Update to Mars Ascent Vehicle Design for Human Exploration

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***Abstract*—Astronauts on a mission to Mars will require several vehicles working together to get to Mars orbit, descend to the surface of Mars, support them while they're there, and return them to Earth. The Mars Ascent Vehicle (MAV) transports the crew off the surface of Mars to a waiting Earth return vehicle in Mars orbit and is a particularly influential part of the mission architecture because it sets performance requirements for the lander and in-space transportation vehicles. With this in mind, efforts have been made to minimize the MAV mass, and its impact on the other vehicles. A minimal mass MAV design using methane and in situ generated oxygen propellants was presented in 2015. Since that time, refinements have been made in most subsystems to incorporate findings from ongoing research into key technologies, improved understanding of environments and further analysis of design options. This paper presents an overview of the current MAV reference design used in NASA's human Mars mission studies, and includes a description of the operations, configuration, subsystem design, and a vehicle mass summary.**

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1. INTRODUCTION

Over the last fifty years, NASA engineers and mission planners have made steady progress in understanding the challenges and complexities of sending humans to Mars, refining Mars exploration architectures as capabilities and technologies evolve, and developing systems to help humans get there. NASA's Space Launch System (SLS), Orion crew module, and lunar Gateway will the first steps of this monumental endeavor. The Mars Study Capability Team under NASA's Human Exploration and Operations Mission Directorate has been evaluating options and developing conceptual designs for the next vehicles required to complete the mission: the Earth to Mars transportation habitat [1] and propulsion, the entry, descent and landing system [2], Mars surface systems [3], and Mars Ascent Vehicle (MAV). These studies are necessary to guide and prioritize technology investments to continue our progress towards enabling human missions to Mars.

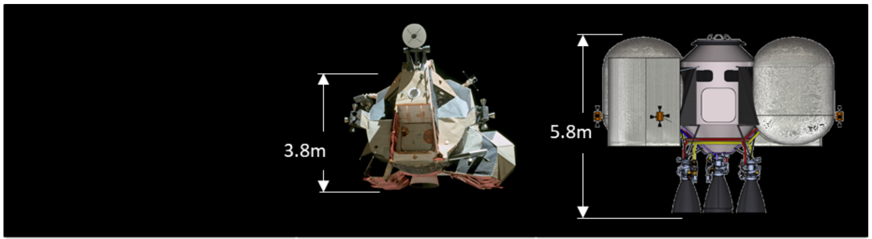
The MAV, which transports the crew off the surface of Mars to a waiting Earth return vehicle in Mars orbit, is a particularly influential piece of the architecture. As the largest indivisible piece of cargo that must be delivered to the surface of Mars, it sets the cargo capacity of the entry, descent, and landing (EDL) system. The size of the EDL system in turn drives the performance requirements for transportation stages from Earth to Mars. MAV design affects the configuration of the landing system and the design of other surface systems such as in situ resource utilization equipment and surface power systems. The way crew get into the MAV affects the design of pressurized rovers and other surface equipment. The operations and performance required of the MAV drive the need for new technologies and developments like advanced insulation and active cooling systems for cryogenic fluid management, deep throttling main engines, and the manufacturing and qualification of all systems will be affected to some degree by the long duration of dormancy required for this mission.

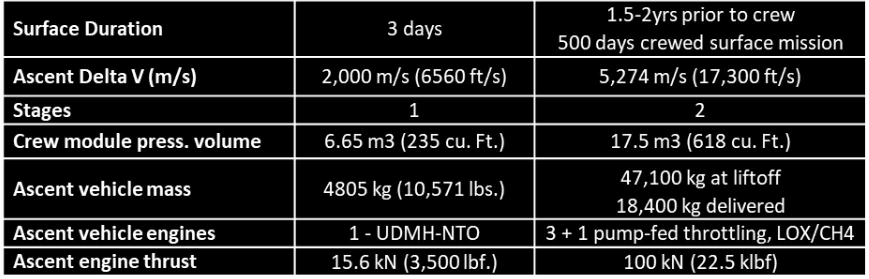
Over the last four years, conceptual designs for the MAV have matured. An initial concept was published in 2015[4] along with a discussion of design drivers [5]. Further refinements to crew operations within the MAV and trades on cabin geometry and propulsion systems were presented in 2017 [6, 7]. This paper presents an overview of the current MAV reference design used in NASA's human Mars mission studies. This design includes refinements in many subsystems that reflect new understanding of propellant tank insulation options, updates to cryocooler performance predictions as reported through ongoing development activities, thermal environments during EDL, the effects of engine plumes at liftoff, and a refined modeling of the ascent trajectory. This paper includes a vehicle overview with a description of the operations and configuration, a discussion of vehicle systems and subsystem characteristics and assumptions, and finally vehicle performance with trajectory design and a vehicle mass summary.

2. VEHICLE OVERVIEW

While crewed launch from Earth has become routine, human ascent from another clestial body has only happened six times. Ascent from the surface of the moon during each Apollo mission is similar in several ways to what can be expected for Mars ascent. The Mars Ascent Vehicle (MAV) is embedded in a lander which acts as its launch pad. The MAV's crew cabin is designed to support crew for a few days in microgravity, and allow for ingress/egress on the planetary surface or while docked with the orbiting transit system. Like the Apollo ascent stage, great effort is applied to minimize the MAV crew cabin mass because ascent vehicles are generally regarded as the largest "gear ratio" item in a given architecture – in other words, every kilogram of ascent vehicle mass needs more Earth-launched mass than other mission elements. While there are similarities with the Apollo ascent missions, one fundamental difference is the mission duration. The entire Apollo mission was less than three weeks. The MAV will be launched from Earth years before the crew will use it and it must operate reliably after long dormancy in space and in Mars surface environments. Communication latency is another difference as there will be no real-time communication with mission control on Earth when it is time to launch the MAV. Round trip communication delays range from 8 to 44 minutes depending on planetary alignments. The MAV will carry twice as many crew members as the Apollo Lunar Module for a total of four crew, and the energy required to get to Mars orbit is about twice what it took to get to lunar orbit, so propellant loads are much higher. To minimize vehicle mass, higher performing cryogenic propellants are used, and the vehicle is staged during ascent. A comparison of the Apollo Ascent Module and a human Mars Ascent Vehicle is provided in Table 1.

Table 1. Comparison of Apollo Ascent Module and Mars Ascent Vehicle





	Apollo Ascent Module	Human Mars Ascent Vehicle
Crew Size (max)	2	4
Surface Duration	3 days	1.5-2yrs prior to crew 500 days crewed surface mission
Ascent Delta V (m/s)	2,000 m/s (6560 ft/s)	5,274 m/s (17,300 ft/s)
Stages	1	2
Crew module press. volume	6.65 m3 (235 cu. Ft.)	17.5 m3 (618 cu. Ft.)
Ascent vehicle mass	4805 kg (10,571 lbs.)	47,100 kg at liftoff 18,400 kg delivered
Ascent vehicle engines	1 - UDMH-NTO	3 + 1 pump-fed throttling, LOX/CH4
Ascent engine thrust	15.6 kN (3,500 lbf.)	100 kN (22.5 klbf)

Functional Requirements

The MAV's primary purpose is to carry crew members and return cargo off the surface of Mars to rendezvous with an Earth return vehicle. Minimum functionality for the MAV includes:

1. Allow for crew ingress/egress on the Martian surface
2. Transport 4 crew members and 250 kg of cargo from the surface of Mars to docking with the Earth return vehicle in Mars orbit

3. Allow for rendezvous and docking with the Earth return vehicle

4. Support microgravity crew habitation during ascent and rendezvous, a minimum of 3 days

5. Minimize the transfer of uncontained Martian contamination to the Earth return vehicle

6. Perform a disposal maneuver after crew and cargo transfer and undocking from Earth return vehicle

7. Operate reliably after 4+ years of loiter with up to 3 of those years on Mars surface

8. Launch integrated with Mars Descent Module on Block 2B SLS with a 10m fairing

Configuration

The MAV consists of a crew cabin and a two-stage propulsion system. Figure 1 shows the integrated vehicle configuration while figures 2 and 3 show the first and second stages independently. The first stage is entirely a main propulsion system (MPS) with three 100 kN main engines and two sets of nested tanks, for liquid oxygen and liquid methane propellants. These components are dropped after the first stage burn, leaving the second stage which contains the crew cabin, propulsion system (both MPS and RCS), along with the supporting subsystems including fixed thermal radiators (wrapped around the second stage tanks). The second stage uses one 100 kN main engine and like the first stage, it has two sets of nested propellant tanks.

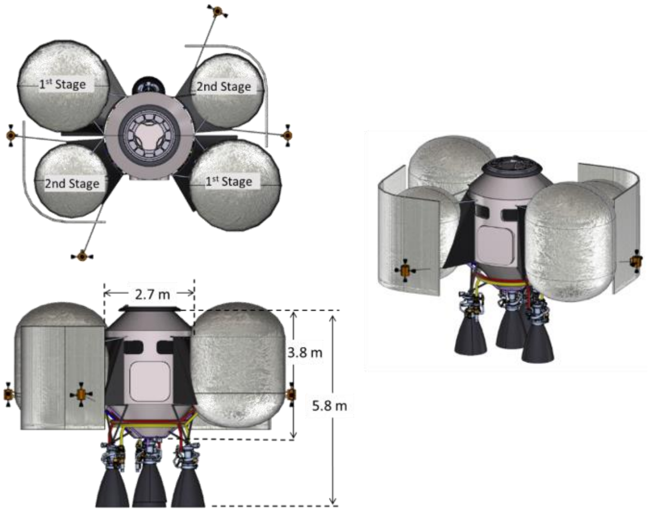


Figure 1. Mars Ascent Vehicle Configuration and Launch Packaging

Figure 2. Mars Ascent Vehicle Configuration: 1st Stage

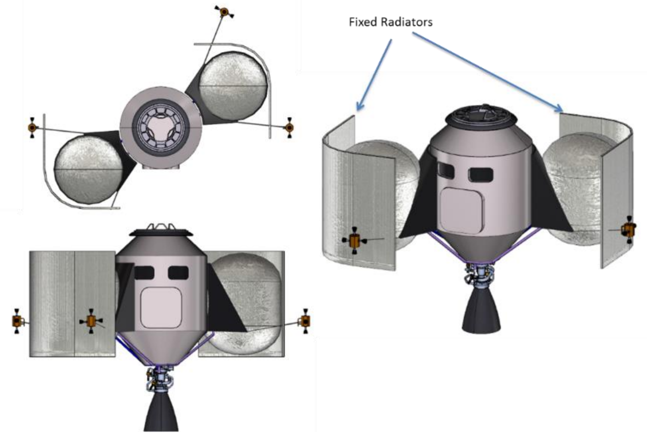


Figure 3. Mars Ascent Vehicle Configuration: 2nd Stage

The current reference crew cabin is a vertical cylinder concept with a diameter of 2.7 m and a height of 3.8 m which provides an internal volume of 17.5 m^3. Two hatches allow for entry from the Mars surface and docking to the Earth return vehicle. The NASA docking system [8] is assumed for the top hatch, and a 1 m rectangular hatch is assumed on the side. Incorporating a MAV crew cabin that is common with other mission elements, such as the horizontal rover cabin, may provide cost and schedule improvements, but analysis showed that the vertical crew cabin was more structurally efficient than the horizontal common cabin, and did not require a docking tunnel to the Earth return vehicle, making the vertical cabin about 400 kg lower mass than horizontal options considered [6]. Because as much as 7 kg of ascent propellant may be needed to boost a single kilogram of crew cabin mass to a low Mars orbit, this single architecture decision translates into thousands of kilograms in ascent propellant mass savings, with flow-down impacts to ISRU production rate which affect surface power system sizing.

This arrangement of cabin and propulsion system components, while unusual when compared to Earth ascent vehicles, allows for relatively straightforward crew access as well as a low center of gravity during landing at Mars, which improves controllability during the entry, descent and landing phases. The atmospheric density on Mars is less than one percent of that on Earth and the liftoff acceleration is limited for crew safety, so drag, while not negligible, is not a driving factor in the design of crewed Mars ascent vehicles.

Acceleration at liftoff is just over 0.6 Earth g's and reaches a maximum acceleration of almost 1.4 g's about 5 minutes later at the end of the 1st stage burn. The 2nd stage burn lasts about the same amount of time with accelerations less than 0.6 g's. While this acceleration range seems fairly mild compared to typical Earth launches, a crew conditioned to the Mars environment will need to be supported with recumbent seats. These seats can be stowed once the vehicle reaches orbit. See figure 4 for basic cabin layout with and without seats. While it is believed that there is sufficient room for the necessary stowage and internal equipment those allocations are not depicted in this graphic.

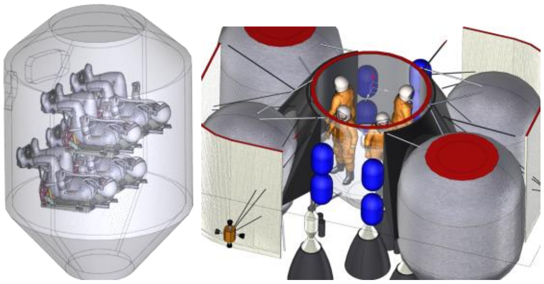


Figure 4. MAV Crew Cabin Layout

Operations

The MAV is launched from Earth using an SLS Block 2B launch vehicle with a 10 m diameter fairing, see Figure 5. It is launched integrated with the Mars entry descent and landing systems, specifically the Mars Descent Module (MDM) component of that system. Once in a highly elliptical Earth orbit, a Mars transportation system is docked to the lander and pushes the combined stack to Mars. Transit time from Earth launch to arrival in Mars orbit could be 6 months to a year or more depending on the transportation system used. During transit, the MAV relies on the MDM for power, communications, and thermal control. The MDM also serves as the launch pad for MAV lift-off. See figure 6 for the MAV configuration during each phase of flight.

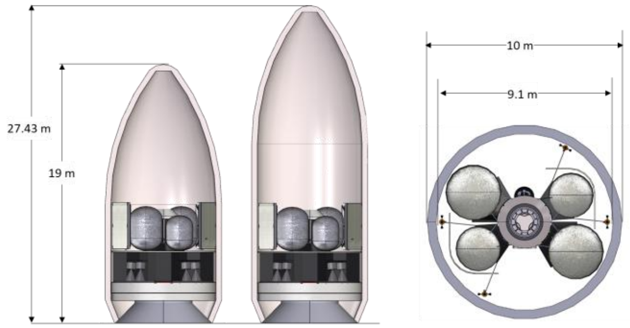


Figure 5. MAV Launch Configuration

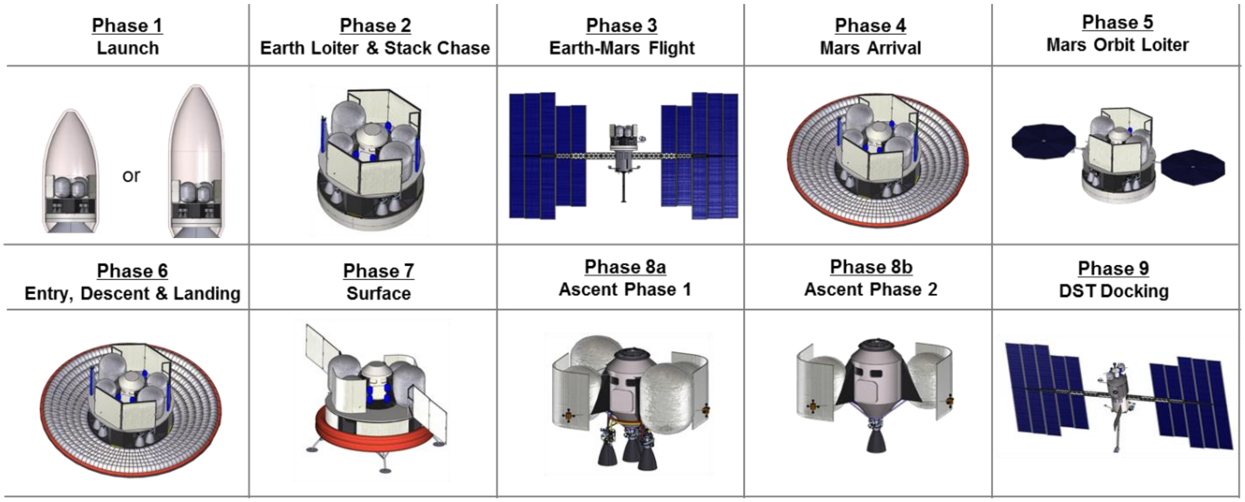


Figure 6. MAV Configuration by Mission Phase

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Shortly after arrival into Mars orbit, the lander carrying the MAV detaches from the Earth-Mars transportation system. After a brief period of final checkouts and phasing to align with the targeted landing site, the lander descends to the surface. The MAV is exposed to the environment during transit to Mars and entry, descent and landing. While there is no direct flow impingement on the MAV during entry, the radiative and convective heating from the surrounding environment, while brief, can be extreme[2]. Once on the surface, the lander must be connected to a surface power generator, currently assumed to be a fission power source that is delivered on an earlier lander. Connection to surface power is assumed to occur within 24 hours after landing.

The MAV is delivered to Mars at least one opportunity before crew arrival with full methane propellant tanks and empty oxygen tanks. The MAV is serviced by an In-Situ Resource Utilization (ISRU) propellant manufacturing system, co-located on the MDM, see figure 7. This system generates oxygen from the Martian atmosphere and pumps it directly into the MAV's propellant tanks. The oxygen production process will be demonstrated by the MOXIE experiment on the Mars 2020 mission, which will generate 10 g/day with 300 Watts of power. The MAV oxygen production and liquefaction process requires more than 30 kW for a production rate of about 50 kg/day[10]. This process also requires additional radiator area. Once on the surface, two sets of radiators located on the MDM top deck are deployed, figure 6 phase 7. With a high mixture ratio propulsion system, more than half of the MAV liftoff mass is liquid oxygen propellant. Generating this propellant on Mars cuts the required cargo capacity of the lander in half.

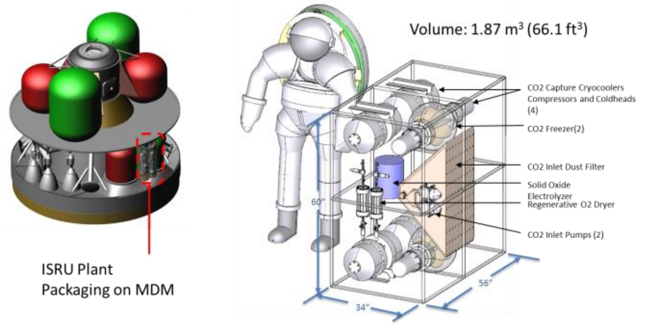


Figure 7. ISRU Propellant Production Plant

The crew is not cleared to land on Mars until the oxygen tanks are confirmed full. While on the surface, the crew will live and operate out of their surface habitation elements. At the completion of the surface mission, the crew will drive over to the MAV in a pressurized rover. They will install an inflatable tunnel between the MAV surface access hatch and the pressurized rover that will allow them to leave their Mars Extravehicular Activity (EVA) suits behind in the rover, and ingress the MAV in lightweight and clean Intravehicular Activity (IVA) suits. See figure 8 and reference [11] for crew access tunnel concepts. This approach is designed to eliminate contamination of the MAV with Martian dust and regolith for planetary protection reasons. It also allows for less bulky and massive suits for ascent that minimizes MAV cabin volume requirements. Crew activities to prepare and fly the MAV have been simulated through vehicle mock up activities and are documented in reference [7].

Figure 8. Rover-to-MAV Crew Transfer Concepts

Just prior to ascent, all support services from the descent stage are discontinued, and the MAV becomes self-sufficient. A roughly 10 minute powered ascent, with the first stage dropping 5 minutes in, leaves the MAV in a 100 x 250 km altitude orbit. The MAV then circularizes into a 250 km orbit and awaits optimum phasing for rendezvous with the Earth return vehicle. Various parking orbits for the Earth return vehicle have been considered, see figure 9. This paper will focus on MAV options to reach both 1 Sol and 5 Sol elliptical Mars orbits, where 1 and 5 Sol refer to the orbital period in Martian days. Allowing 3 days for rendezvous and docking with an Earth return vehicle in a 5 Sol orbit allows for multiple launch opportunities per week, and reasonable launch window durations. Once docking is achieved and crew and cargo are transferred, the MAV detaches and performs a final disposal maneuver into an orbit that will not interfere with future Mars orbit operations.

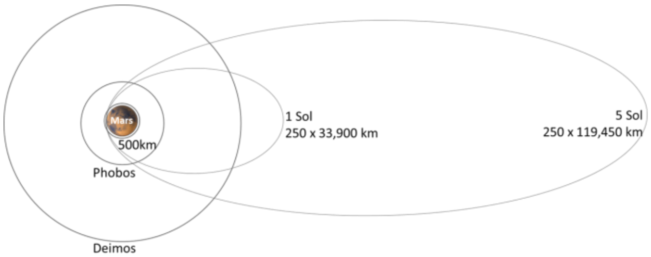


Figure 9. Mars Parking Orbits.

3. VEHICLE SYSTEMS

This section provides a brief summary of each vehicle subsystem, as well as any design drivers, and technology challenges. Life support, EVA and human factors components and systems are captured under Crew Cabin Design, followed by propulsion, thermal, power, avionics, and structures. To minimize MAV mass, wherever possible MDM services are relied upon so that MAV systems need only perform what is necessary during ascent operations. Figure 10 shows interfaces between the MAV and the MDM as well as the MAV and the transit habitat of the Earth return vehicle.

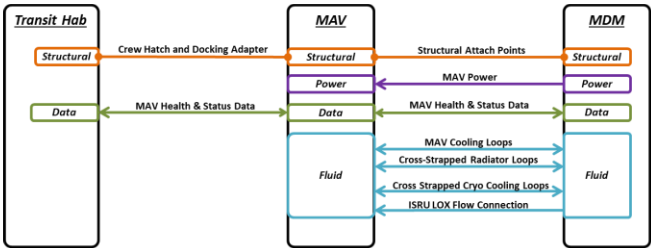


Figure 10. MAV Interfaces with other Elements

Crew Cabin Design

Due to the possibility of a sudden cabin depressurization it is generally assumed that crew will ascend in pressure suits. The choice of ascent suit can impact MAV cabin size not only because the EVA planetary suits are physically larger than the IVA suits, but also because EVA suits will likely be contaminated with surface dust which will require additional equipment to mitigate. Cabin mockup testing [12] identified the EVA suit's bulky design as a potential cabin configuration driver. Simulated microgravity testing performed during the Constellation Program identified problems passing a large, pressurized EVA suit through the docking system hatch tunnel. EVA suits also pose a significant ascent mass penalty over the IVA suits. At up to 75 kg difference between an IVA and EVA suit (not including the life support system backpack), the mass penalty for multiple crew members—multiplied by the propellant gear ratio—adds thousands of kg of propellant (plus larger propellant tanks, more tank structure, etc.) simply to accommodate the larger suits. Crew activities inside the crew cabin are described in more detail in reference [7].

The life support systems for the Mars Ascent Vehicle are based heavily on the Altair life support systems [13]. Some changes are made to the water system to include additional capability for purification due to the long duration of dormancy prior to crew access on the Martian surface. Additionally, nitrogen and oxygen supplies for cabin atmosphere are increased to allow for a small degree of cabin leakage during the vehicle's long duration of dormancy.

The type and quantity of Human Factors equipment needed is a function of a vehicle's crewed duration. Unlike longer-duration vehicles, the MAV's relatively short 2-3-day operational life allows the omission of many standard crew comfort items, such as a food warmer, potty, and exercise equipment. MAV Human Factors mass is best characterized as being limited to consumables and safety gear.

The MAV consumables include food, hygiene supplies (such as wet-wipes), and crew-worn items such as Maximum Absorbency Garments (MAGs). Potable water and breathing gasses are assumed to be part of the ECLS non-propellant fluids. Food consumption is based on a 1.831 kg per crew member per day requirement, including food wrappers plus a stowage bag to secure the food.

Safety gear includes personal radiation dosimeters, cabin illumination, a tool kit for contingency operations (such as a jammed hatch mechanism), a clean-up kit, and recumbent seating. For the purpose of this exercise, recumbent seats are assumed to be similar to the Orion project's seats and are by far the single largest Human Factors allocation at 22.7 kg each. Although MAV ascent acceleration loads are considered relatively gentle for a healthy crew launching from Earth, recumbent seating protects for two contingency scenarios: early return of deconditioned crew, or an incapacitated crew member. Forward work on these contingencies may offer mass reduction opportunities. All crew and cargo mass assumptions are listed in Table 2.

Table 2. MAV Cargo, Human Factors and IVA equipment

Item (# items)	Assumption
Crew (4)	98.5 kg/person
Food + Baggage	1.831 kg/person/day + 1.56 kg
Daily Crew Provisions	0.8825 kg/person/day
Total Mission Provisions	25 kg/person + 87.2 kg
Crew Transfer Bags	30.4 kg
Safety	39 kg
Recumbent Seats (4)	22.7 kg/seat
Umbilical Interfaces (2)	10.5 kg/interface
11 ft Umbilicals (4)	9.07 kg/umbilical
IVA LEA Suit (4)	15.5 kg/suit
Total MAGs	2.6 kg
Sample Container (10)	1.1 kg/container
Samples	239 kg

Propulsion

The propulsion system for the MAV consists of a two stage main propulsion system and an integrated reaction control system. The MAV uses three main engines on its first stage to fly the early portion of powered ascent and a single main engine on the second stage to complete ascent to orbit and the orbital maneuvering required to return the crew to the deep space transport. The main engine is a 22,500 lbf gas generator cycle Lox/LCH4 engine with a minimum guaranteed specific impulse of 360s shown in Figure 11 below. While an engine gimbal has not been included in the current design, an evaluation of the controllability of the MAV during ascent suggests that gimballing the first stage engines may provide significant benefits and will be considered in future iterations of this design. Selection of the Lox/LCH4 propellant combination is driven by compatibility with an atmospheric ISRU process that generates the liquid oxygen required for ascent. With the Lox/LCH4 mixture ration of ~3.2, this means that 76% of the required propellant load will be generated on the Martian surface, drastically reducing the landed mass of the MAV. The ISRU propellant requirement is between 25t and 28t of liquid oxygen over ~520 days. At a production rate of 2 kg/hr, requiring 31 kW of power provided by a nuclear surface power grid, the MAV will be fully fueled by the time the crew arrives. The crew will not descend to the Martian surface until a full propellant load in the MAV has been verified.

Engine Parameters	
Thrust	22,500 lbf
Isp	368 s (360 s min. guaranteed)
Engine MR	3.21
T/W	51.1
Chamber Pressure	1534 psia
Area Ratio	177
Exit Diameter	40 in

Figure 11. Common LOX/LCH4 Engine

This engine is also common with the engine used by the Mars Descent Module for the supersonic retro-propulsion and powered landing phases of cargo delivery. This engine commonality is made possible by selecting a thrust value compatible with both Mars descent and Mars ascent. At the current assumed thrust level of 22,500 lbf the MDM can be controlled through all powered phases of descent and landing with 8 engines. This same thrust level, when applied to the MAV results in a slightly sub-optimal mass result, as shown in the thrust sensitivity plots in figure 12. While the difference in mass is small, this plot shows that the optimal thrust level for the MAV engines is actually higher than the current assumption. Understanding this relationship, designers can realize a potential thrust increase in the engine design to accommodate larger landers that will only bring the MAV design closer to optimal. This engine commonality will provide cost savings across the Mars program by leveraging batch buys of one of the highest cost items in the program. The use of many copies of the same engine across multiple elements in the program also provides an opportunity to build up flight hours and experience on one specific engine design, buying down risk as the program progresses. Additional main propulsion trades and sensitivities are available in references 6 and 15.

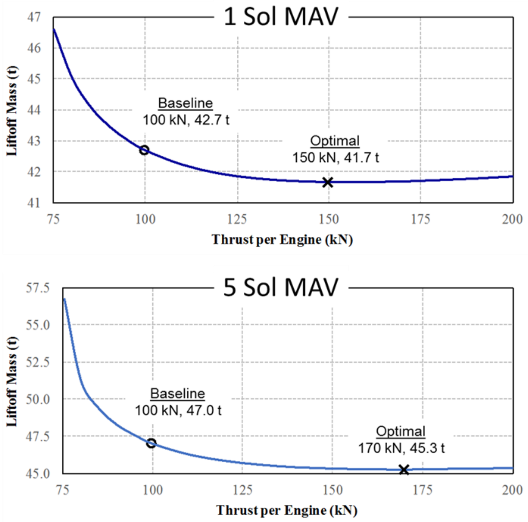
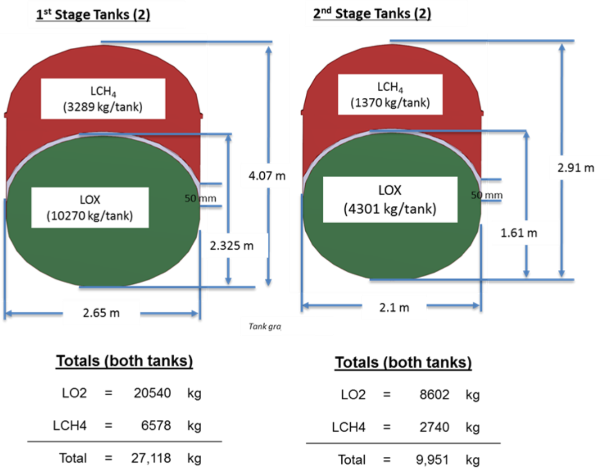


Figure 12. Sensitivity to Main Engine Thrust Level

The integrated RCS is composed of 12 1000 lbf and 12 100 lbf liquid-liquid Lox/LCH4 thrusters. These thrusters are used to perform rendezvous and docking maneuvers, perform course correction and orbit maintenance burns, and provide full attitude control during all stages of powered ascent. What makes this RCS system unique is its integration into the main propellant system. While common in smaller, storable propellant systems used for robotic spacecraft, this kind of combined RCS-MPS system is typically not implemented in cryogenic propulsion systems. All propellants, main engine and RCS, are stored in a common set of propellant tanks and RCS propellant is fed to thrusters from these common tanks via a pumped-loop feed system as needed. By combining propellant storage requirements into one set of tanks, the propellant storage system takes up less space and is more easily integrated with the CFM system. While the general idea of an integrated RCS has been implemented in this design, the detailed design of the system and the additional functional challenges that it presents are the subject of ongoing investigations and design updates to this system will be presented in a future forum.

The MAV propellants are stored in 4 nested aluminum propellant tank sets. These tanks do not carry any structural loads and are held at 50 psia. Each stacked tank set consists of a LCH4 tank placed above a Lox tank, as shown in figure 13. Sharing a common bulkhead between the two propellants is possible because the propellant storage temperatures are common. The use of nested tank sets reduces the height of the MAV center of gravity and facilitates packaging the MAV in the lander that delivers it to Mars. The MAV is a two stage launch vehicle with the first stage consisting of a pair of nested tank sets and three main engines which are dropped part way through the ascent profile. The first stage nested tank sets have an outer diameter of 2.65m and a height of 4m. The second stage has a similar, smaller pair of nested tanks with a diameter of 2m and a height of 2.9m.



Totals (both tanks)

LO2	=	20540	kg
LCH4	=	6578	kg
Total	=	27,118	kg

Totals (both tanks)

LO2	=	8602	kg
LCH4	=	2740	kg
Total	=	9,951	kg

Figure 13. First and Second Stage Nested Tank Sets

A short study was completed to trade the pressurization scheme for the propellant tanks, considering both autogenous and helium-based pressurization approaches. Ultimately, it was decided that a helium pressurization system for both fuel and oxidizer would be the simplest approach and helium pressurization saved significant mass for the Lox pressurization when compared with autogenous pressurization. The helium is stored in composite overwrapped titanium pressure vessels submerged in the liquid propellants in order to reduce storage volume. This approach to helium storage is required to address the packaging issues associated with integrating the MAV with the lander. Helium is flowed through an engine heat exchanger to expand its volume prior to pressurizing the propellant tanks.

Thermal

Traditional vehicle thermal control requirements are supported by a combination of pumped cooling loops, radiators, and water sublimators. Pumped cooling loops pick up heat loads from various internal electronic components and dump that heat energy into radiators and, when radiators are not available, into the water sublimators. Sublimators are employed during the Earth launch phase of the mission and during the aerocapture and EDL phases at Mars. In all other cases, radiators serve as the primary heat rejection system. For the HIAD and ADEPT lander configurations [2], future analyses will seek to address aft body heating experienced by the payloads, including the MAV, during aerocapture and EDL, since these two approaches do not encapsulate payloads like the rigid aerodecelerator concepts do. This is a subject of ongoing analysis and one that is managed by the MDM vehicle thermal control subsystem designers however, the results of those analyses will impact future iterations of the MAV design.

In addition to traditional vehicle thermal control requirements there is a requirement for long duration Cryogenic Fluid Management (CFM). The requirement to support cryogenic propellants drives the need to look at the MAV and MDM as one integrated thermal control system. To help reduce the liftoff mass of the MAV, the CFM systems of the MDM and MAV are cross-strapped and highly integrated. This CFM system operates both in transit to Mars and on the surface of Mars. During transit, the MDM will be responsible for maintaining the methane in the MAV in addition to maintaining its own load of oxygen and methane. Once on the surface thermal management of the MDM propellants ends but and thermal management of the MAV fuel continues along with the additional management of the MAV ISRU generated oxidizer. The liquid oxygen for the MAV is produced in-situ using a process that converts atmospheric carbon dioxide into liquid oxygen. On the surface of Mars, the CFM system must maintain the fuel and oxidizer conditions for the MAV. Due to the unique characteristics of the Martian atmosphere, an extensive set of deployable radiators is used to reject heat during the oxygen production/liquefaction process, a set that is integrated into the MDM and which remains on the surface of Mars after the MAV lifts off. Once the MAV is fully fueled, primary heat rejection is done using the MAV radiators with the MDM radiator system as a backup. The phase-by-phase radiator usage is outlined in Figure 14. The CFM system uses a set of three 90K cryo-coolers, two active, one spare. One cryocooler is located on the MDM while the other active and spare cryocoolers are located on the MAV. Each cryocooler provides 150W of lift (or heat removal) with a required input power of just over 1200W. The MAV (without the oxygen propellant) is pre-deployed years in advance of a crew landing to allow adequate time for propellant generation.

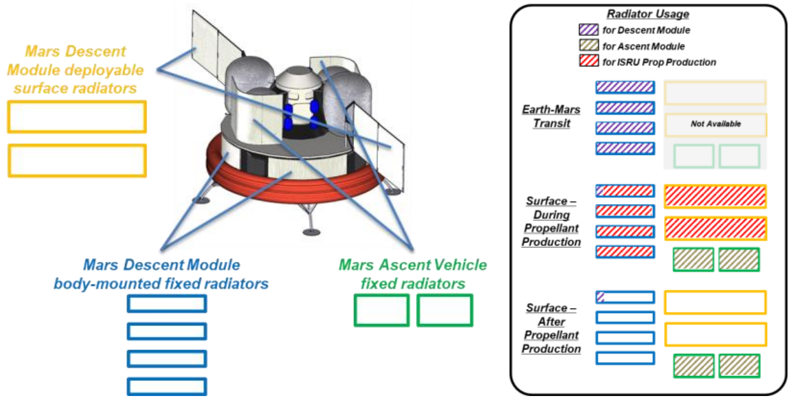


Figure 14: MDM/MAV integrated Heat Rejection

The MAV uses oxygen that is collected and liquefied on the Martian surface along with methane brought from Earth as propellant. Storage of these cryogenic propellants on the Mars surface is a challenge. Traditional multilayer insulation could allow CO_2 from the Martian atmosphere to build up as solid ice on the exterior of the vehicle. Several insulation options were evaluated with various performance, mass and reliability metrics [14], see Figure 15. Broad area cooling tubes are installed under the insulation on the external tank walls. Cryocoolers extract heat from the system to keep the propellants within the required temperature range for the engines. Excess MAV heat is rejected through a loop heat pipe radiator system. Cryocooler performance metrics have been updated to align with recent changes in vendor performance predictions and are informed by ongoing research and development.

Power

The MAV power system uses oxygen-methane fuel cells to produce the required operational power for ascent and return to the deep space transport. Power during the initial cruise from Earth to Mars is provided by the MDM and is specifically required to maintain keep alive power for avionics, thermal, and crew cabin life support systems. For MAV operational phases, starting with the pre-ascent check-out, power is provided by three solid oxide oxygen-methane fuel cells. Given the relatively short operational life of the MAV, fuel cells were the preferred option over solar arrays to avoid additional deployable systems and save weight. Reactants for the fuel cells are provided from the second stage main propellant tanks. Power system schematic and power profile can be found in Figure 16.

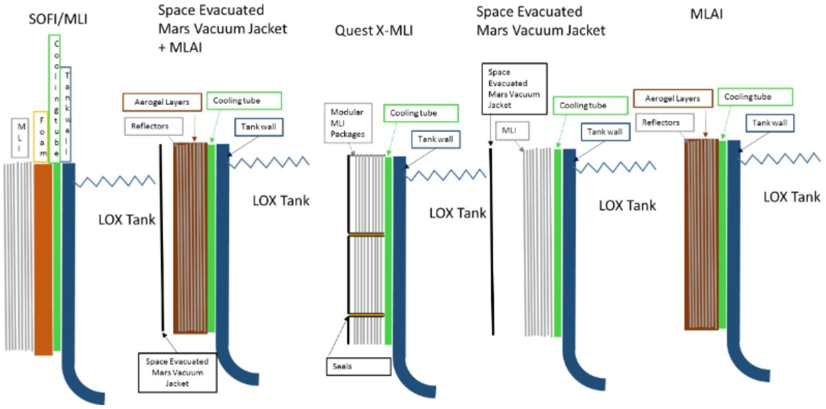
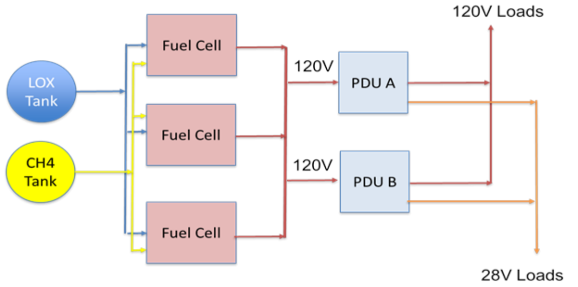


Figure 15. Tank Insulation Options.



28V Loads

Mission Phase	Avionics	Propulsion	Thermal	Life Support	MAV Total	
To Mars	1451	0	954	120	2525	Provided by MDM
Pre-Ascent Checkout	1701	0	954	0	2655	Provided by MAV
First Stage Ascent	1701	2400	954	535	5590	
Second Stage Ascent	1701	2400	954	535	5590	
Coast	1701	470	954	535	3660	
Raise Periapsis	1701	345	954	535	3535	
Phasing	1701	345	954	535	3535	
Height	1701	345	954	535	3535	
Coelliptic	1701	350	954	535	3540	
Lambert Targeted	1701	345	954	535	3535	
Braking Maneuver	1701	345	954	535	3535	
Docking	1701	345	954	535	3535	
Docked Ops	1701	170	954	535	3360	
Undocking/Loiter	1701	345	954	0	3000	
Disposal	1451	345	954	0	2750	

Total Energy	214707 Whrs
Reactant Mass	134 Kg
CH4	27 Kg
O2	107 Kg

Figure 16. Power System Schematic and Power Profile

Avionics

Avionics includes command and data handling (C&DH), communication and tracking (C&T), as well as guidance, navigation and control sensors. Designs for C&DH and C&T are documented in reference 4 and have not been updated since that publication. Navigation and control improvements are in work now. Recent work includes the development of a simulation and assessment of navigation sensor options and performance. A summary of this work can be found in reference 16. New work on vehicle control shows inadequate margins when dispersions are applied. The vehicle seems most sensitive to potential center of mass offsets. Figure 17 shows the gimbal angle necessary to counteract this offset. While it doesn't appear that main engine gimbal is needed for nominal ascent (and is not included in the vehicle mass summary in this paper), when dispersions are applied engine gimbal becomes an attractive solution to maintaining adequate control margins throughout flight. Efforts are currently underway to evaluate options for improving controllability, and solutions will be incorporated in a future design revision.

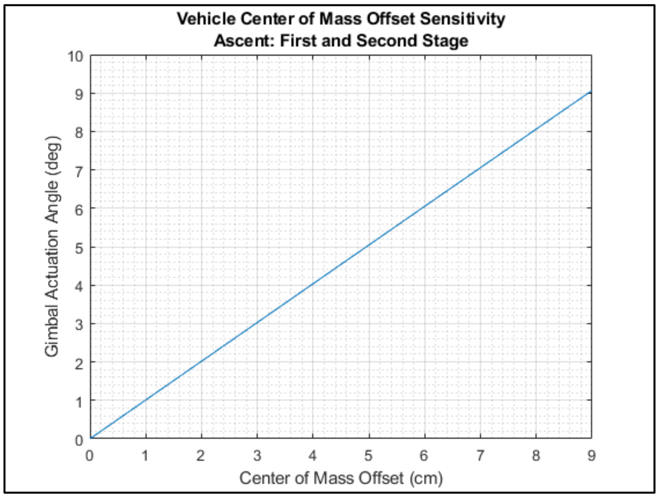


Figure 17. Vehicle Center of Mass Offset Sensitivity

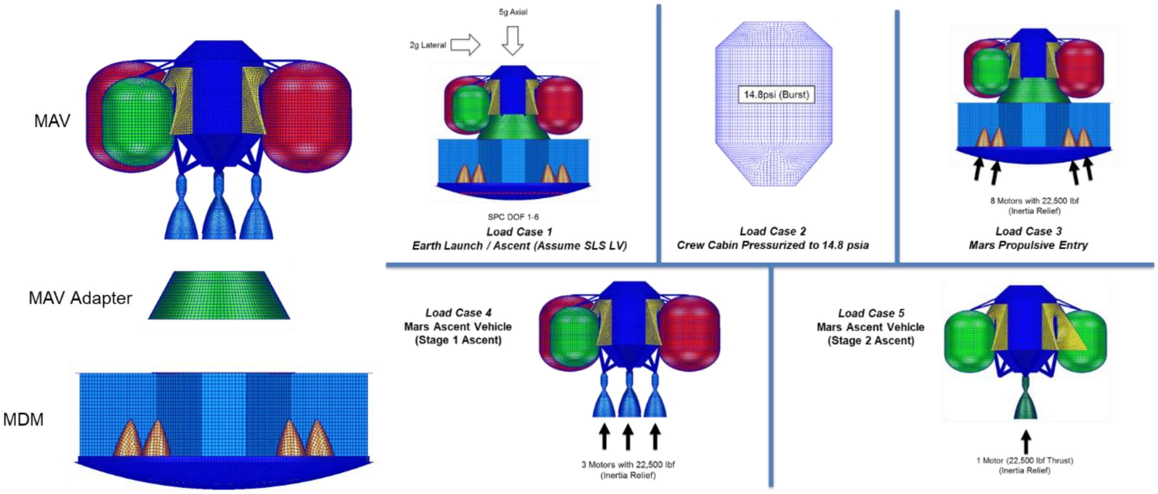


Figure 18. Structural Model and Load Cases Assessed

Structures

A full structural evaluation of the MAV concept was completed using a series of finite element analysis tools. The MAV model was evaluated using MSC Patran, MSC Nastran, and Collier Research Corporation's HyperSizer. Fuel and oxidizer tanks were assumed to be rigid bodies and all subsystems were represented using point masses and multi-point constraint definitions. The MAV structural design assumes composite construction for all shell and truss structures (IM7-8552 Quasi Isotropic and Hexcell Honeycomb). The MAV adapter structure assumes composite construction (IM7-8552 Quasi Isotropic). The MAV configurations were evaluated for both Earth launch loads (5g Axial, 2g Lateral based on projected SLS launch loads) and Mars supersonic retro propulsion loads, assuming eight 22,500 lbf engines at full throttle. The cabin structures were evaluated for burst loads due to internal atmospheric pressure. The MAV was also subject to both first and second stage propulsive loads. All load cases are shown in figure 18 above.

4. VEHICLE PERFORMANCE

This section covers vehicle performance and includes a discussion of trajectory design, aerodynamics, ascent plume interaction and a vehicle mass summary.

Trajectory Design

Trajectory optimization is a key component in assessing vehicle performance during conceptual design. The ascent performance of the MAV was modeled using Program to Optimize Space Trajectories (POST). One of the most influential factors in MAV design is the desired destination orbit. This decision determines the propulsive capability needed and the flight duration which drives decisions about crew accommodations. Ascent to a Low Mars Orbit (LMO) and two highly elliptical high Mars Orbits with orbital periods of 1 Sol and 5 Sol, have been studied. Although achieving low Mars orbit requires the least energy and allows for the shortest ascent flight time, the much larger Earth transit vehicle becomes excessively burdened by the extra propellant required to get into and out of that low energy orbit to meet the MAV and depart for the return to Earth. To alleviate the impact to the Earth return vehicle, a taxi vehicle waiting in LMO could ferry the crew the rest of the way to the Earth transit vehicle in a higher orbit, however this adds cost and risk to the mission. The 5 sol MAV, designed for a three-day ascent, was selected as the best compromise.

While no decisions have yet been made on the first human mission landing site, for the purpose of this design reference the MAV is designed assuming ascent from a site at 30° north latitude and is delivered to an initial low Mars orbit with a 30° inclination. From this intermediate orbit, the MAV then performs a series of phasing and orbit adjustments to achieve a rendezvous and docking with the Earth return vehicle. It is assumed that the Earth return vehicle is in the same orbital plane.

While designing the rendezvous trajectories, consideration was given to launch window availability and window duration. Shorter flight durations from the surface to rendezvous with the Earth return vehicle are possible, but at the expense of additional ΔV, reduced launch window availability, and reduced launch window duration. For example, shortening the ascent to rendezvous duration for the 5 Sol case from 3 days to 12 hours costs an additional 250 m/s of ΔV, the launch windows occur once every 5 days, and the launch window may only be seconds or minutes long. To maximize operational robustness, scenarios that allow multiple launch opportunities per day with launch windows of hours in duration are preferred.

Figure 19 provides an overview of the trajectory to reach a 5 Sol orbit. Figure 20 provides time histories for key parameters during ascent such as vehicle mass, thrust, altitude, pitch angle and sensed acceleration. Table 3 provides a summary of events during ascent.

In an attempt to alleviate the execution time issues associated with POST2 and allow for much broader trade space exploration, a tool for automating ascent trajectory optimization has been developed [17]. This tool captures heuristics developed over years of analyst experience and leverages the power of modern computing to speed up the evaluation of large sets of vehicle trajectories.

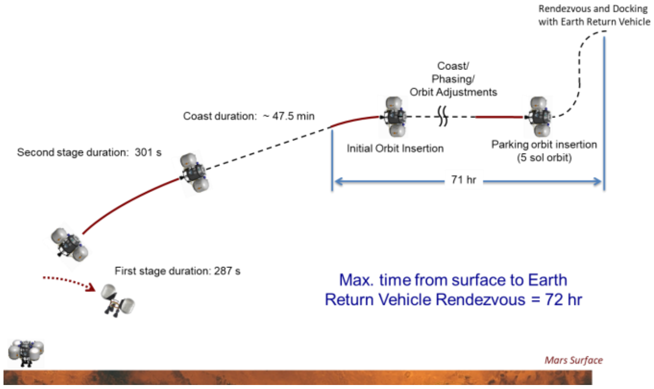
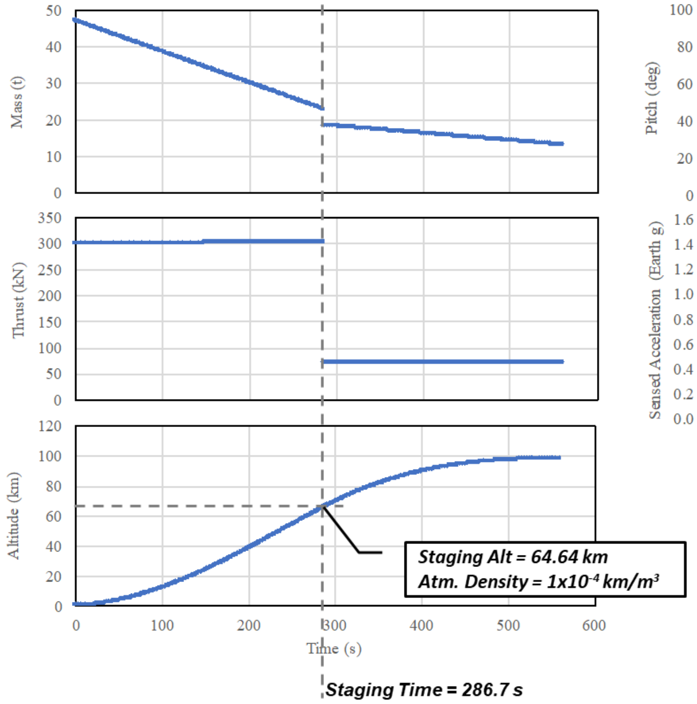
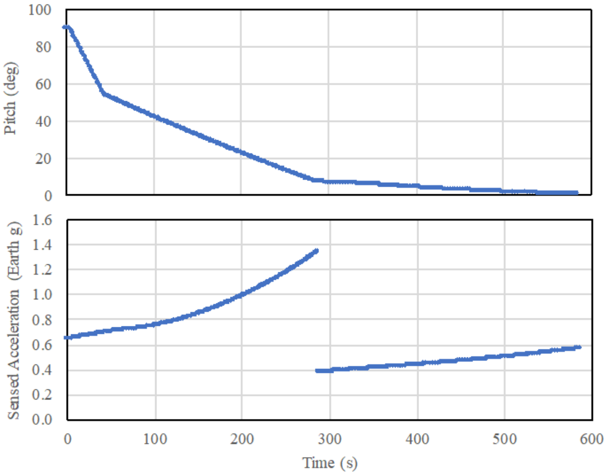


Figure 19. MAV Ascent Trajectory to 5 Sol, Overview

Table 3. MAV Ascent Trajectory Events

Event	ΔV (m/s)	MPS/RCS?	Isp (s)	MR
First Stage Powered Ascent	Determined by POST2	MPS	360	3.17
Drop First Stage	---	---	---	---
Second Stage Powered Ascent (into 100 x 250 km orbit)	Determined by POST2	MPS	360	3.17
Raise Periapsis	15	RCS	330	3.00
Phasing	50	RCS	300	3.00
Height	8	RCS	300	3.00
Coelliptic (NSR)	1 Sol: 1147 5 Sol: 1345	MPS	360	3.17
TPI	4.6	RCS	330	3.00
TPF and Docking	1.7	RCS	330	3.00
Undocking	5	RCS	300	3.00
Disposal	21	RCS	330	3.00





Init Mass	=	47,005	kg
Payload Mass	=	4,476	kg
Stg 1 Prop	=	24,358	kg
Stg 1 PMF	=	0.8494	
Stg 1 Burn Time	=	286.7	s
Staging Altitude	=	64.64	km
Stg 2 Prop	=	10,500	kg
Stg 2 PMF	=	0.7580	
Stg 2 Burn Time	=	300.5	s
Stg 2 Thrust	=	70	kN
Throttle	=	0.70	

Figure 20. MAV Ascent Trajectory to 5 Sol, Details

Aerodynamics

Drag during ascent through the atmosphere has also been assessed. The atmospheric pressure on the surface of Mars is only about 0.6% of Earth's sea level pressure and drops off quickly with altitude, however the effect on ascent vehicle performance cannot be neglected. While this configuration has a large cross sectional area compared to its length, the low acceleration at liftoff and the rapid drop off in atmospheric pressure results in a maximum drag force of only 20 N (4.5 lbf). No attempt has been made to optimize the aerodynamics of this vehicle, though it is believed that the addition of aerodynamic surface could improve performance and will likely be needed to minimize shock interactions and localized heating during ascent.

Plume Interaction

The MAV lifts off with 300 kN or 67,000 lbf of thrust, almost 20 times more thrust than the Apollo ascent vehicle, so its engines, embedded in the descent stage, and their plumes present a challenge. Unlike past robotic Mars landers, the heatshield for the human lander remains attached to the vehicle, effectively sealing off the MAV's engine compartment. Analysis was performed to assess the pressure forces and temperatures on the vehicle during liftoff for two possible configurations. The first option retains the heatshield and uses an open truss structure to connect the MAV cabin to the descent stage upper deck. In this option, plumes are redirected up and around the vehicle until the engine nozzles clear the upper deck of the lander. This option, as expected, resulted in excessive forces on the vehicle. In the second concept, the central section of the heatshield is detached and lowered approximately 0.7 meters to the ground prior to liftoff. This option allows the plumes to disperse both upward toward the vehicle and down around the headshield significantly reducing the forces and temperatures experienced by the MAV. Figure 21 shows the two concepts and a comparison of the resulting integrated pressure force. The second concept was chosen for this design reference.

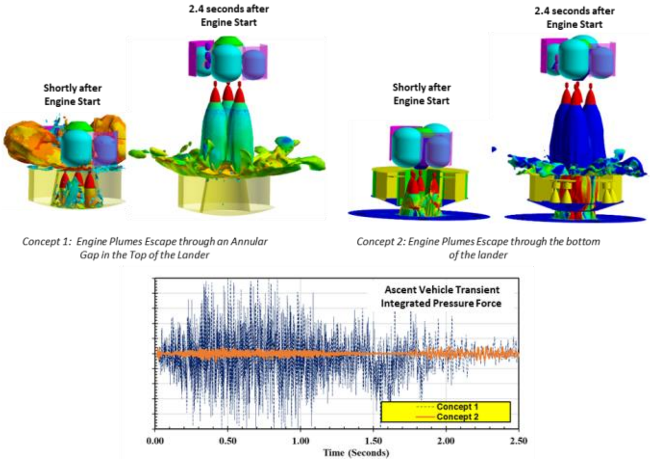


Figure 21. Liftoff Plume Analysis

Vehicle Mass Summary

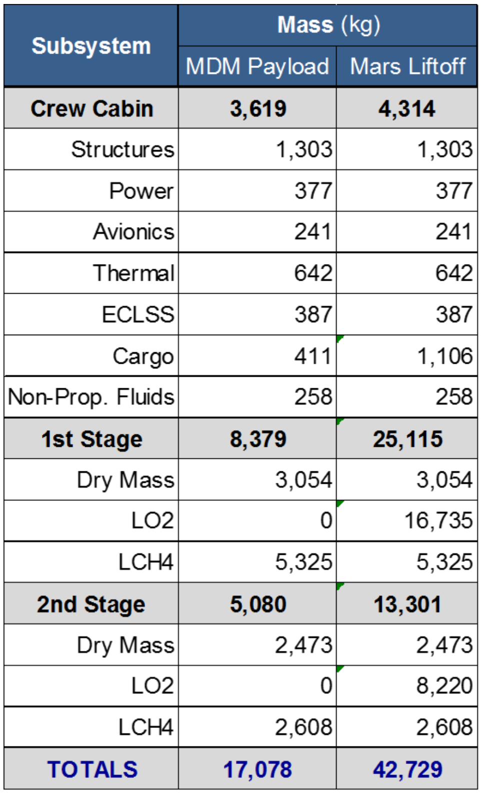
The resulting vehicle mass summary is shown in Table 4. The MDM Payload column indicates the MAV mass at delivery to Mars when there is no crew or cargo on board and the oxygen propellant has not yet be generated. The second column provides the liftoff mass. The liftoff mass is 3,700 kg heavier than what was presented in 2015 [4].

5. CONCLUSIONS

Several investigations have been performed to either increase the overall fidelity of the MAV or investigate a specific threats or opportunities to its design. This work resulted in a significant improvement of our understanding of human Mars ascent vehicle requirements and design options. The findings of these investigations have been incorporated into the integrated vehicle design update presented in this paper. Continued efforts to refine the MAV design and the sensitivities to Mars architecture options will help to identify the most promising options for future human exploration and the necessary capabilities and technologies to make these missions possible.

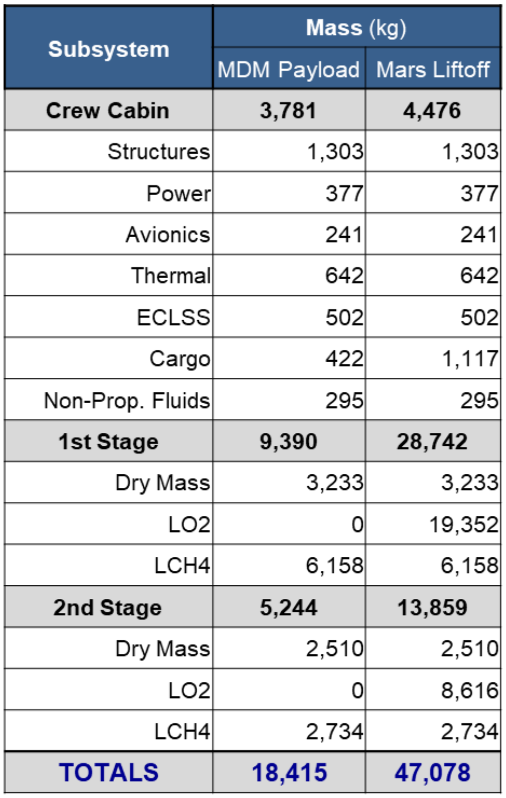
Table 4. Mass Summary for 1 Sol and 5 Sol MAV options

MAV to 1 Sol



Subsystem	**Mass** (kg)	
	MDM Payload	Mars Liftoff
Crew Cabin	**3,619**	**4,314**
Structures	1,303	1,303
Power	377	377
Avionics	241	241
Thermal	642	642
ECLSS	387	387
Cargo	411	1,106
Non-Prop. Fluids	258	258
1st Stage	**8,379**	**25,115**
Dry Mass	3,054	3,054
LO2	0	16,735
LCH4	5,325	5,325
2nd Stage	**5,080**	**13,301**
Dry Mass	2,473	2,473
LO2	0	8,220
LCH4	2,608	2,608
TOTALS	**17,078**	**42,729**

MAV to 5 Sol



Subsystem	**Mass** (kg)	
	MDM Payload	Mars Liftoff
Crew Cabin	**3,781**	**4,476**
Structures	1,303	1,303
Power	377	377
Avionics	241	241
Thermal	642	642
ECLSS	502	502
Cargo	422	1,117
Non-Prop. Fluids	295	295
1st Stage	**9,390**	**28,742**
Dry Mass	3,233	3,233
LO2	0	19,352
LCH4	6,158	6,158
2nd Stage	**5,244**	**13,859**
Dry Mass	2,510	2,510
LO2	0	8,616
LCH4	2,734	2,734
TOTALS	**18,415**	**47,078**

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