Human Mars Ascent Vehicle Configuration and Performance Sensitivities

Tara P. Polsgrove
NASA
Marshall Space Flight Center
Huntsville, AL 35812
Tara.Polsgrove@.nasa.gov

Herbert D. Thomas,
Walter Stephens
NASA
Marshall Space Flight Center
Huntsville, AL 35812

Tim Collins
NASA
Langley Research Center
Hampton, VA 23681

Michelle Rucker,
Mike Gernhardt
NASA
Johnson Space Flight Center
Houston, TX

Mathew R. Zwack,
Patrick D. Dees
Jacobs ESSSA Group
Huntsville, AL, 35806

Abstract— **The total ascent vehicle mass drives performance requirements for the Mars descent systems and the Earth to Mars transportation elements. Minimizing Mars Ascent Vehicle (MAV) mass is a priority and minimizing the crew cabin size and mass is one way to do that. Human missions to Mars may utilize several small cabins where crew members could live for days up to a couple of weeks. A common crew cabin design that can perform in each of these applications is desired and could reduce the overall mission cost. However, for the MAV, the crew cabin size and mass can have a large impact on vehicle design and performance. This paper explores the sensitivities to trajectory, propulsion, crew cabin size and the benefits and impacts of using a common crew cabin design for the MAV. Results of these trades will be presented along with mass and performance estimates for the selected design.**

TABLE OF CONTENTS

1. INTRODUCTION

The Mars ascent vehicle design and configuration can have a significant impact on many of the other elements of a human Mars mission architecture. MAV mass determines lander delivery capability, and lander mass with cargo determines performance requirements for in-space transportation stages to deliver these elements to Mars. NASA's Evolvable Mars Campaign (EMC) study explores architecture options for sending humans to Mars in the 2030's [1], and as part of this study several MAV performance and configuration trades were considered.

The MAV's mission is to lift crew and cargo off the surface of Mars and dock with an orbiting Earth return vehicle. Figure 1 shows the current reference configuration of the MAV, which consists of a vertical cylindrical crew cabin and propulsion system with tanks that wrap around the cabin and engines below. Detailed information on this design can be found in reference 2. In the EMC studies, a crew of four is assumed along with 250 kg of cargo and the destination orbit varies. In the three main architectures studied in 2016, the Earth return vehicle loiters in either a 1 Sol or 5 Sol orbit, see Figure 2. Two of the three main architecture options assume oxygen and methane propulsion systems that take advantage of Mars atmosphere for In Situ Resource Utilization (ISRU) oxygen production to supply MAV propellant. A third explores a storable propulsion option for the MAV. Because the storable MAV cannot rely on in-situ propellant production it must be delivered to Mars fully loaded with propellant and would require more than double the lander payload delivery performance of the other options to land a storable MAV capable of ascending to 1 Sol or 5 Sol orbits. To minimize the necessary lander capability, MAV options with storable propellant are designed to ascent to a low Mars orbit of 500km circular with a separate system, an orbital taxi, responsible for carrying crew and cargo from that low Mars

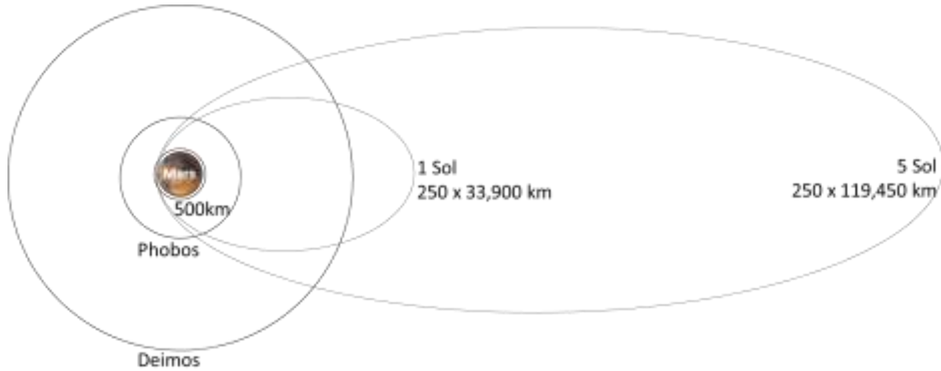

Figure 2. Mars Orbit Options

Table 1. MAV Architecture Options

	Split SEP/Chem	Hybrid SEP/Chem	Hybrid SEP/Chem
Target Orbit	1 Sol	5 Sol	500 km circular
Propulsion	LOX/Methane	LOX/Methane	NTO/MMH
SLS Fairing Diameter	10 m	10 m	8.4 m
Habitable Duration	Ascent only (44 hr)	Ascent only (72 hr)	Ascent only (8 hr +4)
Common Assumptions			
# Crew:	4	Services provided by MDM until Mars liftoff	
Landing Site:	+/- 30 deg	MAV trasmits health/status through orbital relay	
Science Payload:	250 kg	Uncrewed until 2 days prior to Mars liftoff (prep)	
Suit Type:	IVA	Ingress through pressurized tunnel from rover	
Landing Site:	+/- 30 deg	Services provided by MDM until Mars liftoff	
		Ascent is completely auto-piloted	

orbit up to the Earth return vehicle in the higher orbits. Each of these MAV options were evaluated using the vertical crew cabin configuration and are presented in this paper. See Table 1 for a summary of ground rules and assumptions for the three architecture options evaluated.

In addition to those trades assuming a vertical crew cabin configuration, a second configuration was developed and evaluated. Human missions to Mars may utilize several small cabins where crew members could live for days up to a couple of weeks. A common crew cabin design that can perform in each of these applications is desired and could reduce the overall mission cost. Initial vehicle configuration and sizing for a common crew cabin option based on a horizontal cylindrical design has been assessed for one architecture option and is presented in this paper.

2. ASCENT TRAJECTORY DESIGN

The ascent performance of the MAV was modeled using Program to Optimize Space Trajectories (POST). The powered ascent originates from 30° north latitude and ends in the 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 (ERV). Three cases for the ERV parking orbit are considered for this paper: 500 km circular, 1 Sol, and 5 Sol. Each of these cases have a post-powered ascent (i.e. intermediate) orbit of 64 x 200 km for the 500 km case and 100 x 250 km for the 1 Sol and 5 Sol options (see Figure 3). The 500 km MAV is a single-stage-to-orbit vehicle (SSTO) with a storable propulsion system with a specific impulse (Isp) of 335 s, and the 1 Sol and 5 Sol vehicles have two stages (TSTO) and utilize LOX/Methane propulsion systems with an Isp of 360 s. Note that each case requires separate total times from launch to ERV docking. The 500 km MAV requires at least 8 hours of crewed time, whereas the 1 Sol and 5 Sol cases require 44 hours and 72 hours, respectively. These time differences affect the crew cabin designs (discussed in the next section). The maneuver summaries are given in Table 2. Please note that the burn times shown in Figure 3 and the computed delta-Vs (ΔVs) listed in Table 2 are specific to the masses obtained during the most-recent design team iterations (described at the end of the next section). The post-powered ascent maneuvers and times were estimated by Jeff Gutkowski at NASA JSC. Specifics for the 1 Sol case is described in reference [2], and the other cases were taken from charts delivered in previous EMC work.

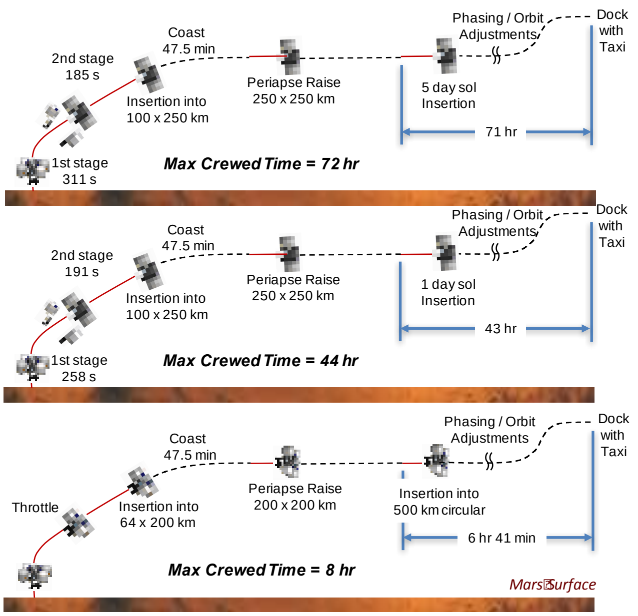

Figure 3. MAV Ascent Trajectory Overview.

Table 2. MAV Maneuver Summary.

Event	Maneuver ΔVs (m/s)		
	500 km	1 Sol	5 Sol
1st Stage Burn	3901	2537	2751
2nd Stage Burn	n/a	1427	1248
Remaining ΔV	275	1449	1622

3. Vertical cabin Design and Performance Sensitivities

In the studied MAV configurations, the MAV sits on top of the lander deck and portions of the propulsion system are imbedded within a central void in the descent module structure (Figure 4). The lander serves as the launch platform for ascent. Configuration choices are driven by the need to minimize the height of the overall lander center of gravity for entry descent and landing and the desire to simplify crew access. Current designs assume crew access via pressurized tunnel from a rover [3]. (Figure 5). In some options the MAV uses oxygen that is collected and liquefied on the Martian surface along with methane brought from Earth as propellant. The MAV (without the oxygen propellant) is pre-deployed years in advance of a crew landing to allow adequate time for liquid oxygen (LOX) propellant production. Oxygen generation and liquefaction on Mars requires significant heat rejection. In those options radiators are deployed soon after landing (Figure 6). Once propellant production is complete and the crew is ready for departure these deployable radiators are no longer needed and can be jettisoned to avoid risk of recontact during ascent.

Figure 4. Configuration after Landing

Figure 5. Crew Access to MAV

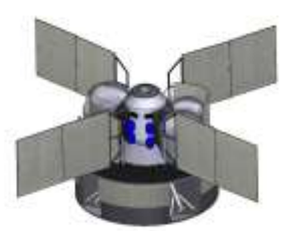

Figure 6. Deployed Radiators for Mars Surface Propellant Production and Conditioning

Vertical Crew Cabin Design

The MAV propulsion system has one function: to lift a crew cabin from the Mars surface to rendezvous with an orbiting habitat for return to Earth. Previous work [4] found that propulsion system sizing is driven by destination orbit and MAV crew cabin size, which in turn depends on how long the crew must remain inside the MAV (and is also a function of destination orbit). For ascent durations less than about 12 hours, the MAV can be considered a “taxi” with few provisions for crew comfort, but for more than 12 consecutive hours, the MAV begins to look like a Habitat with more crew support equipment. The vertical crew cabin configurations were assumed to be purpose-built for the MAV, with little in common to other crew cabins (such as a pressurized rover or habitat module).

Ascent time to orbit was estimated to be only 8 hours for the 500 km circular orbit, so Options 1A and 1B were configured as a short duration taxi, with crew equipment limited to Intravehicular Activity (IVA) space suits, launch restraints, and consumables (oxygen and water). Crew habitable volume for such a short duration can be very limited to a relatively small diameter, compact cabin. For short ascent durations, batteries were found to trade more favorably than fuel cells for power generation.

For the one sol orbit, ascent time was estimated to be as much as 44 hours, including one missed launch opportunity. Because this exceeds the allowable time that crew can remain in their IVA suits, the cabin must be large enough for crew to doff their suits and replace Maximum Absorbency Garments (MAGs), perform daily hygiene tasks, and sleep. Doubling the ascent time increases food, potable water, and oxygen consumables mass, plus hygiene supplies and fuel cell consumables. These additional crew tasks and consumables stowage require a larger habitable volume than in the 500 km circular orbit case.

Ascent time to a five sol orbit was estimated at between three and ten days, depending on launch availability constraints. The longer ascent duration obviously increases crew and fuel cell consumables. For example, a potable water allocation of 2.2 liters per crew per day over a ten day period requires almost 90 kg of potable water, plus containers to store it in. Beyond about two days, crew waste disposal and odor becomes an issue, making the mass penalty for a waste/hygiene compartment trade more favorably than stowing soiled MAGs inside the cabin.

Note that in all three cases, a requirement for 250 kg return cargo (return samples plus storage containers) was included in cabin mass estimates. Table 3 summarizes crew cabin mass by subsystem for the various options. Also, the 5 sol cabin structural mass was scaled from an older 1 Sol MAV value and should be updated.

For the EMC reference architectures to date, a vertical cylindrical crew cabin has been assumed, 2.7 meters in diameter and 3.8 meters tall. This concept draws from the design and mock up evaluations performed as part of the cancelled Constellation Program’s Altair lunar lander. In the worst-case scenario, a surface infrastructure anomaly (such as a habitat failure) could prompt the crew to depart shortly after landing, before they’ve had time to physically recover from more than six months of microgravity during Earth-Mars transit. Although ascent acceleration is not extreme—less than two Earth g’s--it would be difficult for a deconditioned crew to tolerate, and would require recumbent seats for crew safety (Figure 7, center). Aside from adding more mass to the cabin, recumbent seats also require more cabin volume than a standing-crew configuration would require. To assess sensitivities, one of the cabin configurations assumed no recumbent seats, allowing for reduced dimensions of 2 m diameter by 2.5 m tall (Figure 8).

Table 3. MAV Crew Cabin Options

		MAV Cabin Mass (kg)		
Subsystem		**MAV 1A-1B (500 km Circular)**	**MAV 2A-2B (1 Sol)**	**MAV 3A-3B (5 Sol)**
1.0	Structures	1,240	1,267	1,252*
2.0	Power	256	377	377
3.0	Avionics	241	241	241
4.0	Thermal	554	542	542
5.0	Environmental Control and Life Support	416	387	502
6.0	Crew and Cargo (at Liftoff)	1,049	1,106	1,117
7.0	Non-Propellant Fluids	163	258	295
	MAV Payload Total Mass	**3,919**	**4,178**	**4,326**

* Scaled from old 1 Sol structural mass (needs updating)

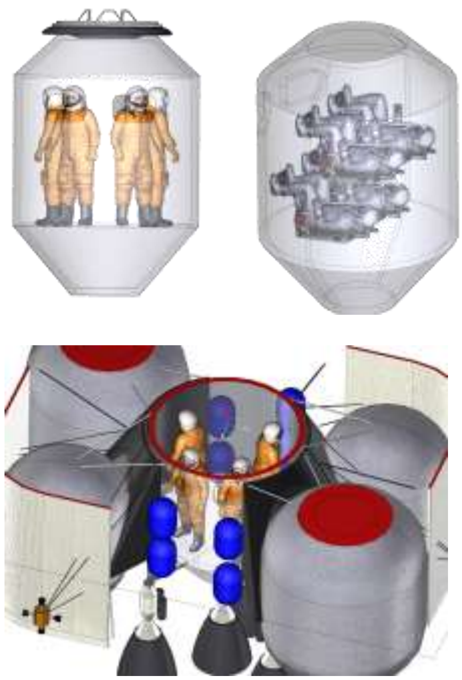

Figure 7. Mars Ascent Vehicle Interior Configuration

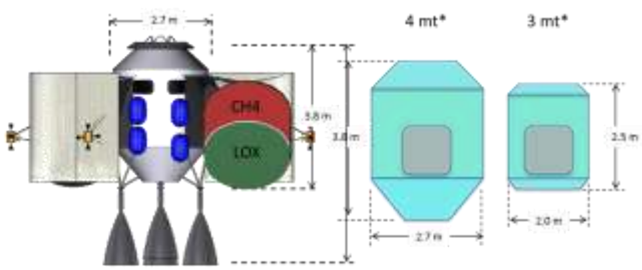

Figure 8. Mars Ascent Vehicle Vertical Cabin Sizes

Propulsion System Design

Mass growth in the MAV results in larger landers to deliver the MAV and a greater burden on in-space transportation stages to deliver the MAV and lander to Mars. For this reason, minimizing MAV mass is of critical importance. One of the most significant ways to reduce the MAV delivered mass is to generate propellant at Mars. Generating oxygen from the Martian atmosphere is the first step and can reduce MAV delivered mass by 25-30 mt. The small production system would reside on the Mars descent module and transfer oxygen to the MAV tanks. A LOX/liquid methane (LCH4) propulsion system was selected for this vehicle for several reasons. This combination has a high mixture ratio, maximizing the benefit of LOX generation and minimizing the amount of fuel that must be carried from Earth. These propellants have similar storage conditions, and are considered space storable during transit in deep space, much easier to maintain than liquid hydrogen. Eventually, in-situ production of methane propellant may be possible, but it is not assumed for the first human mission.

The MAV is designed with a two-stage to orbit propulsion system. The first stage of the MAV uses three 100 kilo-Newton (kN) LOX/LCH4 pump-fed rocket engines with a specific impulse of 360 sec to propel the vehicle for the first phase of ascent lasting 3-4 minutes. The 1st stage separates and is discarded while the 2nd stage continues (after a periapsis raise) to a circular phasing orbit. The second stage has a single identical engine and continues ascent to the 1 Sol or 5 Sol elliptical orbit and rendezvous with Earth return vehicle.

Storable propulsion solutions exist that allow investments in ISRU and CFM technology to be delayed to later missions. Because all ascent propellant has to be launched from Earth, minimizing propellant mass is critical. Lower target orbits and smaller cabins may allow MAV solutions that are close to point of departure lander payload delivery requirements.

Performance Sensitivities

There are three main architecture options studied by EMC in 2016 and a reference MAV design and trajectory for each option. Several variations of MAV assumptions were studied. Single stage to orbit (SSTO) vs two stage to orbit (TSTO), the number of engines on the first stage, launch site latitude, and others. Combinations of different vehicle options were analyzed in this study: Single-Stage-To-Orbit (STSO) and Two-Stage-To-Orbit (TSTO) propulsion systems; cryogenic Liquid Oxygen (LOX)-Liquid Methane (LCH_4) and storable nitrogen tetroxide (NTO)-monomethyl hydrazine (MMH) propellants; and ascent to three different Mars orbits. See Table 4 for cases analyzed and assumptions.

The SSTO POST2 deck was set up to fly to an initial orbit of 64 by 200 km. The deck required an excess delta-v of 275 m/s for reaching a final orbit of 500 km and to include attitude and control during the entire trajectory. Ascent to the initial orbit was achieved using active pitch control, which consisted of a total of seven pitch events. At each of these pitch events, POST2 optimized on the pitch rate. Additional independent variables for optimization included launch azimuth, initial stage propellant mass, along with the time and throttle level for a floating throttle event during ascent. An initial pitch event was assumed to occur at 5 seconds after liftoff. The throttle level of the floating event was held constant throughout the remainder of the trajectory. The minimum throttle level was assumed to be 20%.

The TSTO POST deck was set up to fly to an initial orbit of 100 by 250 km. This deck also required an excess delta-v, which was needed to reach a final orbit. For the TSTO vehicles, two final orbits were implemented: a 1 sol orbit requiring an excess delta-v of 1.449 km/s and a 5 sol orbit requiring an excess delta-v of 1.622 km/s. Similar to the single-stage deck, the TSTO input deck utilized active pitch control to ascend to the initial orbit. The independent variables for optimization of the TSTO vehicle included eight pitch rates, launch azimuth, initial stage propellant masses, and throttle level for the second stage. The first pitch event was again assumed to occur at 5 seconds and two other pitch

Table 4. MAV Vehicle Trades and Assumptions. ***Vehicle options and mass assumptions that are used in the mass sensitivities to thrust and launch latitude.***

	Stages to Orbit	Orbit	Payload	Propellant	Isp	Stage PMF	
						1st Stage	2nd Stage
Option 1	SSTO	500 km Circular	3,919 kg	NTO/MMH	335 s	0.86	--
Option 2A	TSTO, 2 Engine 1st Stage	1 sol	4,178 kg	LOX/LCH_4	360 s	0.83	0.73
Option 2B	TSTO, 3 Engine 1st Stage	1 sol	4,178 kg	LOX/LCH_4	360 s	0.83	0.73
Option 3A	TSTO, 2 Engine 1st Stage	5 sol	4,326 kg	LOX/LCH_4	360 s	0.83	0.73
Option 3B	TSTO, 3 Engine 1st Stage	5 sol	4,326 kg	LOX/LCH_4	360 s	0.83	0.73

events were moved to occur during the first stage burn. The second stage's throttle event occurred at second stage ignition, and the minimum throttle level for the TSTO deck was also constrained to be 20%. For all TSTO cases, the second stage was assumed to have only one engine.

Both SSTO and TSTO input decks utilized the same vehicle input parameters. These parameters consisted of stage propellant mass fractions (PMFs), engine specific impulse, thrust per engine, number of engines, liftoff latitude, and payload mass. Given these input parameters, POST optimized the liftoff mass by adjusting the initial propellant loading of the stage(s) along with the other independent variables discussed previously. Each POST deck was run manually for a variety of vehicle inputs in order to capture the trades of interest. During case execution, POST was allowed 500 iterations and a vehicle was considered closed when the change in the optimized variable (liftoff mass) was less than 1 kg.

POST was run to determine the MAV mass sensitivities to thrust and launch latitude. The vehicles analyzed include SSTO MAV to 500 km circular, TSTO MAV to 1 Sol, and TSTO MAV to 5 Sol. LOX/LCH_4 propulsion systems with an Isp of 360 s are assumed for the 1 Sol and 5 Sol vehicles. The SSTO MAV (to 500 km) utilizes a storable bipropellant system with an NTO/MMH propellant combination and an Isp of 335 s. Only the single-stage vehicles are assumed for the low Mars orbit delivery. Earlier investigations showed very little mass benefit for the added complexity of another stage. The TSTO MAVs trades are separated into 3 engine (baseline) and 2 engine first stage configurations, and the second stages constrained to use a single engine that is identical to those flown on the first stages. The cabin masses and the stage PMFs (listed above) are the result of MAV concept study team efforts during 2016. Also note that all thrust trades assume a due east launches from 30 deg latitude.

SSTO MAV to 500 km circular

Figure 9 shows the mass sensitivity of the bipropellant SSTO MAV to liftoff thrust. For a three engine case, the optimal thrust-per-engine is 120 kN, at which the liftoff mass of approximately 24 t. All thrust trades assume launches due east from 30 deg north latitude. Figure 10 shows the sensitivity to launch latitude for a thrust of 100 kN per engine, which is the current baseline. Launching from 30 deg results in a penalty of only 562 kg respect to the equator case, a change of only 2.4%. The mass change increases more rapidly for the high latitude cases. Launching from 60 deg results in a 10% larger mass than the 0 deg case and a 7.4% change from the baseline 30 deg case.

TSTO MAVs to 1 sol and 5 sol

For the TSTO vehicles, the cabin mass increases to 4178 kg for the 1 sol case. This is due to the longer crewed time of 44 hours, compared to 8 hours for the ascent to 500 km circular. This along with the higher orbital energy results in larger MAV masses. Figure 11 shows the thrust trade for delivery to 1 sol using 3 engines on the first stage. The optimal thrust is 120 kN per engine for a liftoff mass of 39.2 t. The sensitivity for launching at various latitudes is shown in Figure 12. The 2 engine configuration masses are shown in Figures 13 and 14. The masses are slightly higher than the 3 engine values, which may be due to the larger second stage engine thrust and the 20% minimum throttle limit. The optimal engine thrust level for this case is 170 kN. This is a very large engine; dropping to a more reasonable 125 kN engines results in a total mass increase of 2.6 t.

Launching to a 5 sol orbit results in a further increase in mass but not as drastic as the change between the low Mars orbit and 1 sol cases. The cabin mass for this MAV is 4326 kg. Figures 15 through 18 show the trade results for the 3 engine and 2 engine options. The 3 engine, 5 sol optimal thrust is 140 kN with a liftoff mass of 45.5 t, while the optimal thrust and mass values for the 2 engine MAV are 170 kN/engine and 46.04 t, respectively.

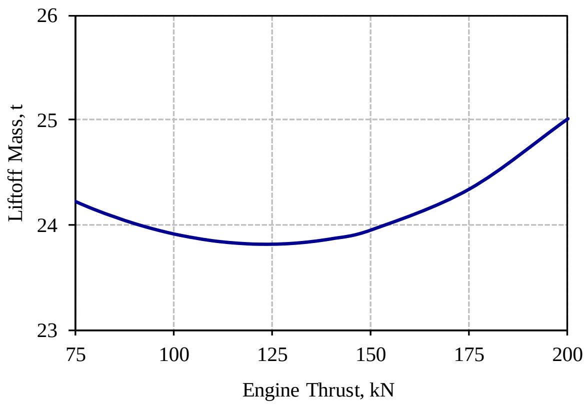

Figure 9. SSTO NTO/MMH MAV liftoff mass vs. per-engine thrust for 3 engine case to 500 km circular. *Launch due east from 30 deg latitude, Isp = 335 s, stage PMF = 0.86, and payload mass = 3919 kg. target orbit = 500 km circular.*

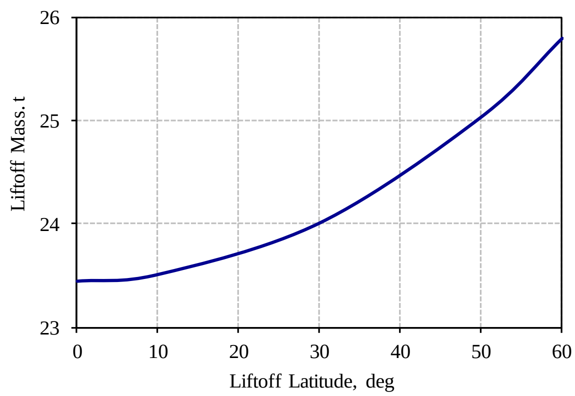

Figure 10. SSTO NTO/MMH MAV liftoff mass vs. launch latitude to 500 km circular. *Launch due east, total thrust = 300 kN, Isp = 335 s, stage PMF = 0.86, and payload mass = 3919 kg, target orbit = 500 km circular.*

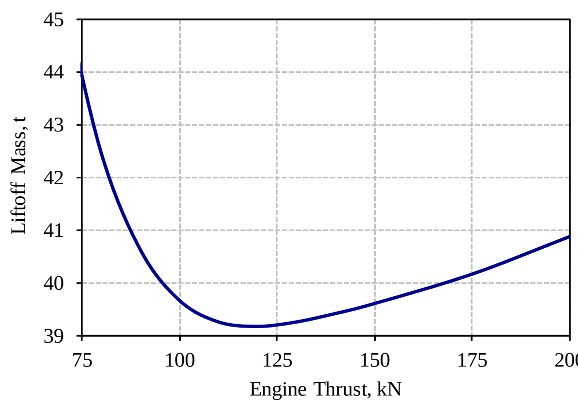

Figure 11. TSTO LOX/LCH_4 MAV liftoff mass vs. per-engine thrust for 3 engine case to 1 sol. *Launch due east from 30 deg latitude, Isp = 360 s, 1st stage PMF = 0.83 2nd stage PMF = 0.73, and payload mass = 4178 kg. target orbit = 1 sol.*

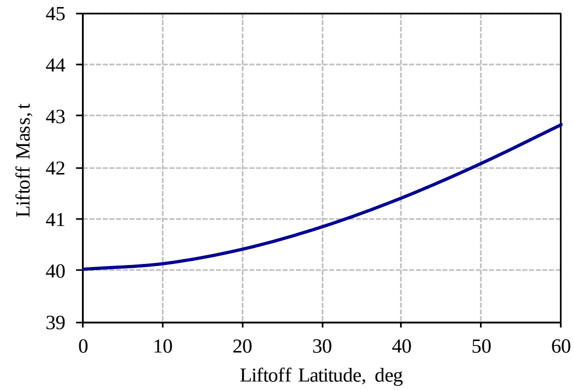

Figure 12. TSTO LOX/LCH_4 MAV liftoff mass vs. launch latitude for 3 engine case to 1 sol. *Launch due east, thrust = 100 kN/engine, Isp = 360 s, 1st stage PMF = 0.83 2nd stage PMF = 0.73, and payload mass = 4178 kg. target orbit = 1 sol.*

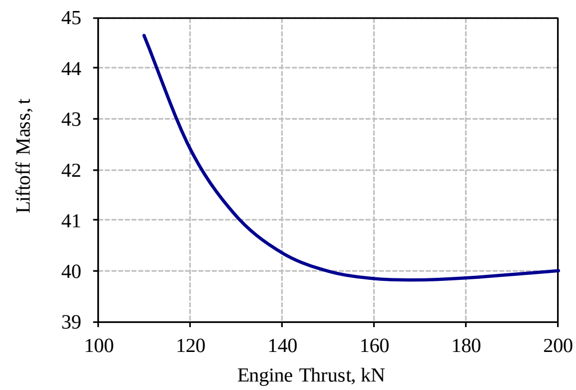

Figure 13. TSTO LOX/LCH_4 MAV liftoff mass vs. per-engine thrust for 2 engine case to 1 sol. *Launch due east from 30 deg latitude, Isp = 360 s, 1st stage PMF = 0.83 2nd stage PMF = 0.73, and payload mass = 4178 kg. target orbit = 1 sol.*

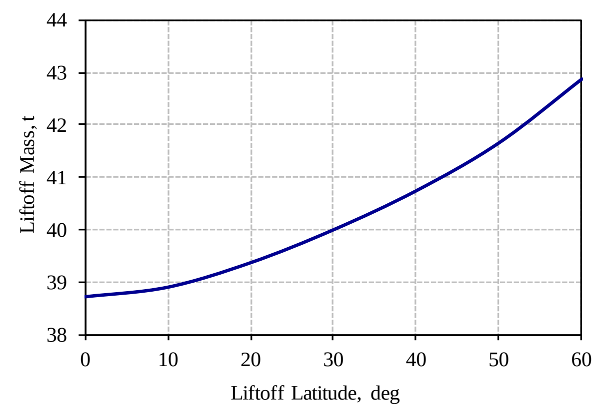

Figure 14. TSTO LOX/LCH_4 MAV liftoff mass vs. launch latitude for 2 engine case to 1 sol. *Launch due east, thrust = 150 kN/engine, Isp = 360 s, 1st stage PMF = 0.83 2nd stage PMF = 0.73, and payload mass = 4178 kg. target orbit = 1 sol.*

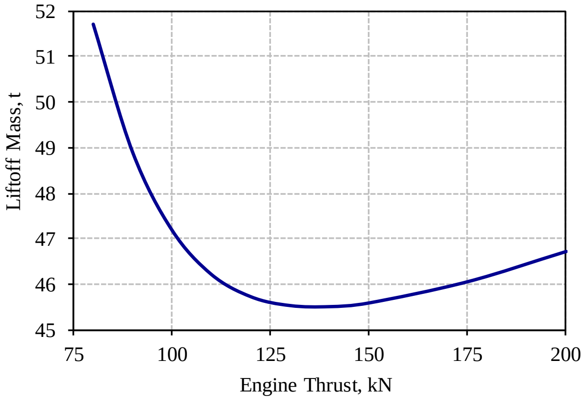

Figure 15. TSTO LOX/LCH$_4$ MAV liftoff mass vs. per-engine thrust for 3 engine case to 5 sol. *Launch due east from 30 deg latitude, Isp = 360 s, 1st stage PMF = 0.83 2nd stage PMF = 0.73, and payload mass = 4326 kg. target orbit = 5 sol.*

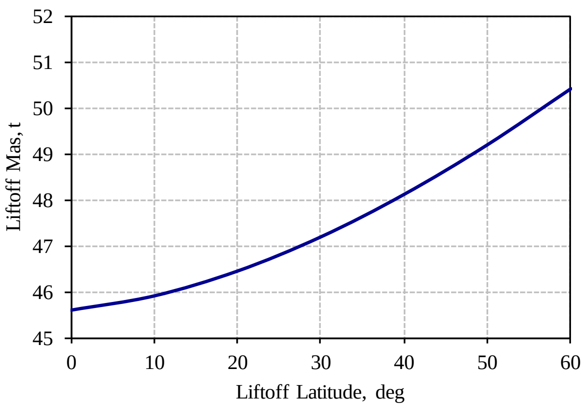

Figure 16. TSTO LOX/LCH$_4$ MAV liftoff mass vs. launch latitude for 3 engine case to 5 sol. *Launch due east, thrust = 100 kN/engine, Isp = 360 s, 1st stage PMF = 0.83 2nd stage PMF = 0.73, and payload mass = 4326 kg. target orbit = 5 sol.*

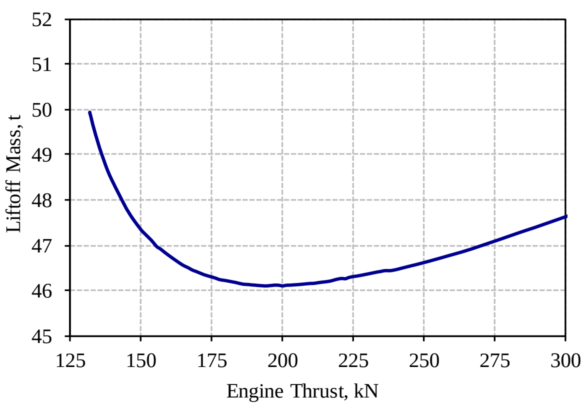

Figure 17. TSTO LOX/LCH$_4$ MAV liftoff mass vs. per-engine thrust for 2 engine case to 5 sol. *Launch due east from 30 deg latitude, Isp = 360 s, 1st stage PMF = 0.83 2nd stage PMF = 0.73, and payload mass = 4326 kg. target orbit = 5 sol.*

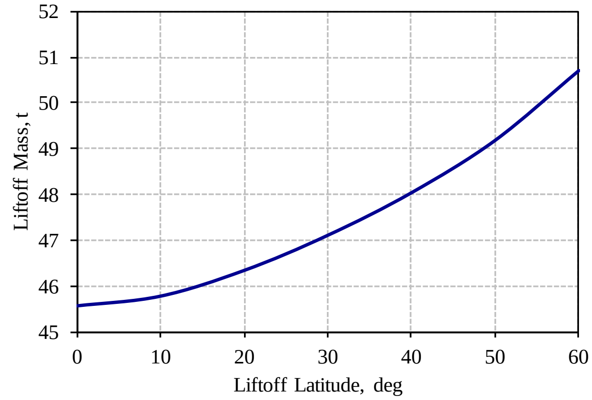

Figure 18. SSTO LOX/LCH$_4$ MAV liftoff mass vs. launch latitude for 2 engine case to 5 sol. *Launch due east, thrust = 150 kN/engine, Isp = 360 s, , 1st stage PMF = 0.83 2nd stage PMF = 0.73, and payload mass = 4326 kg. target orbit = 5 sol.*

Baseline Design-team MAV Results

The final MAV designs (and masses) for the 500 km, 1 Sol, and 5 Sol cases are a result of several iterations of the project design team. The resulting configurations are shown in Figures 19 and 20 for the LOX/Methane 1 Sol and NTO/MMH 500 km MAV vehicles, respectively. Note that the 5 Sol MAV is very similar to the 1 Sol option with slightly larger tanks. The mass results are summarized in Table 5.

Liftoff configuration *2nd stage configuration*

Figure 19. Lox Methane Mars Ascent Vehicle to 1 Sol orbit (Vertical)

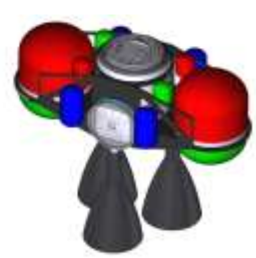

Figure 20. Storable Propulsion Mars Ascent Vehicle to 500 km Circular (Vertical)

Table 5: Mars Ascent Vehicle Characteristics

	SEP-Chem Split	SEP-Chem Hybrid	SEP-Chem Hybrid Storable
Target Orbit	1 Sol	5 Sol	LMO
Habitable Duration (hrs)	44	72	8
Number of Crew	4	4	4
Ascent Cargo (kg)	250	250	250
MAV mass delivered to Mars Surface (mt)	17.2	19.0	23.7
MAV cabin mass (mt)	4.2	4.3	3.9
Oxygen (mt)	25.0	29.2	NTO: 12.2
Methane (mt)	7.9	9.2	MMH: 6.2
MAV Liftoff Mass (mt)	42.9	48.9	24.4
MAV Thrust (kN)	300 / 100	300 / 100	300
Minimum Throttle	20%	20%	20%

4. HORIZONTAL CABIN DESIGN

Human missions to Mars may utilize several small cabins (Figure 21) where crew members could live for days up to a couple of weeks. At the end of a Mars surface mission the Mars Ascent Vehicle (MAV) crew cabin would carry the crew to their destination in orbit in a matter of hours or days. Other small cabins in support of a Mars mission would include pressurized rovers that allow crew members to travel great distances from their primary habitat on Mars while unconstrained by time limits of typical EVAs. An orbital crew taxi could allow for exploration of the moons of Mars with minimum impact to the primary Earth-Mars transportation systems. A common crew cabin design that can perform in each of these applications is desired and could reduce the overall mission cost.

Horizontal Cabin Background

Horizontal variants of the MAV crew cabin (Figure 22) were developed [5] to examine two considerations, 1) the impact and feasibility of imposing crew-cabin commonality on the MAV design, and 2) the general impact of a horizontal pressure vessel (cabin structure) orientation as compared to the Point of Departure (POD) vertical configuration. The 1st consideration is motivated by a desire to utilize existing cabin geometries currently under consideration for rover (and possibly in-space habitat) applications. Existing rover cabins are oriented with crew and equipment in a horizontal configuration suitable for Mars surface operations. Mockup evaluations of the rover cabin have indicated that (from an operations point of view) the cabin configuration is suitable for MAV operations as well. This “dual usage” might result in significant cost and risk reductions [5].

The second consideration is motivated by the fact that there might be independent reasons for considering a horizontal MAV cabin (even if the cabin were not derived from a rover geometry). Possible benefits include: a lower center of gravity, more efficient packaging on the lander deck, and improved ingress/egress for crew via an envisioned tunnel system that connects the MAV to a surface-based rover. To assess the feasibility of the horizontal configuration, structural modeling and analyses of horizontal MAV configurations was performed to assess the first-order structural mass and layout implications of a horizontal MAV concept. For this initial assessment, functional requirements such as those required for Environmental Control and Life Support System (ECLSS), power, avionics, and other systems were not considered. The initial results (by focusing on the implications to layout and structure) are intended to inform feasibility and provide a basis for more in-depth analyses going forward.

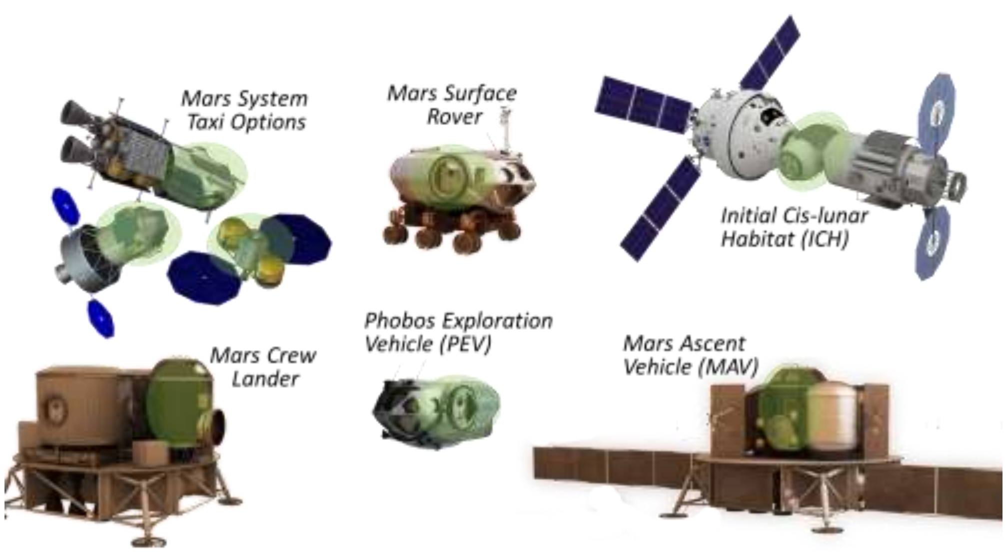

Figure 21. Notional Human Mars Mission Architecture Elements

Figure 22: Horizontal (rover-based) pressure vessel, potentially suitable for MAV operations.

Configuration Brainstorming and Selection

To examine the implications of a horizontal MAV configuration, a clean sheet approach was taken. That is to say that the configurations considered were developed "bottoms up" with the arrangement of propellant tanks, engines, cabin, and supporting structure as part of the open design space (e.g. not predetermined based on any previous work). During initial brainstorming, only approximate layouts and their implications were considered, without consideration of subsystem details. A wide range of layouts were considered and Initial brainstorming resulted in 14 total concepts, including one single-stage-to-orbit (SSTO) configuration, as shown in Figure 23.

The 14 initial configurations were discussed extensively by the project team, including leads representing the major subsystems. Based on a discussion of the various pros and cons for each configuration, six were configurations were selected for detailed discussion and analysis. The six configurations are underlined in Figure 23. These selections were based primarily on considerations related to simplicity or comparison to other (more favorable) configurations in the suite of concepts. It should be noted that the team unanimously agreed that no single configuration is without drawbacks. Absent a detailed analysis of each concept, the selection process inherently relied on a substantial degree of discussion and engineering judgment. This was satisfactory however, because the goal of this work (given limited time and resources) was to examine feasibility for a reasonable concept (and not to develop a final or optimized configuration). The six concepts culled from the initial brainstorming session (14 concepts) were further examined (qualitatively) with the goal of selecting one concept for detailed modeling and analysis, including structural mass estimates. To this end, the concepts were considered in relation to six informally defined figures of merit (FOMs). The FOMs were defined by considering structures, propulsion, center of gravity height, deck space, crew access, and general design flexibility. The six FOMs and their various qualitative considerations are listed in Table 6.

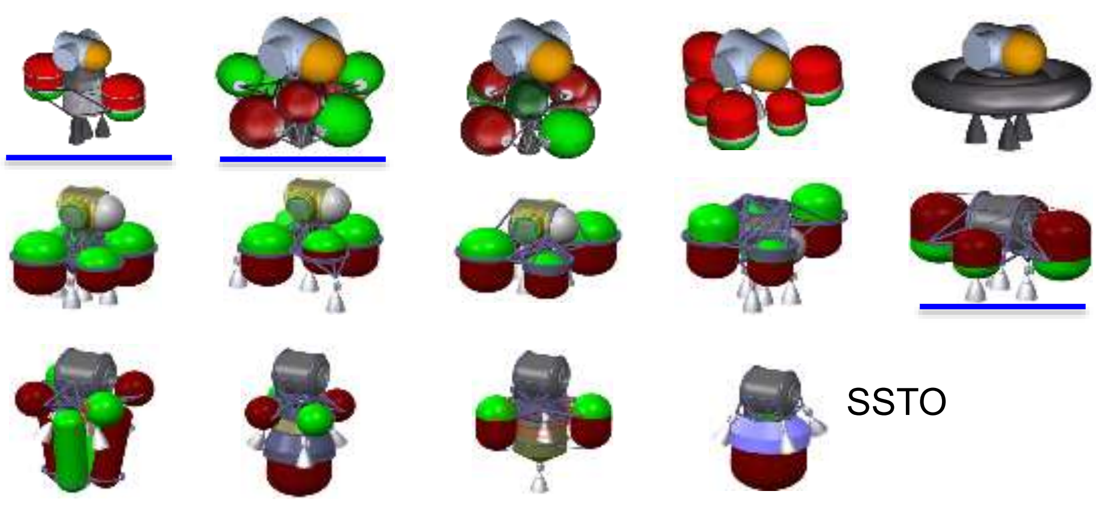

Figure 23: Horizontal MAV concepts resulting from initial brainstorming.

Table 6. Informal FOM s used to select concept for detailed modeling and analysis.

FOM	Associated Considerations
1-Structural System	mass, load path, simplicity, HMAV support structure
2-Propulsion System	mass, tank geometry and complexity, number of tanks
3-Center of Gravity	c.g. height at launch and during entry, descent, and landing
4-Deck Space	space for non MAV cargo, radiators, solar arrays, other subsystems
5-Access	crew access, accommodation of ingress/egress tunnel
6-Design Flexibility	sensitivity to future changes in requirements, ability to evolve

The concepts were ranked using the pair-wise comparison techniques of the Analytical Hierarchy Process (AHP). This process allows for pair-wise comparisons of both the FOMs (to determine their relative importance), and the concepts (to determine their relative performance with regard to each FOM). For the pair-wise comparisons only two concepts (or FOMs) are considered at a time. Although imperfect (like all weighting and ranking systems), the AHP provides an extra degree of impartiality and traceability generally not available with more informal methods. Additionally, the AHP mathematical formulation provides a consistency check that helps identify inconsistent reasoning during the evaluation process. The relative rankings the five (non-SSTO) options are shown in Figure 24. Although the SSTO option ranked very favorably (considering only these FOMs), to allow comparison with previous (vertical and two-stage) MAV concepts, the SSTO option was removed from consideration for the present modeling and analysis. It remains a strong contender for future study depending on the general feasibility of a single-stage to orbit MAV architecture. The relative rankings are based in equally weighted (equally important) FOMs. Sensitivity to the assumptions was examined, but showed only small variations in the ranking results. The configuration ranking highest (center of Figure 24) was selected for detailed modeling and analysis.

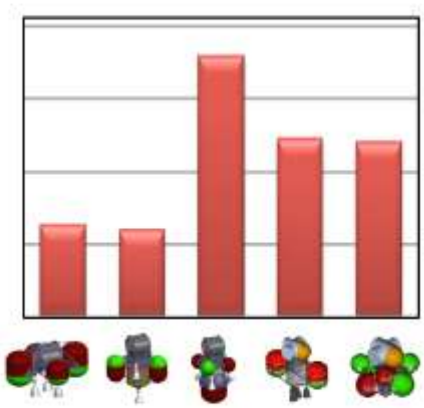

Figure 24. Relative Concept Rankings (all FOMs treated as equally important).

Integration with Lander

After down selection, additional support and interface structure was formulated for construction of CAD and finite-element (analysis) models. The selected configuration is shown with these details (and a notional lander) in Figure 25. The first stage consists of a single nested tank embedded into a central opening in the Mars Descent Module (this opening can be used for cargo on non-MAV missions). The “nested tank” consists of in-line LOX and Methane tanks sharing a common outer shell but each having separate internal bulkheads. The 2nd stage has four smaller and separate tanks. The two stages separate at a single ring frame. The support structure for this configuration efficient, and the configuration allows for unobstructed access to the cabin. A short adapter is used for connection of the MAV stack to the descent module structure. Disadvantages of the configuration include a relatively high c.g. and canted ascent stage engines that are less efficient and may create issues related to exhaust impingement on the lander deck. Figure 26 shows the Horizontal MAV with a horizontal cylindrical cabin. In total, three Horizontal MAV variations were considered, as described below.

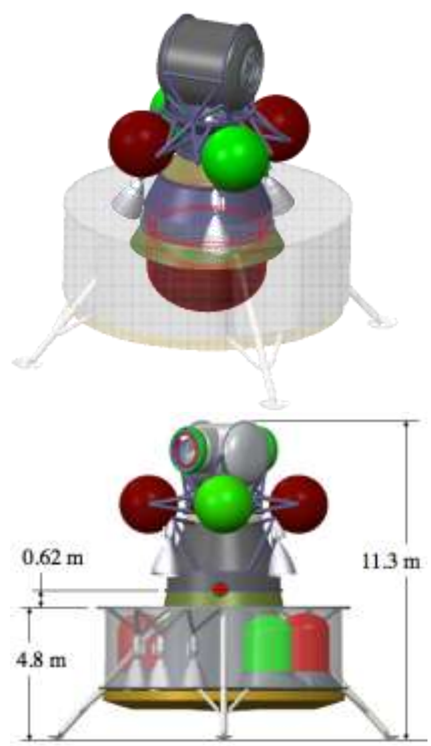

Figure 25. HMAV configuration shown with Mars Descent Module (Lander)

Configuration Variations

In order to compare the effects of introducing the common-cabin geometry and of using a nominal horizontal cabin, three variations of the selected configuration were considered, as shown in Figure 26.

The configuration on the left used the common-cabin derived from current rover-vehicle cabin geometry and described previously. To be consistent with current rover design, the analysis of this configuration utilized an Aluminum cabin. The second (from left) configuration is very similar to the common-cabin variant, but utilizes a more geometrically optimal horizontal cylinder. For the third configuration the horizontal cabin has been rotated to a vertical orientation. These configurations utilize composite-sandwich construction, consistent with past ascent-vehicle analyses. Generation of the three configurations allows for separate comparisons of the impacts due to incorporating the common-cabin and/or the horizontal orientation. For reference, all three configurations were compared to the point of departure (POD) MAV (right side of figure) analyzed during a previous design cycle.

Analysis and Comparisons

Mass results obtained by analyzing the three configuration variants (Figure 26) are summarized in Table 7 along with results for the previously analyzed POD MAV. The table includes results for the primary structure of the cabins, and 1st and 2nd stage supporting structure. The MAV adapter mass is also listed. All masses shown have units of kg, and were obtained by analyzing the configurations with consideration of strength and buckling based structural failures. The driving load case for the analyses was assumed to be launch (5g axial and 2g lateral loads).

The mass of the common-cabin geometry is 38% (248 kg) greater than that of the vertical cabin. All of this mass difference is due to the cabin structure, as the first and second stage structural masses are nearly identical (even though distributed differently). The common-cabin mass increase is due to its metallic structure, non-optimal pressure-shell geometry, and the less efficient horizontal configuration. The vertical cylindrical cabin shifts some structural support mass from the second-stage to the first-stage. This is advantageous due to the so-called "gear ratio" effect, which considers the overall performance benefit of moving mass to a component

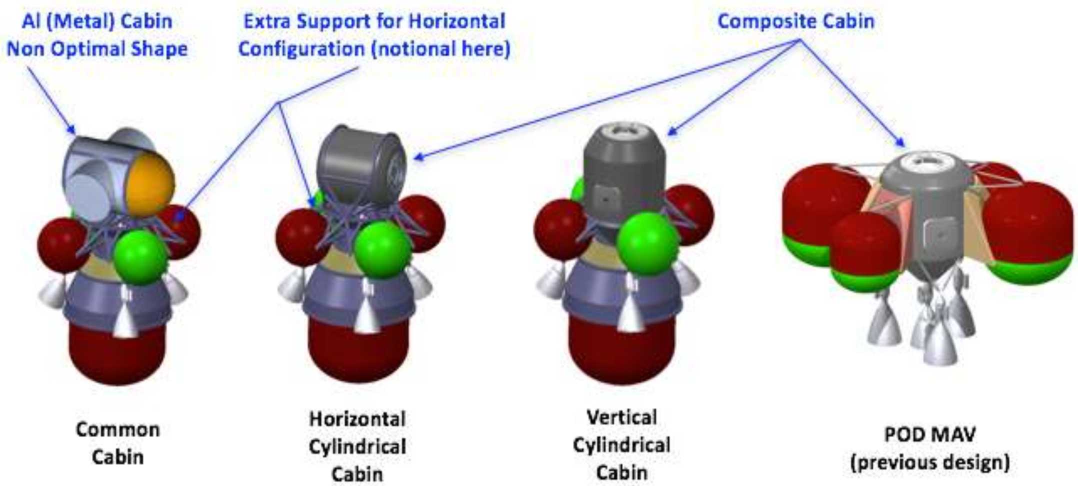

Figure 26. Three variations considered for comparison with each other and to previous POD MAV.

Table 7. Mass (kg) Results Summary for HMAV and previous POD MAV Configurations

Structure	Common Cabin (Horizontal)	Cylindrical Cabin (Horizontal)	Cylindrical Cabin (Vertical)	Previous POD MAV
Cabin	896	*Results fall between the Common Cabin and Verical Cabin Cases (not analyzed)*	648	760
1st Stage	304		366	232
2nd Stage	313		251	127
Total (Primary)	1,513	~1,390 (estimate)	1,265	1,119
MAV Adapter	85	85	85	174

that is discarded early in the flight profile (such as the first-stage structure during MAV ascent). The horizontal cylindrical cabin was not specifically analyzed because it is reasonable to anticipate that the mass will fall between the common cabin and vertical cylindrical cabin results (which essentially are bounding cases). The total primary structure mass for this case is estimated to be approximately 1,390 kg. All of the configurations have mass greater than the previously analyzed (POD) MAV, but at the same time have a more favorable layout with more deck space available for access or packaging of other cargo. The increased cabin height will require additional pressurized tunnel and ladder structures to enable crew access over the previous POD MAV design and that impact has not yet been assessed. The MAV adapter mass is approximately 50% less for the new configurations (primarily due to a reduction in adapter height).

5. SUMMARY

It is clear that MAV design and mass is very dependent upon the target orbit and resulting flight duration, propulsion system choices and operational assumptions for crew access. Performance sensitivity trades were completed for the vertical MAV options and similar assessments can be performed on the new configurations identified utilizing a horizontal common crew cabin approach. Vertical MAV performance sensitivities show that optimal engine thrust level may be higher than the 100 kN (22.5 klbf) assumed in the vehicle design studies. Also the degree to which landing site latitude affects MAV performance is shown.

The vertical MAV liftoff masses for 500 km, 1 Sol, and 5 Sol target orbits are shown in Figure 27. As expected, the low Mars orbit MAV represents the lowest mass at 24.4 t. The 1 Sol MAV is 76% larger at 42.9 t, and the difference between the 1 Sol and 5 Sol vehicles is much smaller (14%) with the 5 Sol MAV mass of 48.0 t. The lower propellant load of the 500 km MAV, with a NTO/MMH propellant combination, can be deceiving. An important aspect of the 1 Sol and 5 Sol MAVs is usage of ISRU for LOX propellant production on the surface of Mars. These MAV options are launched without the LOX propellants, which account for the majority of the masses. Figure 28 shows the MAV options in terms of how much mass must be launched from Earth. It is this mass that determines the required cargo delivery capability for the landers. The 1 Sol MAV at Earth launch is 6.5 t less than the storable LMO vehicle (a 27% decrease). Also reduced is the difference between the 1 Sol and 5 Sol masses. At Earth, the launched 5 Sol MAV is only 10% greater than the 1 Sol vehicle. The storable MAV, while lighter at Mars liftoff, results in a heavier lander which places a larger burden on in-space transportation stages, and requires the use of a separate orbital taxi function to complete ascent to the Earth return vehicle in high Mars orbit.

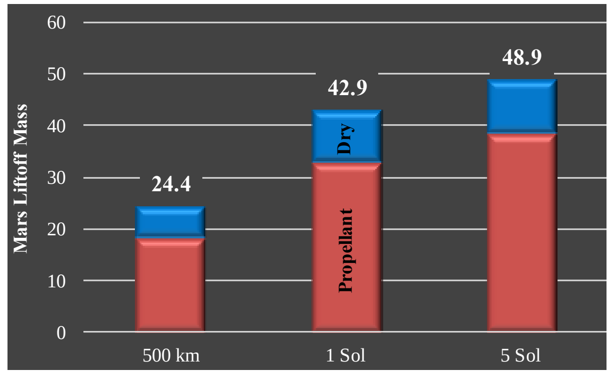

Figure 27. Mars Liftoff MAV Masses for Baseline Vertical Cabin Options.

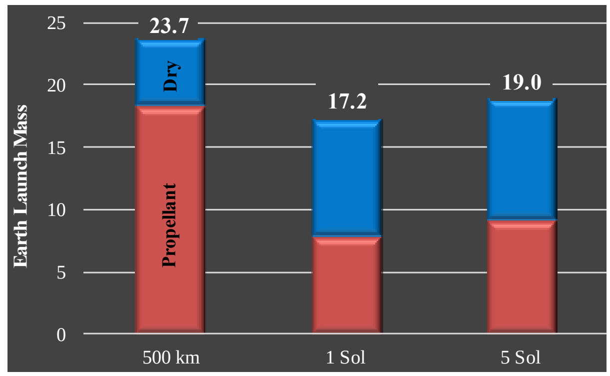

Figure 28. MAV Masses at Earth Launch for Baseline Vertical Cabin Options.

Horizontal cabin MAV configurations were also assessed and the common cabin does incur a significant mass increase; an increase that is compounded by the fact that the cabin is a high “gear ratio” element. The common cabin mass might be reduced by incorporating composite material into the planned rover cabin or taking other steps to optimize the design. The additional mass required for the common cabin implies a redesign of the parent rover cabin. Details of such a redesign were not considered as part of this study. Ultimately, the use (or non-use) of a common-cabin approach may be based on system level considerations other than structural mass. Overall, all three (new) configurations presented herein result in more open lander deck space and increased packaging flexibility. These benefits can be achieved with or without the implementation of the common-cabin itself.

6. CONCLUSIONS

If the goal is to minimize MAV liftoff mass, then clearly going to the lowest orbit is the best solution. However, in the optimization of the overall architecture, the impact of requiring another vehicle to ferry the crew between the 500 km circular orbit to the Earth return vehicle, which is in a much higher orbit, cannot be ignored. While the specific impulse is lower, pump fed storable propulsion is a feasible option with a low Mars liftoff mass and without the need for additional ISRU technology. However, a price must be paid in terms of a higher mass at Earth launch (due to the need to carry the oxidizer propellant to Mars). Storable propulsion for ascent to higher orbits is not reasonable because the lower Isp of the system results in much larger propellant loads and without the benefit of ISRU propellant production would result in significant growth in lander capability and introduce packaging challenges for other lander cargo manifests. Future work can include investigation of a LOX/Methane low Mars orbit MAV, so that the impacts to the overall architecture can be compared to the 1 Sol and 5 Sol options.

With Mars surface ISRU, LOX/Methane propulsion enables ascent to higher orbits (eliminating the need for a taxi) while maintaining low lander mass and low lander payload capability. More savings may be realized with the eventual evolution to methane ISRU, which will allow the MAVs to launch with completely empty tanks and further reduction to the size of the entire lander and, therefore, to the Earth-to-Mars transfer vehicle performance requirements.

Incorporating a MAV crew cabin that is common with other mission elements, such as the horizontal rover hab, may provide cost and schedule improvements, but a major finding of this study shows that the common cabin will be approximately 400 kg greater than the POD vertical cabin. The vertical crew cabin appears to be more structurally efficient than the horizontal common cabin, and does not require a docking tunnel to the Earth return vehicle. However, while analyzing the horizontal cabin cases, a potential alternate configuration to the current baseline was studied which may result in better use of the available lander deck space for a small mass premium.

ACKNOWLEDGMENTS

The authors would like to thank Jessica Garcia, in the Advanced Concepts Office at NASA Marshall Space Flight Center, for help in modifying the POST2 input decks for faster convergence over a wide set of cases.

REFERENCES

[1] Craig, Douglas A., Troutman, Patrick, Herrmann, Nicole, "Pioneering Space Through and Evolvable Mars Campaign," *AIAA SPACE 2015*, Pasadena, CA, August 31-September 2, 2015

[2] Polsgrove, Tara P., Thomas, Herbert D., Sutherlin, S., Stephens, Walter, Rucker, Michelle, "Mars Ascent Vehicle Design for Human Exploration," *AIAA SPACE 2015*, Pasadena, CA, August 31-September 2, 2015

[3] Rucker, M.A., S. Jefferies, A.S. Howe, R. Howard, N. Mary, J. Watson, R. Lewis, "Mars Surface Tunnel Element Concept," 8.0204 IEEE Aerospace Conference, Big Sky, MT, 2016.

[4] Rucker, M., "Design Considerations for a Crewed Mars Ascent Vehicle," AIAA-2015-4518, *AIAA Space 2015 Conference*, Pasadena, 2015.

[5] Gernhardt, M., Chappell, S., Crues, E., Litaker, H., Beaton, K., Bekdash, O., Newton, C., Abercromby, A., "Mars Ascent Vehicle Sizing, Habitability, and Commonality in NASA's Evolvable Mars Campaign," *IEEE Aerospace Conference*, Big Sky, MT 2017 (abstract submitted).

BIOGRAPHY

***Tara Polsgrove** is an aerospace engineer in the Flight Programs and Partnerships Office at NASA's Marshall Space Flight Center. She has been with NASA since 2000 and has worked on many conceptual designs of advanced spacecraft, including performance and vehicle integration for the Altair Lunar Lander. Her background is in interplanetary trajectory optimization and mission analysis. Recent work has focused on Mars transportation and lander designs supporting missions to send humans to Mars. Ms. Polsgrove has a Bachelor of Science in Aerospace Engineering from the Georgia Institute of Technology and a Master of Science in Engineering with a Systems Engineering focus from the University of Alabama in Huntsville.*

***Tim Collins** is a senior structures research engineer in the Structural Mechanics and Concepts Branch at NASA Langley Research Center in Hampton, Virginia. His area of expertise is spacecraft structural design and analysis with an emphasis on conceptual-design trade studies supported by hardware-prototype demonstrations. He has been with NASA since 1987, working on structural concepts for numerous NASA programs ranging from precision telescopes to Lunar and Mars landers. He also* *specializes in structurally efficient concepts for robotic operations, including those required for in-space or surface-based servicing and assembly. Mr. Collins has a Bachelor's Degree in Physics from the University of Rochester and a Master of Science Degree in Mechanical and Aerospace Engineering from the University of Virginia.*

***Herbert Thomas** is an aerospace engineer in the Advanced Concepts Office at NASA's Marshall Space Flight Center. His background is in orbital mechanics, mission analysis, advanced space propulsion, and propulsion system mass estimation. He has been with NASA since 2004 and, before that, worked as a software engineer in industry. He has worked on many conceptual vehicle designs as both an analyst and study lead. Dr. Thomas has a Bachelor of Science in Aerospace Engineering, Master of Science in Engineering, and a Doctor of Philosophy in Mechanical Engineering from the University of Tennessee.*

***Walter Stephens** is an aerospace engineer in the Flight Programs and Partnerships Office at NASA's Marshall Space Flight Center. He has been with NASA since 1990 and previously worked in the Propulsion Laboratory, Preliminary Design Office, Advance Concepts Office, Space Launch Initiative, and the Space Shuttle Main Engine Project Office. He is currently supporting the human mission to Mars conceptual studies. He received a Bachelor of Science in Physics from the Augusta College and a Master of Science in Mechanical Engineering from the University of Alabama in Huntsville.*

***Michelle Rucker** received a B.S. (1984) and M.A. (1986) in Mechanical Engineering from Rice University and has been with NASA for 29 years. She currently serves in the Exploration Integration and Science Directorate at the Johnson Space Center. She began her NASA career as a test engineer at the White Sands Test Facility before moving onto roles as a deputy subsystem manager for the International Space Station, EVA and Spacesuit Systems Deputy Branch Chief, and Altair Lunar Lander Test and Verification Lead.*

***Mathew Zwack** is a systems engineer with Jacobs Technology, supporting the Advanced Concepts Office at NASA Marshall Space Flight Center. His background is in conceptual design and analysis of complex systems. Recent work has been focused on design process improvements within the Advanced Concepts Office, which have been successfully applied to various trade studies for SLS and MAV. Dr. Zwack holds a Bachelor's Degree in Aerospace Engineering and Mechanics with a minor in Astrophysics from the University of Minnesota as well as Master of Science and Doctor of Philosophy degrees in Aerospace Engineering from the Georgia Institute of Technology.*

***Patrick Dees** is a trajectory engineer with Jacobs Technology, supporting the Advanced Concepts Office at NASA Marshall Space Flight Center. His background is in conceptual design and tool development. Recent work has been focused on the automation of trajectory analysis to greatly speed up the trade study process, and has several publications in AIAA Space on the topic. He holds a Bachelor's in Physics from New College of Florida, and a Master's in Aerospace Engineering from the Georgia Institute of Technology.*