MarsDrive Mission Profile

Version 2.0

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Introduction

The goal of MarsDrive is to begin the permanent human habitation of the planet Mars. This paper examines one scenario for accomplishing the first step in achieving this goal.

This exercise assumes the presence of easily-accessible sources of hydrogen, probably in the form of water ice, on the Martian surface. While this presence is still speculative, it is absolutely necessary for the achievement of our goal. Without access to water *in situ*, it is not practical to think of achieving a permanent human presence on Mars without extraordinary means. It is hoped that before the end of calendar year 2008 this presence will be confirmed by missions currently in progress.

This exercise also assumes that MarsDrive will use available Earth launch vehicles and in-space rocket motors. Having to develop and certify a launch vehicle will increase the cost of this mission by an order of magnitude. Likewise, having to design, develop, test, and certify in-space rocket motors will double or triple the cost of the mission.

The goal of this exercise was to produce a first-level profile of the minimum practical manned mission to Mars consistent with the goal of crew safety. This paper is not presented as a complete mission analysis, or a "done deal." It is presented as a kernel around which a wide-ranged discussion can coalesce. It is, if you will, a "straw man" exercise designed to focus our work and to provide a point of departure.

Every attempt was made to standardize as much hardware as practical so as to minimize development costs. The basic mission profile for a crew of three requires seven launches to Earth orbit – one launch of 32mT payload, one launch of 35mT, one launch (crewed) of 19mT, one launch of 58mT, and 3 launches of 66mT. A full analysis was performed for crew sizes of 3, 4, and 6 members to allow flexibility in planning.

The figures given herein are preliminary and have not been peer-reviewed. Only the crewed flight has been analyzed in any detail. The uncrewed flights will be analyzed once the basic mission profile has been decided on.

Mission Profile

The mission flies three spacecraft from Earth orbit to Mars with the possibility of a fourth for redundancy. All but the last flight are uncrewed and are to pre-position assets for the crewed mission.

Mission 1: Pre-positions a tele-operable rover in the most likely candidate area for the crewed landing. The rover will explore the area and provide data to the Mission Control Team regarding the suitability of the sites it explores. This flight launches at least 1 cycle prior to the crewed launch.

Mission 1a: (optional). A duplicate of Mission 1 if funding is available. This rover will set down in a different location. Two rovers will double the area which can be explored for the preferred crewed landing site.

Mission 2: Pre-positions the surface habitat, the crew's surface food supply, and the prototype greenhouse. This lander will be guided to its landing site by a beacon from the on-the-ground rover. This flight will launch in the same cycle as Mission 1 and will loiter in Mars orbit until a landing site is determined.

Mission 3: The crewed flight. After analysis of the option of sending the lander separately, a single Earth-departure stack consisting of the crew's in-flight habitat, the Earth re-entry vehicle, and the Mars Lander was selected.

I. Pre-positioning the Rover

The goal of this mission is to land a tele-operable rover in the most likely landing site for the crewed mission. The rover is initially tele-operable from Earth. It also contains a cockpit so that later it may be ridden by two crew members. Because of the pre-crew power requirements, the rover is driven by electric motors fed from a high-density rechargeable battery system.

The rover contains a digger/scoop for collecting water ice and soil samples. In the pre-crew exploration mode, the rover contains equipment for soil testing and a furlable solar array for recharging its batteries. Because of the high power requirements of both the drive motors and the digger it is likely the rover will have to operate on a two day cycle of one day active, one day quiescent/recharging. Alternatively, the rover could be powered from a nuclear source, most likely radioisotope. Once the crew lands the rover will also be used for collecting water-ice feedstock and transporting it to the propellant and potable water ISRU (*in situ* resource utilization) units.

Rover Mass Budget:

Structure:	1,000	kg
Propulsion:	500	kg
Science package:	200	kg
Digger / Loader:	300	kg
Total:	**2,000**	**kg**

Mars Approach, Entry, Descent and Landing is handled by a combination of propulsive maneuvering and aerobraking. As the vehicle approaches Mars on a minimum-energy Hohmann transfer orbit, it is traveling 2.55 km/sec below the solar orbital velocity of Mars. When vectorially added to Mars' escape velocity of 5.04 km/sec, the vehicle will need to shed 5.65 km/sec to soft land on the surface. Based on experience with similarly-sized payloads, this exercise conservatively assumes that 75% of the necessary ΔV can be shed aerodynamically. The EDL system has been designed to provide 2.0 km/sec ΔV to allow for ample terminal cross-range maneuvering to the desired landing zone. The propulsion system uses storable, hypergolic propellants Nitrogen Tetroxide (N_2O_4) and Monomethylhydrazine ($CH_3N\ H\ N\ H_2$) and off-the-shelf main propulsion and RCS hardware.

Rover AEDL Stage Budget:

Structure:	506	kg
Propellants:	2,955	kg
Aerobraking:	2,500	kg
Total:	**7,311**	**kg**

This requires a net mass of 9,311 kg be injected into the Mars transfer trajectory from Earth (TMI). The Earth departure stage uses LO_2/LH_2 propellants and off-the-shelf main propulsion and RCS hardware.

Rover Earth-departure Stage Budget:

Structure:	4,373	kg
Propellants:	17,843	kg
Total:	**22,215**	**kg**

The total Initial Mass in Low Earth Orbit (IMLEO) is 31.5 mT. Depending on the cost and availability of launch vehicles, this can be carried by a single launch vehicle, or split into two smaller launches of 9.3 mT (payload) plus 22.2 mT (EDS) which can be docked in LEO.

If sufficient funds are available, and if the pre-flight analysis of the best Mars surface data available at the time indicates a wide variety of candidate landing sites, multiple rover launches should be attempted to give the Mission Control Team as much on-the-ground data as possible as input to their landing site decision. Rovers which are close enough to the landing site to rendezvous there will give the crew backup rover capabilities. Rovers which are too remote from the landing site to rendezvous there can be tele-operated by the landed crew, thus extending their range of exploration.

II. Pre-positioning the Surface Habitat

The second launch will pre-position the surface habitat, the environmental ISRU plant, and the greenhouse at the chosen landing site. The habitat will leave LEO in the same launch cycle as the Rover(s) and will loiter in Mars orbit waiting for a landing site to be selected. The detailed mass budget for the habitat remains as forward work.

The habitat is intended to fit into the same aeroshell, use the same EDL system, and the same EDS as the Lander (see sections III.3.2 and III.6 below). The purpose of this is two-fold. First, it requires the development and certification of only one EDS and one aeroshell. Second, it provides a live uncrewed test of both systems. Details of both systems are provided as part of the Crewed mission.

The interior of the Surface Habitat differs from the interior of the Lander in that the necessary propellant tankage for this mission is significantly less than that of the crewed Lander; this vehicle only requires the necessary propellant to land itself on the surface. The interior volume thus gained is used as the surface habitat.

Habitat Volumes:

Crew Size:	**3**	**4**	**6**
Total Volume (m^3):	100.5	112.7	134.2
Less Tankage (m^3):	27.4	31.5	39.0
Less Aero & Structure (m^3):	5.0	5.6	6.7
Total Habitat Volume (m^3):	68.1	75.6	88.5
Volume per crew member (m3):	22.7	18.9	14.7

Target masses for the habitats were selected so the Crewed Mission’s EDS could perform the TMI maneuver (see section III.6 below). The target mass given in the table below includes interior furnishings, scientific equipment, solar arrays, environmental ISRU units, and the greenhouse. The “Habitat Wet Mass” includes of the mass of the structure itself, the aeroshell and aerobraking equipment, and the propulsion system.

Habitat Mass:

Crew Size:	**3**	**4**	**6**
Habitat Mass (mT):	5.2	6.9	10.5
Habitat Wet Mass (mT):	35.2	40.6	52.1
Required EDS Wet Mass (mT):	66.0	75.1	94.6

This require a two-launch mission. First, the Habitat/Lander is launched into Earth orbit. After check-out, the EDS is launched. The two rendezvous and dock and the EDS performs the TMI maneuver. This will be our first test of on-orbit rendezvous and docking.

While in Mars orbit the vehicle will eject a communications satellite which will serve as a two-way store-and-forward relay between the Martian surface and Mission Control on Earth.

III. The Crewed Stack

The crewed mission will fly the in-space Habitat, the Mars Lander and the Earth re-entry vehicle in a single stack. Various options for flying the components separately were investigated and discarded for two reasons. First and foremost, flying the components separately did not reduce the IMLEO for this mission, it just split it into smaller pieces. Flying the single stack with a two-stage Earth Departure vehicle helps mitigate this issue. Second, because of the orbital mechanics of the Earth-Mars Hohmann trajectory, this mission has no post-TMI abort option. Thus almost any conceivable failure resulting in a Loss of Mission (LOM) fault will also become a Loss of Crew (LOC) fault. Thus it was felt to be a risk-management advantage to have all the components which can contribute to a LOM/LOC fault either be pre-positioned on Mars or be in the crewed stack so that should an in-flight fault occur, humans would be present and available to correct the problem if at all possible.

III.1 – The Earth Re-entry Vehicle

It is assumed for the purposes of this analysis that the crew will ascend into Earth orbit in the same vehicle in which they will re-enter the Earth's atmosphere and land at the conclusion of their mission. On ascent, the crew will rendezvous and dock with the remainder of the stack. The ERV will be quiesced and will not be used until the habitat returns to Earth. The ERV will remain docked to the in-space habitat and parked in Mars orbit while the crew is on the surface.

It is assumed that a suitable capsule will be available off-the-shelf by the time this planning process has reached that stage where selection of this vehicle becomes critical. For this analysis, a place-holder mass of 5 mT was assumed for this vehicle.

III.2 – The In-space Habitat

The in-space habitat provides work and living space for the crew during the outbound and inbound cruise phases of the mission. It will be parked in Mars orbit, unmanned and semi-quiesced, while the crew is on the planet. During this time the habitat will serve as a store-and-forward communications relay between Mars surface operations and Mission Control on Earth, and as a repeater relay between out-of-line-of-sight assets on the Martian surface.

The possibility of using one or both propellant tanks from the final EDS was examined and discarded. The mass savings (IMLEO) were insignificant and the added problems of storing and then positioning all the habitat interior panels and equipment were considered excessive.

Environmental systems in the habitat will recycle 50% of the crew's oxygen needs and 80% of their potable water needs. Habitat stores will include the remaining outbound oxygen and water requirements, the entire mission food supply, plus a 30-day supply of oxygen and water to be carried down to the surface in the Lander.

In-space Habitat Mass and Volume Budget:

Crew Size:	**3**	**4**	**6**
Volume (m^3)	60	80	120
Structure + Interiors (mT):	3.0	4.0	6.0

III.3 – The Mars Lander

The Mars Lander is the single largest piece of hardware flown in this mission. Fundamentally, the job of the Lander is to bring the crew from Mars orbit to the surface and return them to Mars orbit. The Lander will touch-down tanks-dry and will be refueled from its on-board propellant ISRU (PISRU) plant. On lift-off, the Ascent vehicle will separate from the landing deck, support structure, PISRU plant, and power supply, which will remain on the surface. The same engines and propellant tankage will be used for both the descent and the ascent propulsive maneuvers.

The lander propulsion system uses liquid oxygen and liquid methane propellants. Main engines and RCS will be off-the-shelf. As a place-holder, the Orion CEV-SM engine was assumed, as this engine will probably have the most in-flight experience of any available LO_2/LCH_4 engine by the time we need to finally select an engine. This engine is under-powered for the Ascent maneuver, requiring a cluster of five engines for the 3- and 4-crew missions, and 6 engines for the 6-crew mission. The availability of a certified, restartable pressure-fed engine of at least 135,000 Newtons vacuum thrust would greatly relieve this constraint.

Two scenarios for the lander were examined:

III.3.1 – Small Lander

This Lander was sized just large enough to return tanks-dry to Mars orbit. In this scenario the ΔV necessary for Mars Orbit Insertion (MOI) and for injection into the Earth-return trajectory (TEI) must be provided by a separate stage. Further, the TEI propellants must be carried all the way from the Earth's surface. Because of unfavorable IMLEO trade-offs, this scenario was not considered further.

III.3.2 – Large Lander

In this scenario the Lander was sized to carry the TEI propellants from the Martian surface. This requires the Lander to have sufficient tankage for both the Mars Ascent-to-orbit ΔV as well as for the TEI ΔV with the parked in-space habitat and ERV in the stack. Because the Lander carries the TEI propellants, it is simpler to let the Lander itself perform the TEI propulsive maneuver, thus obviating the need for a separate TEI stage or for complicated and risky in-orbit propellant transfer. Further, because the Lander tankage is sufficient to hold both the MOI propellants as well as the Mars Descent propellants, this scenario uses the Lander to perform the MOI propulsive maneuver as well, thus obviating the need for a separate MOI stage.

While the dry mass of the "*large lander*" is greater than that of the "*small lander,*" this scenario significantly reduces the IMLEO of the mission and so was the scenario which was further developed.

Having a fully-fueled lander of this design as part of the crewed stack provides several advantages. Because the lander's engines provide all propulsive maneuvers after TEI, the lander's control system becomes the *de facto* control system for the entire crewed stack, obviating the need for (and the mass of) a separate control system. Also, because the design of the lander places the crew cabin inside the cluster of fuel tanks, these provide extra radiation protection for the crew, especially during the outbound cruise phase of the mission when the tanks are full of propellant.

III.3.3 – Mars Entry, Descent and Landing

EDL is handled by a combination of propulsive maneuvering and aerobraking. As of this writing, this phase of any mission to Mars is the most speculative; we have no experience with landing payloads above a few metric tons. With this caveat in mind, conservative estimates of aerobraking effectiveness were made. For this analysis, it was assumed that two-thirds (67%) of the required ΔV will be provided aerodynamically, the remaining one-third, plus a terminal maneuvering capability of 500 m/s will be provided propulsively.

This analysis assumes that the crewed Lander and the pre-positioned surface habitat will use the same aeroshell – the aerodynamic braking system consisting of the heat shield, aerodynamic shell, and parachutes. This assumption saves the cost and effort of designing, building, and certifying two separate EDL systems. Further, pre-positioning the surface habitat, as detailed above, will serve to prove the worthiness of the crewed EDL system.

The EDL system is a truncated conic based on the Orion Cycle III CEV. This shape has a 20° sidewall, providing the maximum interior volume of any of the designs which demonstrate a monostable aerodynamic attitude with an appropriate center-of-mass.

Lander Volumes:

Crew Size:	**3**	**4**	**6**
Crew cabin (m^3):	6.7	7.4	8.2
Tankage (m^3):	59.6	68.4	84.7
Aero & Structure (m^3):	34.2	36.9	41.3
Total (m^3):	100.5	112.7	134.2
Base Diameter (m):	6.60	6.85	7.25
Height (m):	6.4	6.7	7.3

These lander base diameters are slightly beyond the capabilities of current launch vehicles. However they are close enough to present limits that advances in commercial launch vehicle capabilities over the next 10 to 15 years should bring at least the smaller diameters within reach. This is one important factor which should be taken into consideration by the Mission Planning Team when selecting crew size.

Descent Stage Mass Budget:

Crew Size:	**3**	**4**	**6**
Structure (mT):	1.5	1.5	1.6
Engines (mT):	2.0	2.0	2.4
Tankage (mT):	2.4	2.7	3.4
Aerobraking (mT):	5.1	5.5	6.2
Landing Deck (mT):	1.0	1.0	1.0
PISRU + Power (mT):	1.5	1.5	1.5
Dry Mass (mT):	**13.5**	**14.2**	**16.0**
Crew + Cargo (mT):	5.5	7.3	11.0
Propellants (mT):	11.5	13.1	16.4
Mass in Orbit (mT):	**30.5**	**34.7**	**43.4**

III.3.4 – Mars Ascent and Orbital Insertion

Mars Ascent is the critical maneuver in determining engine power. The ascent vehicle, with full propellant tanks, must generate enough acceleration to move away from the Martian surface at a rate sufficient to minimize gravitational losses. A cluster of five Orion CEV-SM MPS engines provide barely adequate acceleration for crew sizes of three and four. A sixth engine must be added for a crew size of six. The availability of a proven, more powerful LO_2/LCH_4 engine would greatly help this restriction.

Ascent Stage Mass Budget:

Crew Size:	**3**	**4**	**6**
Structure (mT):	1.5	1.5	1.6
Engines (mT):	2.0	2.0	2.4
Tankage (mT):	2.4	2.7	3.4
Dry Mass (mT):	**5.9**	**6.2**	**7.4**
Crew + Cargo (mT):	2.7	3.3	4.5
Ascent Propellants (mT):	36.8	41.8	52.6
TEI Propellants (mT):	12.5	14.4	18.3
Mass at Lift-off (mT):	**57.9**	**65.8**	**82.7**

III.4 – The Trans-Earth Injection (TEI) Maneuver:

After ascent from the Martian surface, the Lander will rendezvous and dock with the in-flight habitat and ERV in Mars orbit. The empty ascent propellant tanks and all but one engine are discarded.

After the crew re-activates the in-flight habitat, the Lander's remaining engine performs the TEI maneuver. Reserve propellants in the Lander can be used during the cruise back to Earth to perform at least one mid-course correction.

TEI Mass Budget:

Crew Size:	**3**	**4**	**6**
ERV (mT):	5.0	5.0	5.0
Habitat (mT):	3.0	4.0	6.0
MAV Structure (mT):	1.5	1.5	1.6
MAV Engine (mT):	0.4	0.4	0.4
Tankage (mT):	0.6	0.7	0.9
Crew + Cargo (mT):	1.9	2.2	2.8
Consumables (mT):	3.1	4.1	6.2
TEI Propellants (mT):	12.5	14.4	18.3
Mass at TEI (mT):	**28.0**	**32.3**	**41.1**

III.5 – The Mars Orbit Insertion (MOI) Maneuver:

For the purposes of this analysis it was assumed that 100% of the MOI maneuver would be performed propulsively. No MOI aerobraking was assumed. The stack at MOI consists of the ERV, the in-flight habitat and the fully-fueled Lander. The Lander performs the MOI propulsive maneuver.

After achieving the desired parking orbit, the habitat is semi-quiesced into a station-keeping mode. The habitat will continue to maintain high-data-rate communications with Earth and will serve both as a store-and-forward relay between Earth and Mars and as a repeater relay between Mars surface assets which are out of common line-of-sight.

MOI Mass Budget:

Crew Size:	**3**	**4**	**6**
ERV (mT):	5.0	5.0	5.0
Habitat (mT):	3.0	4.0	6.0
Lander Dry Mass (mT):	13.5	14.2	16.0
Descent Propellants (mT):	11.5	13.1	16.4
Crew (mT):	0.9	1.2	1.8
Consumables (mT):	4.6	6.1	9.2
MOI Propellants (mT):	32.9	37.6	47.5
Mass at MOI (mT):	**73.7**	**84.3**	**106.3**

III.6 – The Earth Departure Stage (EDS):

The masses shown in the bottom line of the **MOI Mass Budget** table above must be boosted from Earth Orbit to the Mars transfer orbit injection velocity. Performing this maneuver with a single stage Earth Departure Stage (EDS), even using LO_2/LH_2 propellants requires EDS wet masses of 136mT, 156mT, and 197mT, respectively. These are clearly too large for even the most optimistic scenario of commercially-available launch vehicles in the next 10 to 15 years.

The decision was made to use a two-stage EDS using two identical stages using LO_2/LH_2 propellants. As a place-holder, a single J2(x) engine was assumed. The decision to use two identical stages for the EDS instead of optimizing the staging point was made to save the project the considerable cost of having to develop, test, and certify multiple stages.

As stated earlier, the mass budget of the pre-positioned surface habitat was constrained so it would use a single-stage EDS using this same stage. This decision, if it holds up to further scrutiny, will again save the project considerable pre-flight funds. Further, the successful launch of the surface habitat will also serve as an in-flight test of the crewed EDS.

EDS Mass Budget:

Crew Size:	**3**	**4**	**6**
Structure + Tankage (mT):	6.3	7.3	9.2
Engine (1 – J2x) (mT):	2.4	2.4	2.4
Stage Dry Mass (mT):	**8.7**	**9.7**	**11.6**
Propellants (mT):	57.4	65.8	83.0
Stage Wet Mass (mT):	**66.1**	**75.4**	**94.6**

IV – Conclusion:

Based on the results of this analysis, it seems to be prudent to concentrate on crew sizes of either three or four members. A crew size of six, while offering much greater flexibility in terms of crew skill distribution, increases the Mission IMLEO to the point where the assumption of a commercially-available launch vehicle with the necessary throw-weight becomes much riskier.

This analysis was very conservative in terms of reliance on aerobraking using the Martian atmosphere. If further investigations indicate that aerobraking can contribute to the MOI ΔV or that more than 67% of the descent ΔV can be achieved aerodynamically, the IMLEO figures will fall dramatically. For this analysis I wanted to present the worst case.

As always, comments, criticisms, and suggestions are always encouraged. Hopefully this exercise will move us closer to our goal of a permanent human presence on the planet Mars.

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