Updated Human Mars Ascent Vehicle Concept in Support of NASA's Strategic Analysis Cycle 2021

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Abstract—**Significant progress has been made to NASA's Moon to Mars campaign over the last several years, which drives changes to the agency's current human exploration strategy. With Strategic Analysis Cycle 2021 (SAC21) the team was asked to consider new areas of the trades space not fully understood in the past. Specific to the Mars Ascent Vehicle (MAV), the team was asked to consider a concept based on a nitrogen tetroxide (NTO) and mono-methyl hydrazine (MMH) two stage propulsion system which would utilize surface propellant transfer, as opposed to In Situ Resource Utilization (ISRU). The vehicle supports two crew members from the surface up to 84 hours nominally. This paper presents further details of the current MAV reference design used in NASA's SAC21, including descriptions of the operations, configuration, subsystem design, and vehicle mass summary. Additional detail is also provided on rational that drove specific design changes since the last MAV concept, published in 2019.**

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1. INTRODUCTION

Mars continues to be an Agency horizon goal, extending human exploration efforts through the Artemis enterprise [1,2]. As Agency goals shift, so too has the design of reference human Mars exploration elements. NASA engineers have continued to make steady progress in understanding challenges and complexities of sending humans to Mars, refining reference Mars exploration architectures as capabilities and technologies evolve. The Mars Architecture Team, under NASA's Human Exploration and Operations Mission Directorate, has continued the work of the Mars Study Capability Team since 2019, developing conceptual designs for human Mars exploration [2] including: in-space transportation systems [3], Mars surface systems [4,5], and entry, descent, landing (EDL), and ascent systems [6]. This includes the Mars Ascent Vehicle (MAV). These studies are crucial to informing technology investments and priorities to continue progressing towards enabling human exploration of Mars.

The National Aeronautics and Space Administration's (NASA) Mars Architecture Team (MAT) was challenged to develop a mission architecture capable of transporting humans to the surface of Mars and back as fast—and as soon—as practical. This challenge represented a significant departure from previous approaches that minimized Earth-launched mass and maximized in-space transportation efficiency, often resulting in roundtrip missions of three years or more in duration. In the interest of crew health, MAT's cross-Agency team of subject matter experts was challenged to develop an architecture capable of shortening crew time away from Earth to about two years. MAT was given specific mission constraints, such as number of crew, as well as mandates to minimize surface infrastructure as much as possible. The resulting concept, referred to here as the Strategic Analysis Cycle 2021 (SAC21) architecture, includes the smallest practical Mars Ascent Vehicle (MAV). To minimize surface infrastructure, only two Mars crew would descend and explore the martian surface for 30 martian days, or sols, before returning to Mars orbit aboard their MAV and rejoining additional crew on the Deep Space Transport for the Earth return voyage. Because the MAV is the largest indivisible cargo item delivered to the martian surface, this approach was intended to inform the minimum required lander payload capacity needed for a human Mars surface mission. Larger crew complements, requiring larger MAVs, which in turn would require larger landers are still in the trade space, but NASA was interested in characterizing this more modest corner of the trade space.

The MAV is ultimately responsible for transporting crew members from the surface of Mars to rendezvous with the Earth return element in orbit. The MAV is a particularly influential component of the end-to-end architecture, due in no small part to its high wet mass sensitivity to even slight dry mass changes, and the fact that it is the most massive indivisible cargo item. The ultimate size of the EDL system is heavily dependent on the mass that must be delivered to the surface of Mars, and in turn, drives the in-space transportation system's performance to deliver that mass to Mars vicinity. Furthermore, MAV design influences EDL system configuration, as well as necessary surface systems and surface concept of operations. The way in which crew ingress the MAV on the surface impacts the design of pressurized rovers, surface mating systems, and surface power demands, just to name a few. Current reference MAV concepts drive the need for new technologies such as nitrogen tetroxide (NTO) and mono-methyl hydrazine (MMH) deep throttling pump-fed engines, as well as qualifications and standards for extended dormancy of corrosive and highly toxic propellants.

Conceptual designs for the MAV have continued to mature since the last design update information was publicly published in 2019 [7]. This paper presents an overview of the current MAV reference design used in NASA's Strategic Analysis Cycle 2021 (SAC21). This design includes refinements in many subsystems that reflect recent changes in Agency guidance which impact system design and operation. There is a current desire to explore a minimal surface infrastructure in support of initial human exploration of Mars. This results in only two crew members to the surface, which also results in a significantly reduced cabin concept for the MAV. The Agency also would like to reduce the overall number of technology investments required to field the first humans to Mars. As a result, In-Situ Resource Utilization (ISRU) was assumed to be unavailable for initial missions, driving decisions for NTO/MMH main propulsion systems, as well as surface propellant prepositioning and surface propellant transfer. This paper includes a vehicle overview with a description of the operations and configurations, a discussion of vehicle subsystems, and finally vehicle performance and mass summary.

2. VEHICLE OVERVIEW

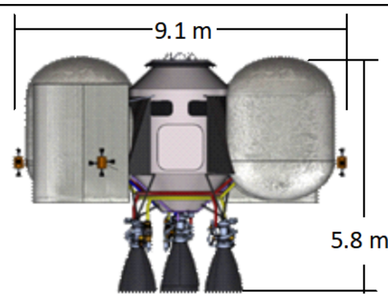
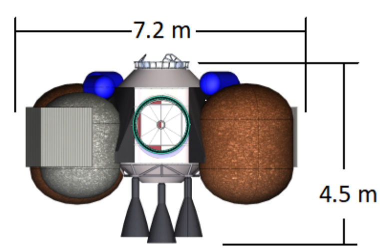
Although launching humans from Earth has become more of a routine activity in recent years, launching crew from any other celestial body has only been done six times during the Apollo program. The updated design configuration maintains many features of previous designs such that it is possible to leverage as many similarities to crewed lunar operations from the Apollo program. The SAC21 reference MAV concept relies on the EDL element to act as a launch platform. The MAV cabin is designed to support crew for a relatively short duration of only a few days during ascent and rendezvous with the Transit Habitat. The MAV is still responsible for providing ingress and egress of crew on the surface and with the Transit Habitat in orbit.

Functional Requirements

The MAV's primary purpose is to carry crew and return cargo off the surface of Mars to rendezvous with the Transit Habitat. Minimum functional requirements for the MAV include:

1. Allow for crew ingress and egress on the surface of Mars
2. Transport two crew and 100 kilograms (kg) of cargo from the surface of Mars to docking with the Transit Habitat
3. Support crew in a microgravity environment for up to 3.5 days
4. Minimize the transfer of uncontained Martian material to the Transit Habitat per planetary protection best practices [13], [14].
5. Perform a controlled disposal maneuver after crew and cargo transfer
6. Operate reliably for 5.5 years, with up to 4 years on the Mars surface

Table 1. Comparison of Recent Human Mars Ascent Vehicle Concepts

		
	c. 2019	**SAC21**
Crew Size (max)	4	2
Surface duration	1.5-2 years prior to crew 500 days crewed surface mission	5.5 years prior to crew 30 days crewed surface mission
Ascent Delta V (m/s)	5,274 m/s	5,109 m/s
Stages	2	2
Crew module press. Volume	17.5 m^3	10.5 m^3
Ascent vehicle mass	47,100 kg at liftoff 18,400 kg delivered	36,830 kg at liftoff 21,067 kg delivered
Ascent vehicle engines	3 + 1 pump-fed throttling, LOX/LCH4	4 + 1 pump-fed throttling, NTO/MMH
Ascent engine thrust	100 kN (22.5 klbf)	44.5 kN (10 klbf)

Primary Design Changes

Table 1 provides a brief overview of the current reference MAV concept and how it compares to the previous iteration presented in 2019 [7]. Key changes include a reduction in crew capacity from four to two. This was driven by a desire to minimize surface infrastructure needed to support initial crewed Mars missions. Because number of crew to the surface have significant impact across the surface architecture, it was expected to significantly reduce the number of unique surface elements and associated technologies required for the early missions. This reduction in number of crew is what primarily drove the physical size reduction of the vehicle compared to the 2019 reference concept, and subsequently, the mass of the vehicle. The other primary difference between the two vehicles is the main propulsion system. Previous iterations of the MAV concept opted for cryogenic main propulsion systems for the increased performance potential, coupled with the ability to utilize ISRU to manufacture components of the propellant on the surface of Mars, thereby reducing the amount of mass that would need to be delivered. The SAC21 reference MAV concept opted for a storable-based NTO/MMH pump-fed main propulsion system. The selection was made to understand potential impacts of such a main propulsion system on the architecture, while also making use of current investments in pump-fed storable main propulsion systems under lunar exploration efforts. However, because of reduced MAV mass, along with maintaining relatively common engine performance parameters of existing developments, the total number of main propulsion system engines on the first stage had to be increased to ensure sufficient thrust at Mars ascent.

Configuration

The MAV consists of a crew cabin and a two-stage propulsion system. Figure 1 shows the overall configuration of the MAV, while Figure 2 shows the two stages of the vehicle, Figure 2.a is the first stage of the vehicle which consists of only a main propulsion system with four 10 kilo pound force (klbf) pump-fed NTO/MMH main engines and two sets of nested NTO/MMH tanks. Figure 2.b shows the second stage which consist of the crew cabin, detailed in Figure 3, as well as independent main propulsion and reaction control systems. The second stage main propulsion system contains a single main engine identical to those on the first stage. The reaction control system is an independent pressure-fed system.

Figure 3 is a cross-section view of the crew cabin. The current reference crew cabin is a vertical cylinder 2.3 m in diameter and 2.9 m tall, with roughly 10.5 m^3 of habitable volume. The vertical orientation was maintained for the same reasons identified in the previous design studies [8]. The crew cabin also contains all the necessary avionics, power systems, thermal control, and ECLSS to support the crew for the 3.5-day ascent to rendezvous with the Transit Habitat. The cabin has two access points for crew ingress/egress, as well as integrating with other architecture elements: an axial mounted NASA docking system (NDS) [9] and a radial mounted 1 m square hatch, similar to those found on the International Space Station US orbital segment. Though the MAV is expected to be the active vehicle during docking operations, a passive NDS mechanism was selected to minimize mass due to the high mass sensitivity of the MAV. However, sensors and communications systems required to

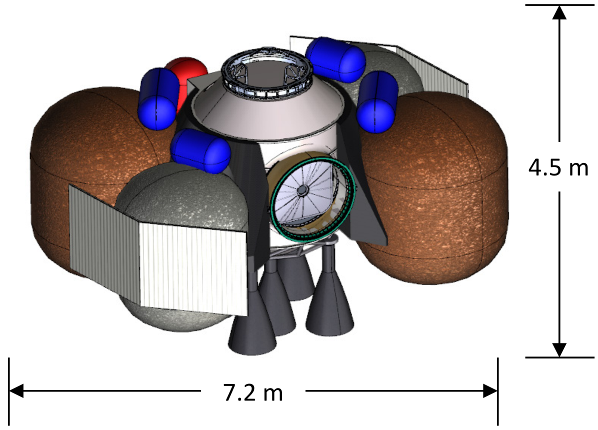
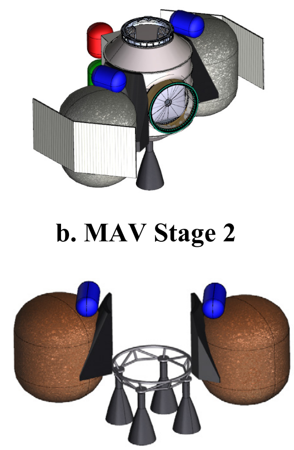


Figure 1. Mars Ascent Vehicle (MAV)



b. MAV Stage 2

a. MAV Stage 1

Figure 2. Mars Ascent Vehicle Configuration

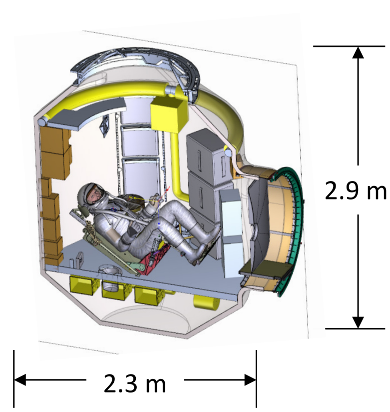


Figure 3. MAV Crew Cabin

be the active vehicle during docking are maintained. The Transit Habitat is assumed to have androgenous docking mechanisms capable of interfacing with either active or passive docking systems. A 1 m square hatch was selected for the radial hatch as a result of previous studies and tests concluding that this dimension hatch was sufficient to allow suited crew ingress/egress in partial gravity environments [10].

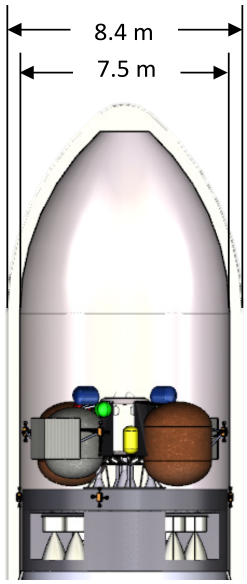


Figure 4. MAV Launch Configuration

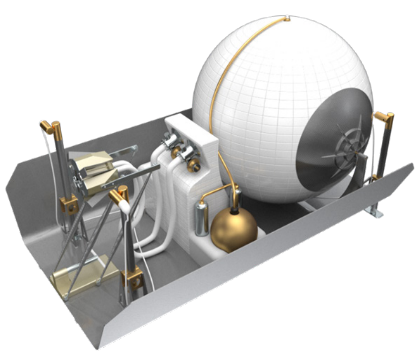


Figure 5. Notional Mars Surface Propellant Transfer Package

The overall configuration of the vehicle allows for a relatively compact design with a low center of mass which supports stability during EDL, as well as relatively straightforward crew access during key mission phases. The crew are seated in 45-degree recumbent seats during ascent to improve crew comfort. During powered ascent, sensed accelerations can reach nearly 1.5 Earth g's. Though this may not seem like much, a crew member conditioned to the Mars environment will need to be supported to mitigate potential health concerns.

The final major configuration change to the vehicle design compared to the 2019 reference is the overall diameter constraint of the MAV. Previous design iterations allowed for up to a 9.1 m overall diameter to accommodate dynamic envelopes of notional 10 m fairings. However, the updated configuration was constrained to a 7.5 m diameter dynamic envelope to conform to notional 8.4 m diameter fairings currently planned for SLS, as shown in Figure 4. This was feasible due to the smaller overall form factor achieved by the reduced number of crew, combine with the more compact NTO/MMH main propulsion system, allowing maximum flexibility with future heavy lift launch vehicle fairing configurations.

Operation

The MAV is launched from Earth and aggregated with a Mars transportation vehicle in cis-lunar space. It is launched integrated with the lander system. The lander system is responsible for providing power and communications during the transit phase of the mission, which may range up to one year, depending on the design of the transportation vehicle. The MAV with lander system is inserted into Mars orbit by the transportation element. Upon arrival at Mars, the MAV and lander system separate from the transportation vehicle and prepare for entry, descent, and landing. This consists of several checkout operations and final orbit adjustments to target the final landing site. These operations are again performed by the lander system. Once on the surface, the lander system is connected to surface power systems within 24 hours to provide power for the MAV for the remainder of the surface operations. Surface power systems are assumed pre-emplaced by an earlier lander.

The MAV is delivered to Mars one opportunity before crew arrival with full MMH propellant tanks and partially filled NTO tanks. Propellant must be offloaded to accommodate the limited 25 metric ton payload mass capability of the SAC 21 Mars Descent System. It was desired to minimize the number of fluids to be transferred on the surface to simplify the process. Of the two main propulsion system propellants, MMH is the desired constituent due to reduced toxicity and corrosiveness on transfer hardware. However, the total mass of loaded MMH on the MAV does not allow for enough mass offloading to meet landing system mass limitations. As a result, NTO was selected as the transfer fluid.

The MAV is serviced by a surface propellant transfer infrastructure which is also delivered to Mars on an earlier lander, along with the remaining NTO to fully fuel the MAV [11]. A propellant transfer package, shown notionally in Figure 5, carried by an autonomous rover, would be responsible for transporting NTO delivered on the first lander, and pumping it to the MAV on the second lander. There may be appreciable distances between the lander, currently estimated at 1 km. The process would have to occur autonomously over several trips due to the limited cargo capacity assumed of the rover. Currently, the refueling process is expected to require about 11 round trips of the rover. This process would require appreciable time to complete the transfer of the full complement of NTO to the MAV and is the reason for requiring the MAV to be delivered one opportunity prior to crew arrival. The crew will not be cleared to land on Mars until the full propellant compliment required for powered ascent is confirmed.

While on the surface, the crew are not expected to live or operate out of the MAV cabin. At the completion of the surface mission, the crew will drive a pressurized rover to the MAV and attach an inflatable tunnel between the rover and MAV for crew ingress. This tunnel allows for a protected environment to support planetary protection protocols and minimize the potential of returning uncontained Mars material to the Transit Habitat and Earth. See Figure 6 and reference [12] for details on crew access tunnel concepts.

Figure 6. Rover-to-MAV Crew Transfer Concepts

Just prior to ascent, all support services from the descent vehicle are discontinued and the MAV becomes self-sufficient. Powered ascent takes approximately 10 minutes, with first stage separation occurring roughly 5 minutes into flight. This places the MAV into an initial low Mars orbit before performing a series of maneuvers to place the MAV on a final intercept trajectory with the Transit Habitat. For the SAC21 architecture, the Transit Habitat is expected to be in a 5-sol orbit to minimize the amount of additional work the in-space transportation vehicle must perform while inserting into and departing from Mars orbit. Transfer between the initial low Mars parking orbit and rendezvous in the 5-sol orbit is expected to take roughly 3.5 days. This transfer duration allows for multiple launch opportunities per week and reasonable launch window durations. Figure 7 provides a depiction of the 5-sol orbit, as well as several other Mars aggregation orbits. Note that the durations and delta-Vs shown in this figure are approximate and ideal. Actual values will vary with more detailed trajectories and propulsion system performance.

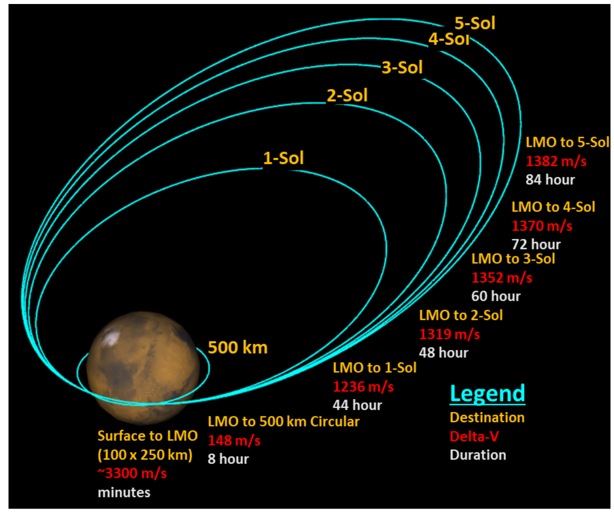


Figure 7. Mars Aggregation Orbits

3. VEHICLE SYSTEMS

This section provides a summary of each major vehicle subsystem. Life support and human factors components are captured under Crew Cabin Design, followed by propulsion, thermal, power, avionics, and structures. To minimize MAV mass, lander system services are relied upon so that the MAV systems need only perform what is necessary for crew ascent operations. Figure 8 shows the various interfaces with other architecture elements.

Crew Cabin Design

The environmental control and life support (ECLS) system for the MAV are based on Orion life support systems. It is an open loop design, as the relatively short 3.5-day crewed duration does not outweigh the penalties of carrying closed loop systems. Prior to crew ingress, the system is maintained in a standby state to reduce consumables during the long loiter duration of 5.5 years. shows the system schematic for the ECLS system. Major components include the pressure control system (PCS), air revitalization system (ARS), particulate control, emergency management system (EMS), temperature and humidity control, and waste management system (WMS). Due to the limited crew duration, certain human factors items were omitted, such as exercise equipment and food warmers.

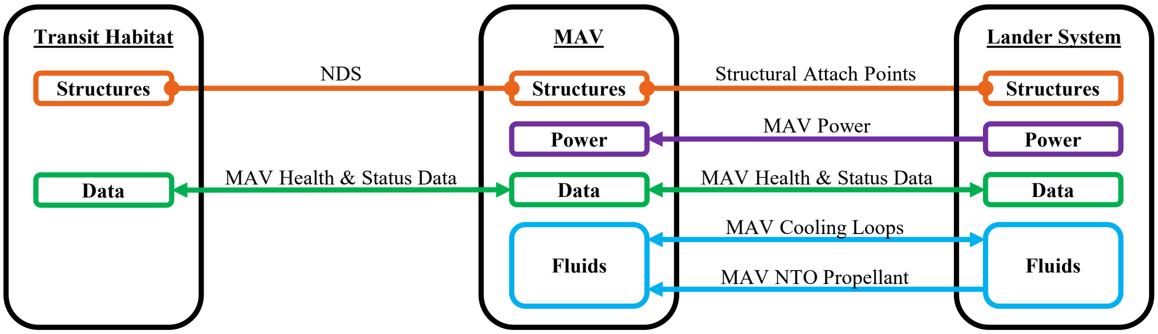


Figure 8. MAV Interfaces with other Elements

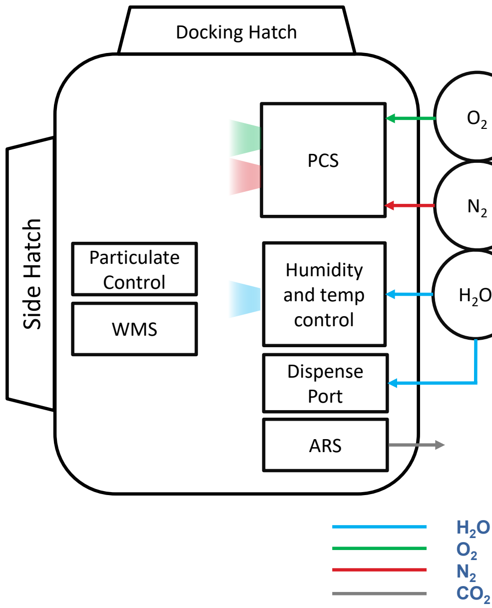


Figure 9. MAV ECLS System Diagram

Table 2. Cargo and Human Factors Equipment

Item (# items)	Assumption
Crew (2)	98.5 kg/person
Food	1 kg/day/person
Crew Provisions	2.5 kg/day/person
Total Mission Provisions	30 kg/person
Safety	36 kg
Sleep Systems	8.2 kg/person
Recumbent Seats (2)	22.7 kg/seat
OCSS Pressure Suite	23 kg/suit
Utilization	100 kg

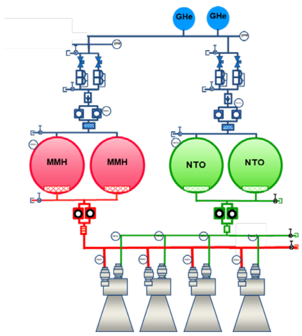
Crew provisions include items such as food bars and drink bags, tool kits, towels and hygiene supplies, trash bags, fecal collection and cleaning supplies, and personal provisions. These items total to roughly 30 kg per crew member. Several of these items are expected to be transferred to the MAV after the crew arrives at Mars due to storage duration limitations of perishable items and the long idle durations of the MAV.

Safety gear includes items such as medical kits, personal radiation dosimeters, cabin illumination, and restraints. Each crew member is provided a sleeping system which includes a sleeping bag, cushion, pillow, and restraint. It is expected that sleeping will only be in a microgravity environment. A 100 kg mass allocation is also provided for utilization, to encompass scientific sample return and any stowage systems required. Table 2 provides a summary of the various cargo and human factors equipment allocations for the MAV.

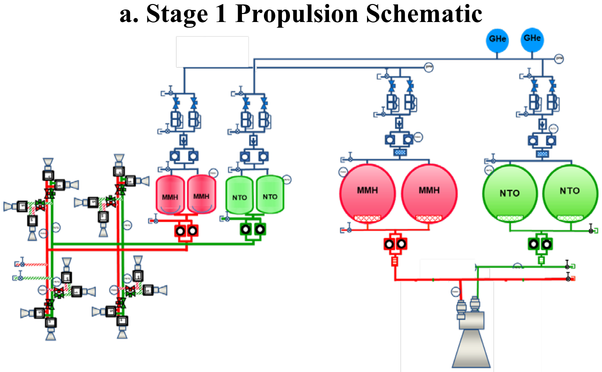
Propulsion

The propulsion system for the MAV consists of a two-stage pump-fed main propulsion system and an independent pressure-fed reaction control system. The MAV uses four main engines on the first stage and a single engine on the second stage. All five main engines operate during initial ascent to provide sufficient thrust based on a reference engine designed derived from the XLR-132. The main engine is a 10,000 lbf gas generator cycle NTO/MMH engine with a minimum guaranteed specific impulse of 340 s. Selection of the NTO/MMH engine is based on leveraging potential investments from lunar exploration activities while also limiting additional technology investments, namely, ISRU. Without ISRU, and in order to maintain the 25 metric tons (t) payload limits imposed by the reference landing system, significant portions of the MAV's propellant must be off loaded to other landers and then autonomously transferred to the MAV while on the Martian surface.

Figure 10 shows the first and second stage propulsion system schematics. Propellants are stored in nested tank sets to facilitate a compact configuration and minimize the height of the center of mass for landing stability purposes. The first stage consists of only a main propulsion system, while the seconds stage contains independent main propulsion and reaction control systems. An independent reaction control system was selected to simplify the design and increase system reliability. The reaction control system is composed of sixteen 110 lbf R-4D class thrusters. These thrusters are used to perform rendezvous and docking maneuvers, course correction and orbital maintenance burns, and attitude control during all stages of powered flight.



a. Stage 1 Propulsion Schematic



b. Stage 2 Propulsion Schematic

Figure 10. MAV Propulsion System Schematics

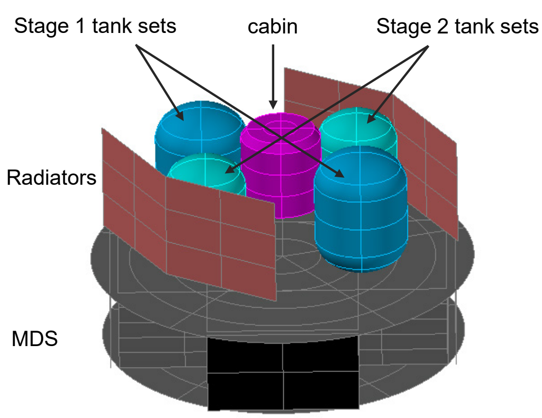


Figure 11. MAV Thermal Model

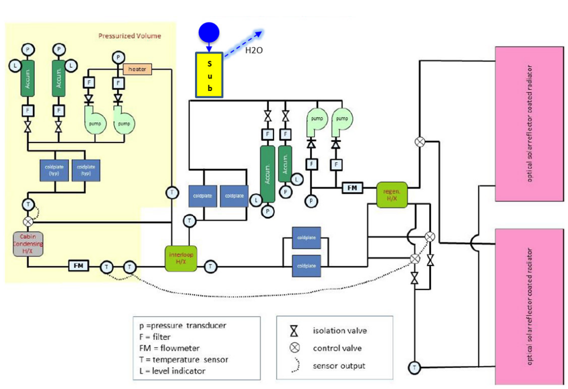


Figure 12. MAV Thermal Control System Schematic

Thermal

With selection of storable propellants for the main propulsion system, the thermal system design has been simplified greatly without the needs for maintaining cryogenic propellants. Instead, heaters and MLI blankets are required to ensure proper temperatures are maintained to prevent degradation of propellant from the cold during transit and on the surface of Mars. A heat rejection system is also sized to radiate waste heat from sources such as avionics and crew cabin heat loads. The thermal model representation of the configuration can be seen in Figure 11.

The thermal control system is a dual-loop, pump-driven system with redundant pumps and accumulators for heat collection and transport. The system uses a fluid loop radiator technology for primary heat rejection, with a sublimator to supplement peak crew cabin heat loads. A schematic of the thermal control system can be found in Figure 12. Tanks and the crew cabin thermal management utilize multi-layer insulation blankets in conjunction with electrical resistive heaters. Components of the thermal control system were designed to accommodate both the worst case cold and hot environments during transit and on the surface of Mars. Peak thermal management power loads are experienced just prior to ascent, when propellants must be conditions to engine operational temperatures, while also maintaining cabin environment with crew inside.

Power

The MAV power system uses oxygen-methane fuel cells to produce the required operational power for the ascent and return to the Transit Habitat. Power during the initial cruise from Earth to Mars, as well as time on the surface prior to crew arrival, are provided by other architecture elements such as the landing system and surface power system. Three parallel solid oxide fuel cells feed two parallel distribution units for system redundancy. Each power distribution units provides a 120-volt and 28-volt supply for various vehicle loads, shown in Figure 13. Previous studies concluded that fuel cells were the preferred power system due to the relatively short operational period, and to limit additional deployable systems. Furthermore, the mass of solar panels and batteries to provide sufficient power for the MAV were found to be heavier than the equivalent fuel cell-based system.

A breakdown of the power subsystem loads during the crewed ascent phase of the mission can be found in Table 3. Fuel cell power plant are sized to accommodate a peak power of 7.8 kW, seen during main propulsion system operation. The MAV requires roughly 2.9 kW of power during crewed non-propulsive operations, such as orbit phasing or coasting. The crewed phase of the MAV's mission requires 185 kiloWatt-hours (kW-hrs) of total energy, which translates to 158 kg of fuel cell reactants. Though the fuel cell reactants share the same elements as the propulsion system, oxygen and methane, they are stored in separate tanks due to the

Table 3. MAV Power Budget

	Duration (Hrs)	Prop Peak (W)	Prop Avg (W)	Avionics (W)	Thermal (W)	Life Support (W)	Total Peak Power+30% (W)	Total Avg Power+30% (W)	Total Energy (Whrs)
First Stage Powered Ascent	0.097	4503	2632	656	155	696	7813	5381	522
Second Stage Powered Ascent	0.077	4503	2632	656	155	696	7813	5381	414
Coast to Apoapsis	0.862	736	368	639	155	696	2894	2415	2082
Periapsis Raise	0.047	736	368	639	155	696	2894	2415	114
Coast/Phasing	9.902	736	368	639	155	696	2894	2415	23917
Apoapsis Raise	0.065	4503	2632	639	155	696	7791	5359	348
Coast to Apoapsis	71.95	736	368	457	139	696	2636	2158	155268
Dock with MTV	1	736	368	576	139	696	2791	2313	2313
								Total Energy	**184978**

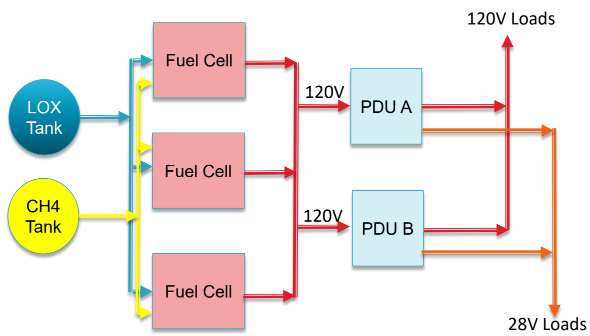


Figure 13. MAV Power System Schematic

higher feed pressures required by the fuel cell stacks, and to reduce vehicle complexity.

Avionics

Avionics include command and data handling, communication, and tracking, as well as guidance, navigation and control. No significant changes to the avionics subsystem design have been made since the last MAV concept, documented in 2019 [7]. The MAV is assumed to be the active vehicle during rendezvous and docking operations with the Transit Habitat. It should be noted that the design of the MAV avionics does not support direct to Earth communication. It is dependent on other orbital assets, such as the Transit Habitat, in-space transportation vehicle, or communications relays, to communicate back to Earth, shown graphically in Figure 14. The purpose for this choice was to minimize avionics system mass and power requirements due to the high mass sensitivity of the MAV.

The avionics subsystem utilizes mostly heritage hardware, such as Orion-derived flight controls for crew interface, as well as the Mustang avionics suite as a baseline. Each redundant primary flight computer is split across two boxes. The MAV requires a minimum 100 kbps link for telemetry and communication. MAV avionics are designed assuming a constellation of low Mars orbit relays, providing low mass, continuous link coverage through the entire crewed ascent to rendezvous with the Deep Space Transport (DST). A direct link to the DST is possible, though would result in increased avionics mass and power requirements and would result in communications blackouts during pre-ascent operations and low Mars orbit phasing. Availability of orbital communication assets will also impact surface mission operations.

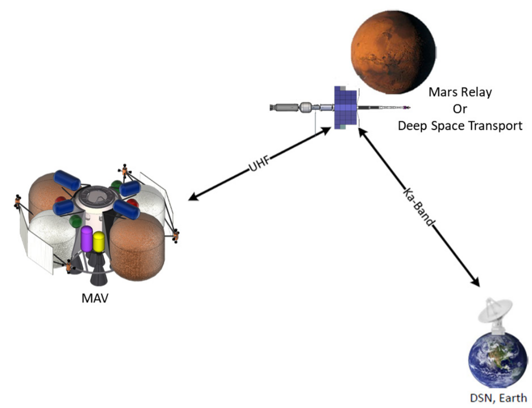


Figure 14. MAV Communication Architecture

Structures

A full structural evaluation of the MAV concept was performed using a series of finite element analysis tools including MSC Patran, MSC Nastran, and HyperSizer. Structural models and design approaches from the previous design concepts were heavily utilized for this updated analysis. Geometries and forces were updated to represent the current configuration presented here, shown in Figure 15. Most primary structures, including the crew cabin, assume metallic aluminum constructions. The exception is the main propulsion system tank supports, which assume a composite carbon fiber construction.

Three load cases were assumed for sizing the structures of the MAV: 1. Earth launch and ascent, 2. Mars first stage ascent, 3. Mars second stage ascent. For Earth launch and ascent, SLS Block 2 flight loads of 4.1g axial and 1.5g lateral were assumed, with a maximum 8 Hz first lateral constrained mode. For Mars ascent cases, loads data was derived from POST ascent trajectory analysis, discussed in the Vehicle Performance section.

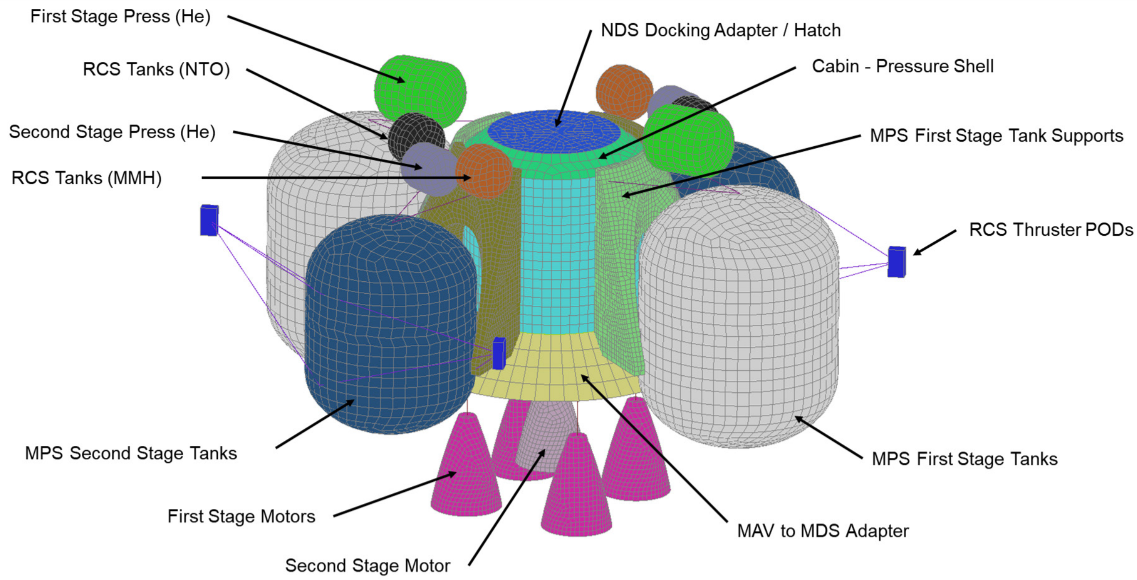


Figure 15. MAV Structural Model

4. VEHICLE PERFORMANCE

This section covers vehicle performance and includes a discussion on trajectory design, design sensitivities, and 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 the Program to Optimize Simulated Trajectories II (POST2), with atmospheric information provided by the Mars Global Reference Atmosphere Model (GRAM). One of the most influential factors in MAV design is the desired aggregation orbit. This decision determines the propulsive capability required as well as flight durations for crew support. It is recognized that a low Mars orbit would be ideal to minimize propulsive and duration requirements on the MAV. However, because the design of a Mars architecture is a system of systems problem, what is optimal for the MAV may not be optimal for the end-to-end architecture. The in-space transportation elements become excessively burdened by the extra propellant required to get into and out of lower altitude Mars orbits which would favor the MAV. A 5-sol orbit capable MAV was ultimately selected as a compromise between the two elements, while not introducing additional propulsive elements, and hence, complexity, to the end-to-end architecture.

Considerations have been given to launch window availability and window duration in previous studies. Shorter flight durations from the surface to rendezvous with the Transit Habitat are possible, but at the expense of additional delta-V, reduced launch window availability, and launch window duration. Figure 16 provides an overview of the trajectory to reach a 5-sol orbit. Figure 17 shows time histories for key parameters during ascent such as mass, thrust, altitude, pitch, and sensed acceleration.

Landing Site and Dust Sensitivities

Several studies involving sensitivities to landing site and atmospheric dust were performed. Previous design iterations assumed a 30-degree North latitude, 0 km MOLA reference landing site. However, parameters associated with the landing site, such as latitude and altitude can have measurable impacts on the required performance of the MAV. Furthermore, atmospheric dust can have significant impacts on atmospheric conditions which result in MAV trajectory variations. Studies into these sensitivities indicate the up to 6% mass variation due to potential mid-latitude landing sites, as well as a 1% mass variation due to atmospheric dust and other atmospheric condition parameters, such as Martian season. Reference [6] provides details of these sensitivity analyses. As a result, a 35-degrees North, -1 km MOLA altitude landing site has been utilized for the reference MAV design to ensure robustness to uncertainty in landing site selection.

Vehicle Mass Summary

The resulting vehicle mass summary is shown in Table 4. The Mars delivery column indicates the MAV mass at delivery to Mars when there is no crew or cargo on board and the NTO propellant has not been transferred. The is the mass that must be delivered by the landing system. The liftoff mass is provided in the Mars ascent column.

5. CONCLUSION

As the largest indivisible cargo item, the MAV described in this analysis was intended to anchor what NASA considers the minimum viable corner of the trade space, which in turn anchors the minimum Mars lander payload capacity.

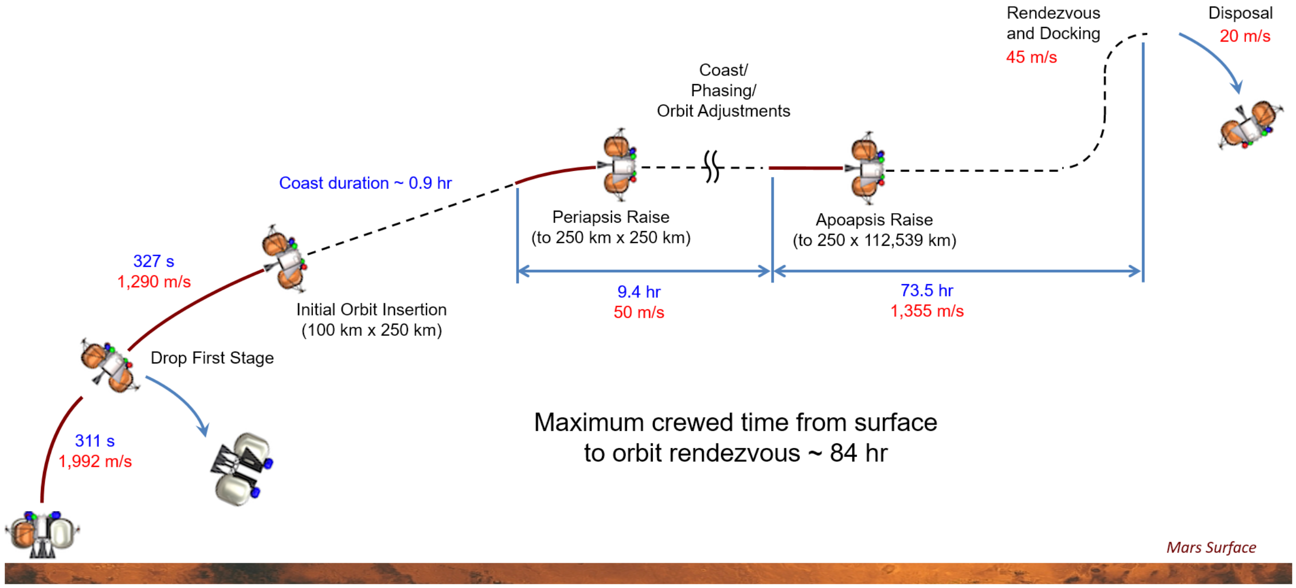
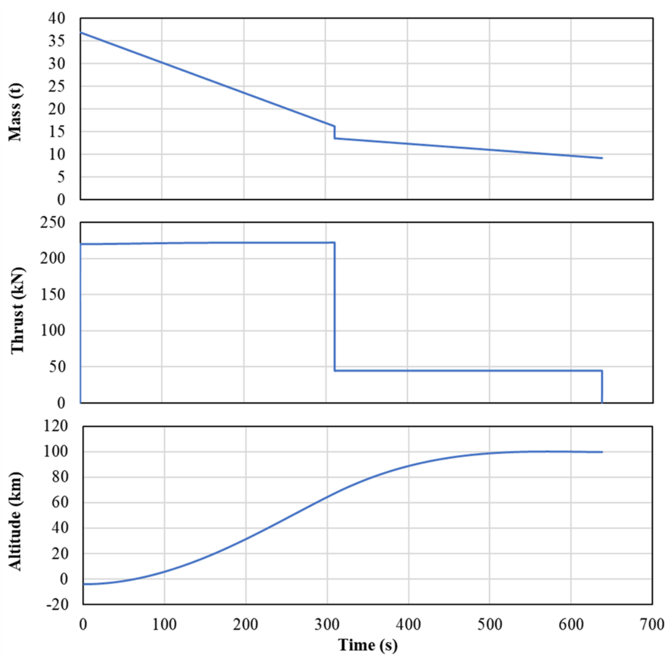
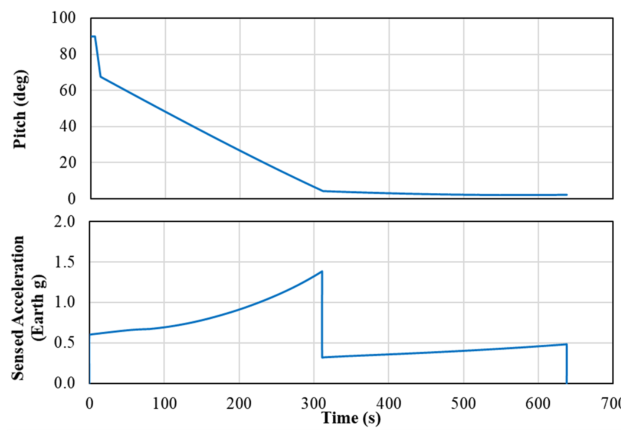


Figure 16. MAV Ascent Trajectory to 5-sol, Overview





Init Mass	=	36,834	kg
Payload Mass	=	3,538	kg
Stg 1 Prop	=	16,499	kg
Stg 1 PMF	=	0.8621	
Stg 1 Burn Time	=	311.0	s
Stg 1 Delta-V	=	1992.46	m/s
Staging Altitude	=	67.80	km
Stg 2 Prop Total	=	12,136	kg
Stg 2 PMF	=	0.8573	
Stg 2 Burn Time	=	326.8	s
Stg 2 Delta-V	=	1290.01	m/s
Stg 2 Prop During Stage 1	=	4124.4	kg
Stg 2 Thrust	=	44.48	kN
	=	9999.95	lbf
Throttle	=	1.00	

Figure 17. MAV Ascent Trajectory to Initial Orbit Insertion, Details

Studies have been performed to either increase overall fidelity of the MAV or investigate specific sensitivities to its design and performance. This work resulted in an updated MAV reference design, aligning with current Agency strategic goals for SAC21, and better leveraging expected developments through the Moon to Mars campaign.

It is important to note that NASA does not have a formal human Mars program and no decisions have been made; the architecture described here is intended to fill in an often-overlooked corner of the trade space, helping to complete the menu of options available to decision-makers as they chart the course for humans to Mars. Efforts to refine the MAV concepts, understand system sensitivities and impacts to Mars architectures, will continue.

Table 4. Mass Summary for SAC21 Reference MAV

Subsystem	Mass (kg)	
	Mars Delivery	Mars Ascent
Ascent Cabin (AC)	**2,798**	**3,212**
Structures	918	918
Power	472	472
Avionics	337	337
Thermal	211	211
ECLSS	473	473
Crew Systems	110	110
Cargo	0	414
Non-Prop. Fluids	277	277
Ascent Stage 1 (AS1)	**12,556**	**18,940**
Dry Mass	1,633	1,633
NTO	5,020	11,404
MMH	5,903	5,903
Ascent Stage 2 (AS2)	**6,065**	**13,999**
Dry Mass	1,273	1,273
NTO	425	8,359
MMH	4,367	4,367
System Intg. Margin	**676**	**676**
TOTALS	**22,095**	**36,827**

ACKNOWLEDGEMENTS

The authors recognize the following team members as key contributor to the MAV design refinements presented here: Mike Baysinger, Jay Garcia, Pete Capizzo, Leo Fabisinski, Quincy Bean, Thomas Brooks, Bill O'Neil, and Michael Interbartolo. Additionally, the Surface Mobility Team, led by Mike Gernhardt, provided key technical details relating to the surface propellant transfer concept, unique to this concept.

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