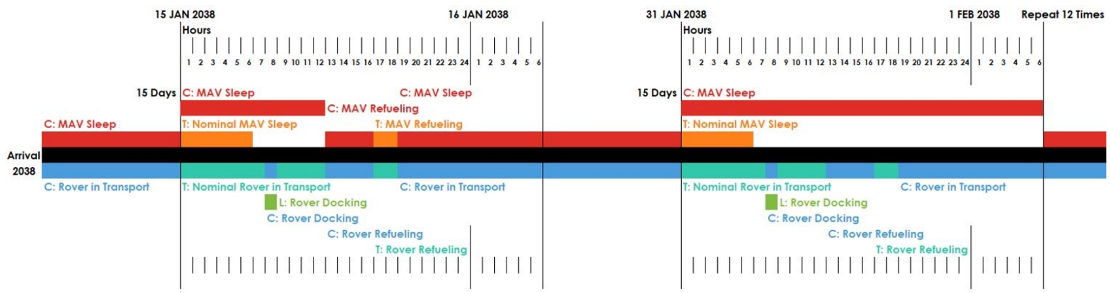


Fig. 14 Example Ground Telecommunications Schedule

components. Specifically, the MAV incorporates two separate On Board Computers (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. This redundancy also enables the MAV to continue taking measurements from its sensors and cameras, even if one of the components malfunctions. The primary OBC, manufactured by BAE Systems, boasts an impressive performance of 3.7 Giga Floating-Point Operations Per Second (GFLOPS), and comes equipped with 1 Gigabyte of Flash memory. 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.

V. End of Mission

The 50kg Martian samples will be transported as shown in Section III.B and held to Planetary Protection Protocol (PPP) as well as Committee on Space Research (COSPAR) standards and policies. It should be reiterated that the extraction and selection of the samples is out of the scope of our mission though the MAV will have the capability to hold and transfer the samples to the awaiting Deep Space Transit Vehicle. 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.

Adhering to guidelines set forth by the Office of Safety & Mission Assurance, both MAV and SPDR architectures are given Category IV rating under the Planetary Protection Protocol. This categorization is due to the mission's design where MAV, SPDR, and Landers will not be returning to Earth and will remain on Mars after the mission has been completed. It is therefore of the utmost importance to limit Martian contamination from Earth. As such, all architectures will be manufactured to a minimum ISO Class 8 Cleanliness level. 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.

VI. Cost

NASA's PCEC (Project Cost Estimating Capability) software was utilized to estimate total overall cost of all elements between both architectures. To account for inflation and changes in price over the period of design and production, a 15% management reserve was accounted for. Although the MAV and SPDR rovers are both complex systems, they have the benefit of using flight-proven components with high heritage which lowers the overall cost of design. The rover, specifically, uses design cues and heritage from other Mars rovers including Perseverance and Curiosity. The PCEC software shows compliance with Req. #0.01 with the MAV and SPDR having a combined cost of $3.9 Billion dollars. The various component systems of the mission and their costs can be seen in Figure 15 for the MAV and in Figure 16.

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**

Fig. 15 MAV Overall Cost

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**

Fig. 16 SPDR Overall Cost

VII. 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.

A. Appendix

A. Work Breakdown Structure

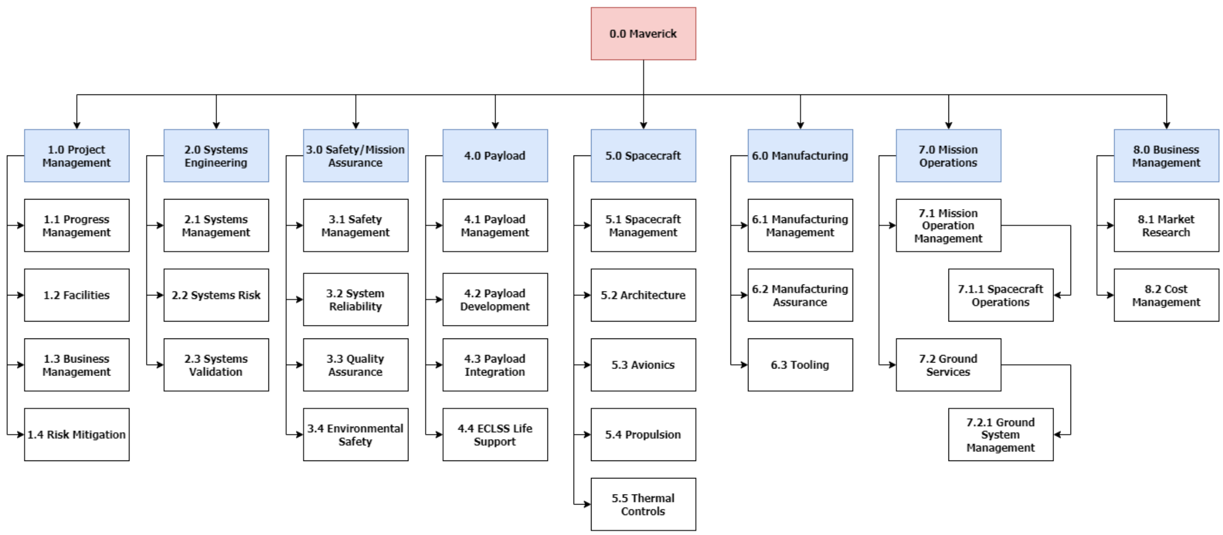


Fig. 17 Work Breakdown Structure

Table 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 be throttleable
5.4.07	Engines shall be re-ignitable

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References

[1] Connolly, J., "Exploring Mars: NASA's Mission to the Red Planet," , 2017. URL https://nvite.jsc.nasa.gov/presentations/b2/D1_Mars_Connolly.pdf, accessed on 9/10/2023.

[2] AIAA, "2023 AIAA Undergraduate Team Space Design Competition," , 2023. URL https://www.aiaa.org/docs/default-source/uploadedfiles/education-and-careers/university-students/design-competitions/2023-aiaa-space-design-competition.pdf?sfvrsn=8194e58e_0, accessed on April 2023.

[3] Cianciolo, A. D., Dillman, R., Brune, A., Lugo, R., Polsgrove, T. P., Percy, T. K., Sutherlin, S., and Cassell, A., "Human Mars Entry, Descent and Landing Architecture Study: Deployable Decelerators," *NASA*, 2020.

[4] OrbitFab, "RAFTI™ User Guide: Refuelable Spacecraft Requirements Specification," , 2023. URL https://www.orbitfab.com/wp-content/uploads/DOC-00012-A_RAFTI_User_Guide.pdf, accessed on May 2023.

[5] Polsgrove, T., "Human Mars Ascent Vehicle Configuration and Performance Sensitivities," , 2017. URL https://ntrs.nasa.gov/api/citations/20170003391/downloads/20170003391.pdf, accessed on April 2023.

[6] Trent, D., Thomas, H., and Rucker, M., "Updated Human Mars Ascent Vehicle Concept in Support of NASA's Strategic Analysis Cycle 2021," *IEEE Aerospace Conference*, 2021.

[7] Brown, C. D., *Elements of Spacecraft Design*, AIAA Education Series, 2002.

[8] *Space Launch System (SLS) Mission Planner's Guide*, 2018. URL https://ntrs.nasa.gov/api/citations/20170005323/downloads/20170005323.pdf, accessed on January 2023.

[9] Smithsonian Institution National Air and Space Museum, "Today, Mars is warmer than Earth. See how we compare." , January 2018. URL https://airandspace.si.edu/stories/editorial/today-mars-warmer-earth-see-how-we-compare, accessed on May 2023.

[10] "Nitrogen Tetroxide," , ˙ URL https://cameochemicals.noaa.gov/chemical/4075, accessed on March 2023.

[11] NASA, "Mars Realtime Sequence of Events," , ˙ URL https://mars.nasa.gov/MPF/mpf/realtime/mars2.html, accessed on February 2023.

[12] Cianciolo, A., Korzun, A., Edquist, K., Samareh, J., Sostaric, R., Calderon, D., and Garcia, J., "Human Mars Entry, Descent, and Landing Architecture Study: Phase 3 Summary," 2020.