MarsDrive Reference Mission

"Mars for Less"

"The Earth is the cradle of mankind, but one cannot stay in the cradle forever."
Konstantin Tsiolkovsky

"By the year 2000 we will undoubtedly have a sizable operation on the Moon, we will have achieved a manned Mars landing, and it's entirely possible we will have flown with men to the outer planets." ***Wernher von Braun, 1969***

MARSDRIVE CONSORTIUM

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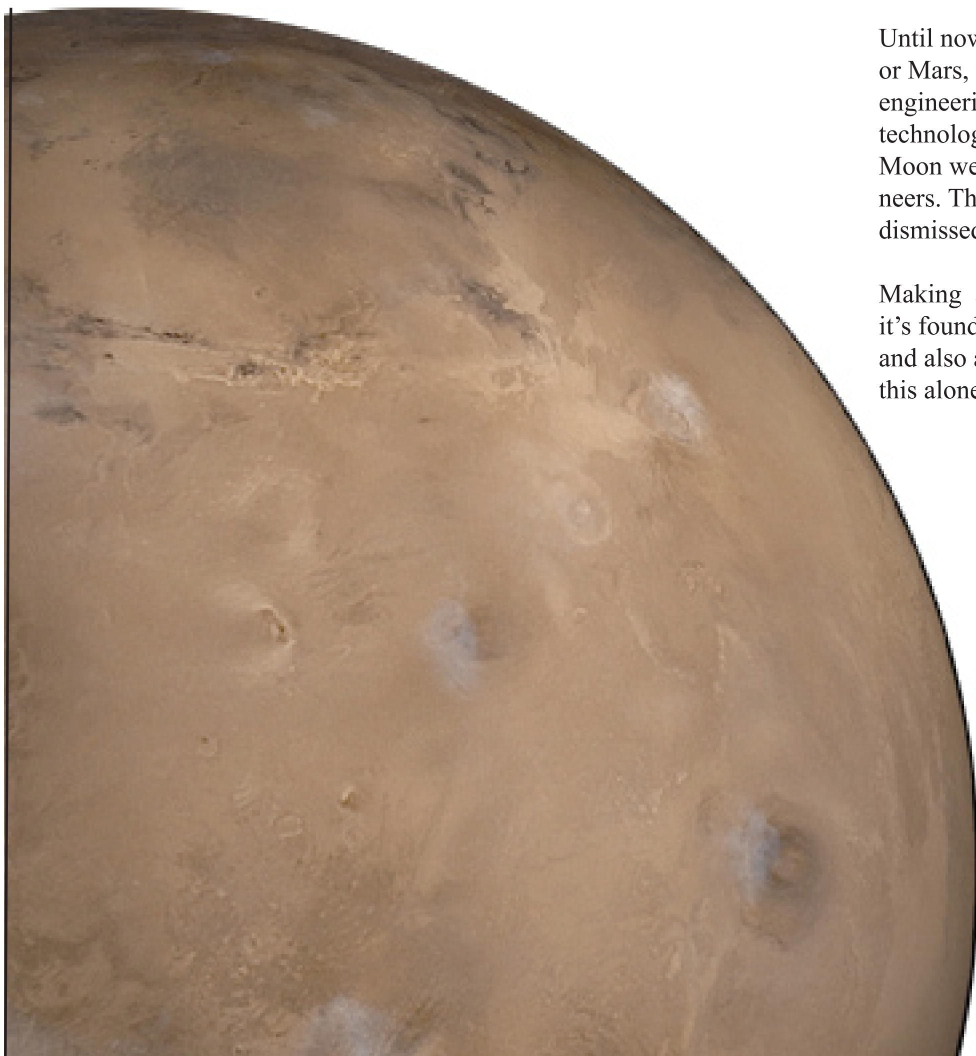
WHAT IS THE MARSDRIVE CONSORTIUM?

What is The MarsDrive Consortium? We are a group of people interested in sending humans to Mars in the next two decades via the combined resources of the large number of space advocates and the building of the largest public support base ever seen. We also acknowledge the dedication of current space advocate groups and seek to combine them with our public support base into more than just a powerful political lobby. Our goals include reaching for the human settlement of both space and Mars from our own resources.

Until now, when a private space group has said they want to send people to the Moon or Mars, they have not been taken seriously. The requirements of rocket science and engineering to build the Saturn V launch vehicles were ranked as one of mankind's finest technological achievements in the 20th century. The successful Apollo missions to the Moon were unique and brought together tens of thousands of dedicated workers and engineers. These requirements are why private organizations undertaking this feat have been dismissed as uninformed, unenlightened day dreaming at best.

Making a mission to Mars successful, especially from private resources will require at it's foundation, a nexus of people leading and working on all aspects of such a mission, and also a public support base to make such efforts affordable. No single group can do this alone and that is why the MarsDrive Consortium has been founded



MARSDRIVE CONSORTIUM

Our goals at MarsDrive are clear. We, along with and our Consortium partners, aim to send human missions to Mars and establish a permanent base there within the next two decades. To successfully accomplish these goals we will:

1. Build-
Establish a broad public and private support base with large scale outreach programs.
2. Network-
Join together with and support other space advocate groups and businesses.
3. Go-
Secure the necessary resources through our memberships and partnerships to launch a human mission to Mars and for establishing a private base on Mars.

2. THE MYTH OF THE HEAVY LIFT

The Myth of the Heavy Lift - Heavy-lift launch vehicles (HLLVs) are regarded by many as the key technology for an aggressive, cost-sustainable program of human spaceflight beyond low-Earth orbit. Indeed, decades of Mars mission analysis have been dominated by mission plans calling for the development of at least Saturn V-class launch technology, capable of delivering 100 tonnes or better to low-Earth orbit – and on the surface, this would appear quite prudent. A human expedition to the red planet will necessarily mass in excess of 100 tonnes initially; and because bigger boosters can carry larger amounts of payload in far fewer launches, they have been championed by a majority of astronautical engineers as the most cost-effective technology to carry the future of manned spaceflight. Correspondingly, NASA has recently adopted the design of a shuttle-derived heavy-lift launch vehicle (SDLV) to support the first priority of the agency's new mandate: a series of lunar return missions to commence within 15 years. Production of this booster is slated to begin by 2012.

NASA - HLLV
1st launch date 2014-17

Yet there remain significant drawbacks to the development and use of a heavy-lift booster. A shuttle-derived HLLV – while certainly more economical than building a comparable booster "from scratch" – is nevertheless projected to cost upwards of $10 billion U.S.; one of the largest expenses in a program that has grown increasingly difficult to justify in the wake of recent events, and which may furthermore be problematic to sustain through the pending administration change in 2009. While it may be possible to accelerate the current timeline of the SDLV program, the new vehicle will certainly require significant modifications to the existing facilities at Cape Canaveral – and consequently, accelerating its development will almost certainly be synonymous with retiring the shuttle, which in turn could adversely impact the International Space Station prior to completion of NASA's Crew Exploration Vehicle. Attempting to develop a heavy-lift launch system will necessarily have significant ripple effects throughout the entire agency – an impact which may not be fully appreciated by those who most aggressively advocate the rapid development of a major new booster.

However, perhaps more significant than the uncertainty of HLLV development are its implications to the private sector. If the current NASA administration succeeds in developing its shuttle-derived heavy lifter, then a program of human spaceflight beyond low-Earth orbit will evolve in the next few decades that only NASA itself will be capable of undertaking. Because NASA spacecraft will be optimized for launch on heavy-lift boosters, there will be limited potential at best for either the private sector or other countries to become involved in a significant way. No other nation in the world has the necessary resources to build a HLLV, and no private initiative will be capable of developing comparable technology anytime in the foreseeable future; and consequently, spaceflight beyond Earth orbit will remain within the realm of NASA exclusively. The private launch industry won't be encouraged to grow, and the United States government will be shouldering all major program launch costs with taxpayer dollars.

3. Reaching Mars for Less

The Mars for Less architecture [1] was designed to circumvent the need for heavy-lift vehicles entirely. Rather than basing plans for human expeditions to Mars on as-yet undeveloped technology, Mars for Less is predicated on the use of more modest, more realizable medium-lift launch vehicles, with approximately 25-tonne to low orbit payload capacities. By dividing Mars-bound spacecraft and propulsion systems into smaller components, and launching them on smaller boosters as opposed to heavy-lift vehicles, the need for significant new launch technology can be eliminated; consequently, the only vehicles requiring development "from scratch" would be those actually used for Mars exploration, resulting in a program that is fundamentally easier to initiate.

SpaceX - Falcon 9-S9
1st launch date 2007-8

4. THE MISSION

Mars for Less is essentially Robert Zubrin's Mars Direct mission architecture, divided into smaller components and delivered to orbit by smaller launch vehicles. Comprehensively discussed in reference [2], the Mars Direct plan represents a global minimum-energy solution for any given launch opportunity, and leverages surface resources and long-duration stays to maximize both surface time and capability on Mars, while simultaneously permitting reasonably expeditious piloted flight times without the need for advanced (i.e. nuclear) in-space propulsion systems.

Each complete mission in the Mars Direct architecture requires two spacecraft, launched approximately 26 months apart:

**** An Earth Return Vehicle (ERV), which flies to Mars unmanned and fuels itself automatically with methane/oxygen bipropellant manufactured primarily from indigenous Martian resources; and***
**** A crewed Mars Transfer and Surface Vehicle (MTSV), which houses a crew of 4 astronauts during the outbound leg of each mission and for the majority of each surface stay.***

In the Mars for Less mission design, each of these spacecraft are launched and assembled in 6 components, delivered separately to orbit using medium-lift vehicles. For each spacecraft, the first launch would deliver a two-level common habitat element, to which the second would mate a lander, aeroshield and mission-specific modules, consisting of empty propulsion stages, hydrogen feedstock and a chemical reactor for the ERV; and a garage/storage module for the MTSV. Subsequent launches would deliver 4 high-energy hydrogen/oxygen propulsion stages to each payload, which would be mated aft like train cars and ignited at successive perigees, widening the orbit of each spacecraft until the final stage imparts sufficient energy for trans-Mars injection.

The unmanned ERV would proceed to Mars on a near-minimum energy transfer with a flight time of approximately 8 months, while the crewed MTSV would be assembled about 2 years later and follow on a slightly expedited flight lasting 4-6 months, depending on the specific opportunity. Piloted spacecraft have the option of generating artificial gravity using tethers and burnt-out propulsion stages as counterweights. Each spacecraft would aerobrake into Mars Orbital Capture (MOC) and land with the aid of parachutes and rockets at a common site. As in Mars Direct, each crew would remain on the surface for approximately 1.5 years, during which broad exploration could be performed. Astronauts would be afforded the natural protection of the Martian atmosphere from the hazards of interplanetary space for the duration of their stay, at the conclusion of which they would board their fully-fuelled ERV and launch directly from the surface of Mars onto an Earth-bound trajectory. Upon return, the crew aerobrakes into Earth orbital capture with the ERV, and recovery is possible using either orbital rendezvous or by targeting the ERV capsule for a direct Earth reentry and Apollo-style ocean splashdown. The rationale for selecting a crew of 4 is discussed at length in references [2] and [3]. An example mission timeline for a 2018 launch is presented in Table 1, and both ERV and MTSV reference designs are shown in Figures 1, 2 and 3. One of the most promising candidate launch vehicles for this architecture – the SpaceX Falcon 9-S9 – is shown in Figure 4.

5. THE MISSION CONTINUED

While mating spacecraft and propulsion stages in orbit is a less robust approach than launching each Mars-bound spacecraft directly from the Earth's surface using a heavy-lift vehicle, it does represent an easier architecture to develop, having been designed around existing medium-lift launch vehicles. The approximately 25-tonne components of both spacecraft described above can be placed in LEO using either a combination of existing launch vehicles (such as the Ariane V or Delta IV-H), or alternatively, by emerging launch vehicles with wider payload fairings (such as the Solid-Rocket Booster (SRB)-derived NASA Crew Launch Vehicle or the SpaceX Falcon 9-29).

While the need for orbital assembly is frequently cited by detractors as detrimental to any space mission design, it is noteworthy that – of all the factors required for a piloted Mars mission to succeed (trans-Mars injection, aerobraking into MOC, successful surface landing and rendezvous, and making rocket fuel from Martian air), orbital rendezvous and assembly are the two operations which today's space agencies actually have the most experience with. The spacecraft and propulsion stages outlined above would be much easier to assemble than either space stations or candidate spacecraft from past studies, since there would be no need to extend a complex life support system across the entire series of modules. With discrete, compartmentalized propulsion stages, little more than truss sections would be required to react and re-transmit propulsion loads between them; and with only structural considerations being primary, the entire assembly and integration process for spacecraft in Mars for Less would be much simpler than for projects such as Mir or the International Space Station.

Using smaller launch vehicles to assemble and launch Mars Direct-style missions allows for a dramatic reduction in development costs, making this method of undertaking piloted expeditions much more practical for either non-American or privately-sponsored initiatives.

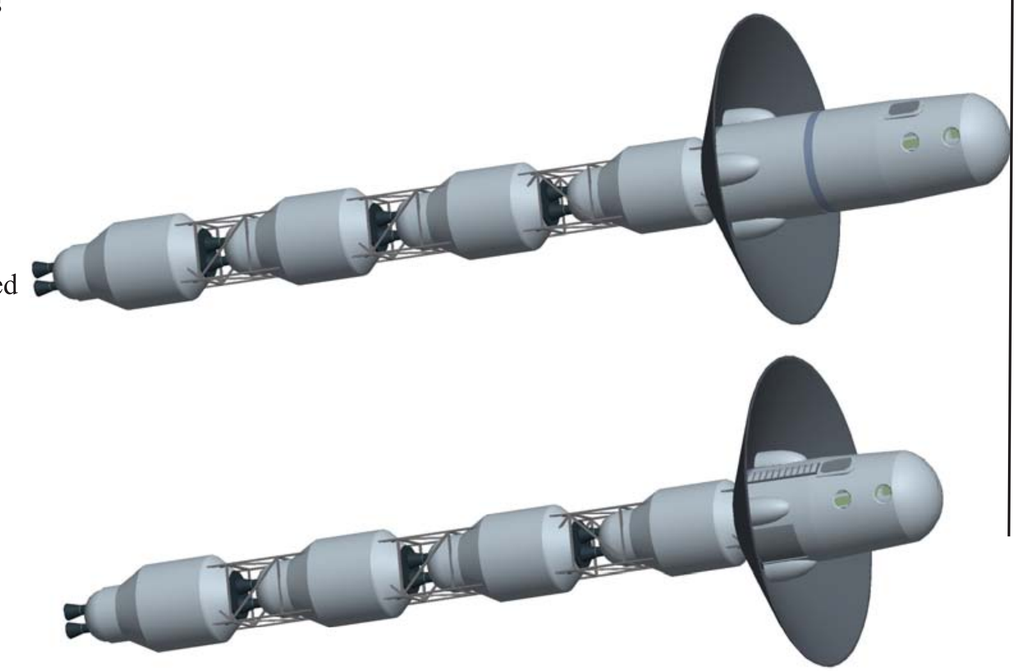
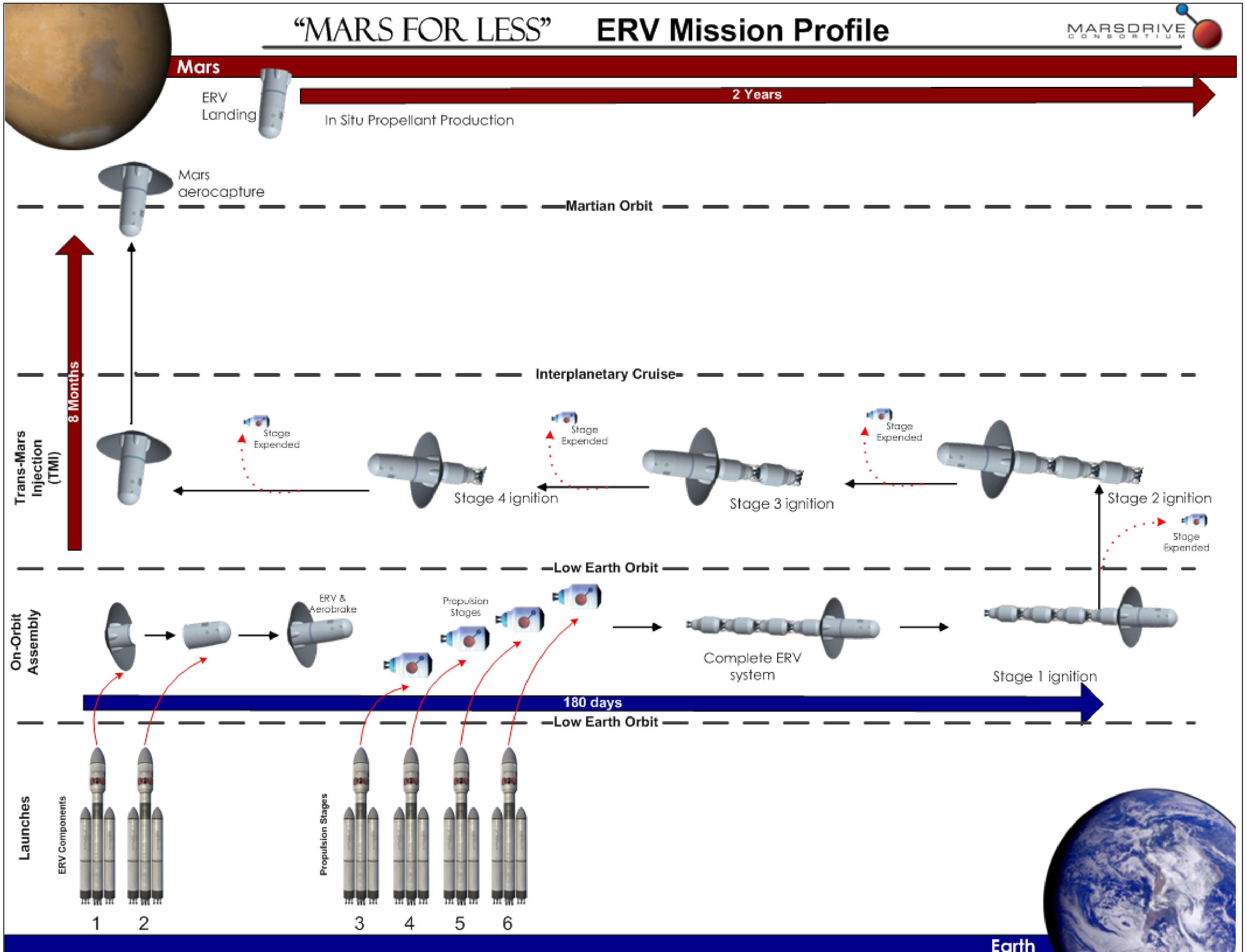


Figure 1: *Earth Return Vehicle (ERV, top) and Mars Transfer and Surface Vehicle (MTSV, below)*

6. ERV Mission Profile



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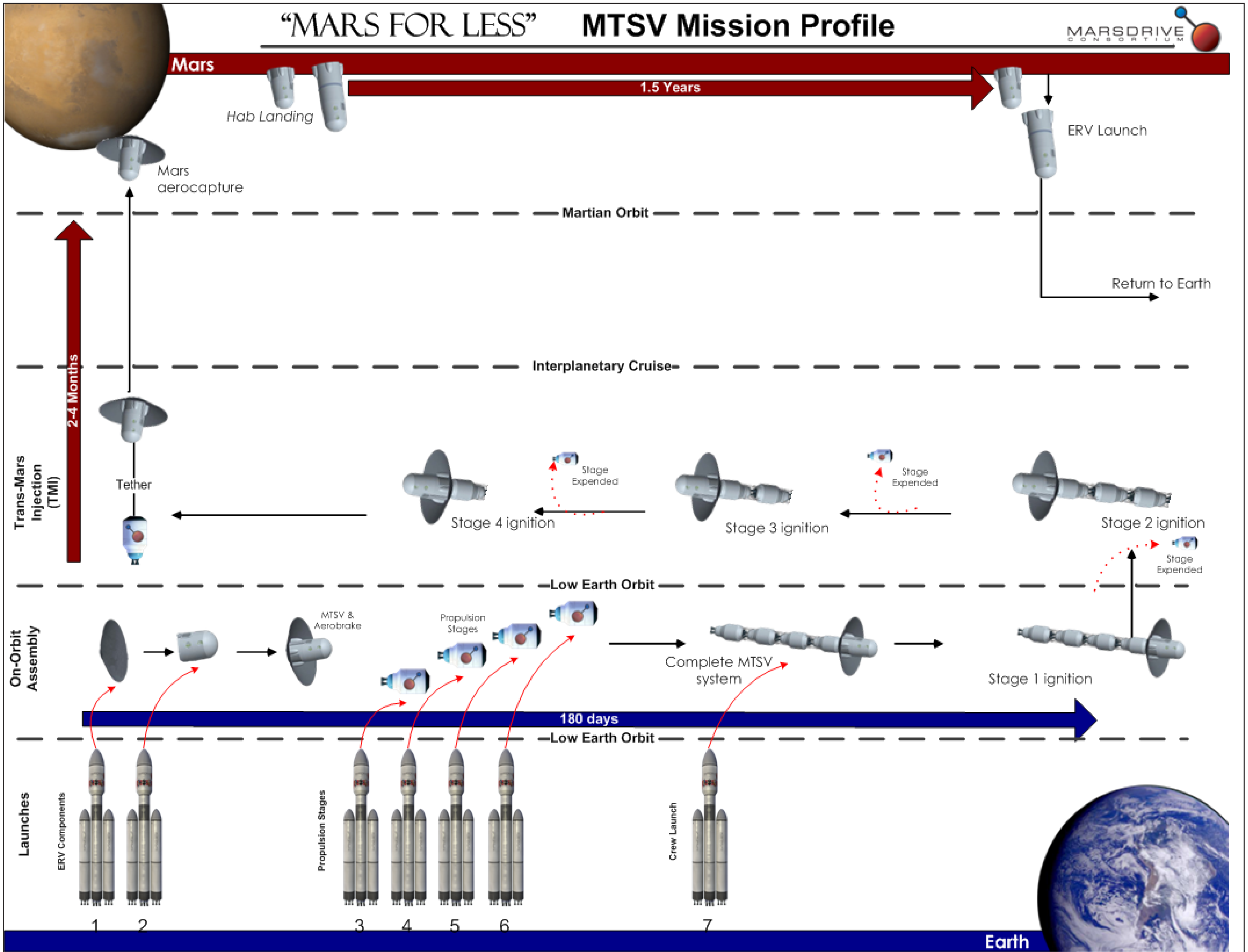
8. MTSV MISSION PROFILE



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9. MTSV MISSION TIMELINE

Table 1: *Mars for Less Mission Timeline for 2018 Launch of MTSV*

Mission Time Index	Mission Event
t – 180 days	▪ Launch 1: MTSV Cabin Module. Optional human presence for check-out
t – 150 days	▪ Launch 2: MTSV Garage, Lander and Aerobrake. Optional human presence for assembly.
t – 120 days	▪ Launch 3: Propulsion Stage 1
t – 90 days	▪ Launch 4: Propulsion Stage 2
t – 60 days	▪ Launch 5: Propulsion Stage 3
t – 30 days	▪ Launch 6: Propulsion Stage 4
-30 days < t < 0 days	▪ Verification and final checks. If crew was not delivered on first launch, crew is delivered by either dedicated CEV launch or equivalent (such as TXSpace CXV) ▪ Stages 4,3, and 2 ignited. MTSV moves to Highly-Eccentric Earth Orbit
t = 0 days	▪ Stage 1 ignited, completing trans-Mars injection
t + 180 days	▪ Mars arrival and orbital capture. Weather permitting, crew descends and lands at ERV site.
180 < t < 725 days	▪ Surface stay. Broad exploration capability provided by long-range rover, substantial science payload, and replenishment of fuel, oxygen and water supplies using Martian resources.
t + 725 days	▪ Mars launch and trans-Earth injection
t + 905 days	▪ Earth return and orbital capture. Direct descent option or crew recovery using CEV or equivalent

10. TRAJECTORIES & ENERGY REQUIREMENTS

Low-energy, conjunction-class transfers are specified for both cargo and crewed spacecraft in this architecture. Propulsion systems for unmanned payloads are designed to provide a C3 (specific departure energy, or departure velocity squared) of 15 km2/s2, ensuring that trans-Mars injections can be performed for all minimum-energy launch opportunities. This performance requirement dictates the need for 4 high energy propulsion stages per cargo flight, massing 25 tonnes each (with 22 tonnes propellant).

For crewed vehicles, a higher-energy trajectory with C3 = 25 is assumed. This transfer both significantly reduces flight time (to between 4 and 6 months, depending on the specific opportunity) and also corresponds to an Earth-resonant trajectory with an orbital period of 2 years, thus providing crewed spacecraft the option of free Earth return in the event that landing on Mars is impossible.

Designing for the above trajectories, the total Δv requirements for spacecraft departing low-Earth orbit, including 5% gravity losses, are 4.50 km/s for piloted vehicles and between 3.87 and 4.08 km/s for Earth Return Vehicles. (These values are conservative, as much smaller losses can likely be achieved contingent on specific TMI propulsion characteristics.)

Table 2: *Summary of Major Propulsive Manoeuvres Assumed for Piloted Mars Expeditions*

Maneuver	**Δ*v* (m/s)**
Trans-Mars Injection (cargo, C3 = 15 km^2/s^2)	4080
Trans-Mars Injection (piloted, C3 = 25 km^2/s^2)	4522
Earth-Mars Midcourse Correction	100
Post-Aerocapture Maneuvers	100
Descent and Landing	550
Mars Ascent and Orbit Insertion/Rendezvous	5340
Trans-Earth Injection (Depart from 250 x 33,000 km HEMO, C3 = 16 km^2/s^2)	1740
Mars-Earth Mid-Course Correction	100
Deterministic Maneuvers (each way)	50

Plane changes, mid-course corrections, post-aerocapture maneuvers and landing are accomplished using spacecraft reaction control systems. The velocity change values used for spacecraft and propulsion sizing are summarized in Table 1.

11. PROPULSION AND SPACECRAFT DESIGN

Propulsion Stage Design

Dividing spacecraft propulsion into stages allows a vehicle to discard otherwise parasitic mass incrementally. Specific to the focus mission, staged trans-Mars injections are used to further enhance propulsion performance by restricting engine operation to short intervals deep in Earth's gravity well, allowing spacecraft to draw greater kinetic energy from each successive burn. Energy is also saved by circumventing the need to accelerate a single heavy upper stage through the entire TMI maneuver.

High performance hydrogen/oxygen stages are baselined for all TMI propulsion in this mission design: The most efficient propellant in use today, current engines burning H_2/O_2 can yield vacuum specific impulses between 440 and 465 seconds. The individual stages assumed in this architecture have dry masses of 3 tonnes (2 tonnes structural and engines, 1 tonne reserved for docking systems and insulation), propellant masses of 22 tonnes, 220 kN total thrust and Isp = 465 seconds (i.e. 2 Pratt and Whitney RL-10B-2 engines).

Hydrogen/oxygen bipropellants are very cryogenic, and will tend to boil off when stored in space for appreciable amounts of time. Fortunately, this effect can be largely mitigated using multi-layer insulation – 50 sheets of MLI (specifically, insulation consisting of aluminized kapton with dacron net separations) can slow the rate of H_2/O_2 propellant loss to roughly 1% of the total mass per month [2]. While options may exist for chilling oxygen tanks with hydrogen gas as it boils away to further restrict propellant losses per month, the feasibility of such a system is beyond the scope of this paper, and its use is not assumed.

The performance degradation of multi-stage cryogenic propulsion systems in low-Earth orbit is analyzed in reference [1], and has been shown to not represent a serious issue for performing trans-Mars injection provided that spacecraft are assembled in time periods not exceeding 4 months. The performance of this mission's candidate propulsion system was analyzed assuming that each stage was delivered at an equal interval over a total assembly time of 6 months, with the maximum LEO wait time experienced by the upper-most stage not exceeding 4 months. It is noteworthy that, within these time constraints, a launch delay for a given stage would actually have the effect of increasing its performance, since the delayed stage would spend a reduced amount of time in space prior to use.

Methane/Oxygen Stages

The principal design consideration for focus mission spacecraft is ensuring that all components are compatible with existing launch systems – both MTSV and ERV modules must fit within the payload dimensions and mass limits of candidate medium-lift boosters, and both must be deliverable to orbit with as few launches as possible. The recommended spacecraft in this mission design would have exterior diameters not exceeding 5 metres, and either folding or rigid-conical aeroshields that can be adapted to the payload fairing of candidate launch systems. A common crew cabin for both transfer and return vehicles is assumed in all reference designs, with additional sections dedicated to storage or propulsion systems respectively.

Methane/Oxygen Stages (continued)

With an individual dry mass of 2.5 tonnes, propellant mass of 22.5 tonnes and a specific impulse of 375 seconds, 5 CH_4/O_2 stages would be needed to launch both cargo and piloted spacecraft in the focus mission; if the specific impulse was increased to 400 seconds, then cargo could be launched with only 4 propulsion stages, though this is not assumed.

Since methane/oxygen is the ideal fuel for Earth Return Vehicles, as it can be readily produced on Mars, it may be possible to design common rocket engines for both TMI and ERV propulsion. Even partial commonality between Mars-bound spacecraft and their stages would be extremely beneficial in terms of development costs; the specifics of this, however, are beyond the scope of this paper.

Propellants with lower energy than methane/oxygen – such as kerosene/oxygen or mono-methyl hydrazine/nitrogen tetroxide – can all successfully launch cargo to Mars; for crewed flights however, greater than minimum energy trajectories are desirable, and propellants with lower performance cannot expedite piloted flight times in less than 6 stages. Therefore, the Mars for Less mission restricts TMI propulsion consideration to hydrogen/oxygen and methane/oxygen systems, in the interest of minimizing the number of launches required for vehicle assembly.

Spacecraft Design

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The common habitat for both spacecraft is a predominantly cylindrical, slightly tapered structure with a maximum diameter of 5 metres. The basic reference cabin design is two levels, with additional vehicle-specific units consisting of a storage compartment for the CTV and 2 methane/oxygen propulsion stages for the ERV; habitable sections in this design are connected by a double layered half-cylinder 1.4 metres in diameter running through the centre of the spacecraft. Deck 1 contains a galley, washroom and two sleeping quarters, while deck 2 encloses a laboratory, exercise sections, and 2 additional sleeping quarters, as well as command systems and the primary cabin airlock. This design has three central access points per deck: swinging hatches open into common areas, and sliding doors on the flat section of the hub would permit access to individual crew quarters. The curved portion of the hub would be filled with water, and this combined with absorbent polyethylene doors would serve as a protective shelter from radiation in the event of a solar particle event. Sleeping quarters are small but functional, permitting each astronaut approximately 3.8 square metres of floor space and 2.5 metres of overhead (Figure 5).

Spacecraft Design

oth spacecraft would be optimized primarily for vertical takeoff, flight and landing. With only one major load path, structural reinforcement can be restricted to one principal axis, thus sparing otherwise significant mass penalties. Mars Orbital Capture (MOC) and atmospheric entry profiles would be ballistic in nature to minimize the amount of thermal protection required; while spacecraft such as the shuttle fly on lifting trajectories rather than ballistic, such profiles actually maximize the surface area subjected to heating as well as exposure time. The failure of the shuttle Columbia unfortunately serves to illustrate this point – the less ballistic the trajectory, the longer the spacecraft is exposed to thermal stressors, which increase failure potential for heat shields and protection systems.

CH_4/O_2 reaction control systems with a steady-state specific impulse of 380 seconds are assumed for both spacecraft. RCS rockets would control spacecraft attitude during orbital assembly, and additional fuel modules that fit within the excess LEO capacity of early launches would be delivered to supplement propellant expended during assembly. For both spacecraft, these thrusters would perform the assumed 100 m/s mid-course correction required in transit, and would aid with orbit and descent manoeuvres at Mars. For the MTSV, this system would be further capable of delivering the spacecraft to the Martian surface without the aid of parachutes, as well as returning the spacecraft from a stranded position between Earth-escape and minimum-energy trans-Mars injection in the event of TMI failure. Post-abort manoeuvring performance in the latter scenario could further be increased by jettisoning the spacecraft's cargo module and aeroshield prior to any retro engine burn.

Mars Transfer and Surface Vehicle (MTSV)

Earth Return Vehicle (ERV)

Figure 5: *Common Habitat Element*

Assembling the Spacecraft

Each spacecraft in the Mars for Less mission would require two launches to place in low-Earth orbit. For the Earth Return Vehicle, launch 1 would deliver the upper TEI propulsion stage, ERV cabin, propellant plant and hydrogen feedstock, a total mass of 24.8 tonnes. The second launch would contain the lower TEI stage, nuclear reactor, aeroshield and lander, also massing 24.8 tonnes for a combined mass of 49.6 tonnes. The first MTSV launch would carry a 24.2 tonne habitat module and its supplies, to which the second would mate the storage module, aeroshield and lander for a total of 46 tonnes. Once each vehicle is delivered to orbit, TMI stages would be launched and mated individually, restricted to assembly time periods discussed above. Mass allocations for all Earth-to-orbit payloads are presented in Table 2 by launch.

The target spacecraft assembly orbit is assumed to be 200 km circular; while inclination is tentatively specified as 28.5 degrees, the specific angle will be subject to variation depending on the particular launch system chosen for delivering each component. (For example, the performance of the Ariane 5 is degraded somewhat by launching heavier payload to this orbit, but would still be able to deliver a lighter component such as the MTSV cargo module.) It is noted once more that NASA has been docking spacecraft at comparable altitudes since the 1960s.

Table 3: *Mass Allocations for Mars for Less Mission*

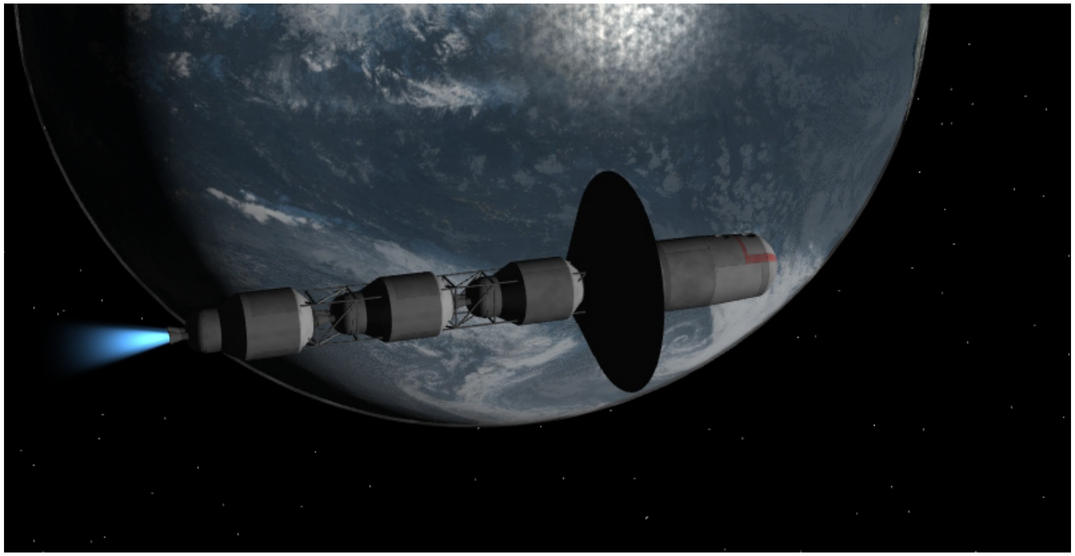
Earth Return Vehicle		Mars Transfer and Surface Vehicle	
Allocation	**Mass (tonnes)**	**Allocation**	**Mass (tonnes)**
Launch 1		*Launch 1*	
Habitat Structure	3.0	Habitat Structure	3.0
Life Support System	1.0	Life Support System	3.0
Consumables	3.4	Consumables	9.0
Power (5 kWe PVA)	1.0	Power (5 kWe PVA)	1.0
Reaction Control System	0.5	Reaction Control System	0.5
RCS Propellant	3.3	RCS Propellant	3.0
Communications and Data	0.1	Communications and Data	0.2
Interior	0.5	Interior	1.0
EVA Suits (4)	0.4	EVA Suits (4)	0.4
Margin	1.5	Biomedical Package	0.2
Heat Shield	1.8	Crew (4)	0.4
Upper Propulsion Stage	1.5	Margin	2.5
Hydrogen Feedstock	6.3	**Launch 1 Total**	24.2
Chemical Plant	0.5	*Launch 2*	
Launch 1 Total	**24.8**	Cargo Module Structure	2.0
Launch 2		Science Equipment and Lab	2.0
RTG (100 kWe)	3.0	Open Rover	0.5
RTG Truck	0.4	Pressurized Rover	2.0
Lower Propulsion Stage	6.0	Margin	1.0
Aeroshield	6.2	Aeroshield	5.8
Lander (fully fuelled)	9.2	Lander (fully fuelled)	8.5
Launch 2 Total	**24.8**	**Launch 2 Total**	21.8
ERV Total	**49.6**	**MTSV Total**	**46.0**

Spinning up to Martian G

Exposure to long periods of zero-gravity such as those inherent to manned Mars missions will inevitably result in detrimental health effects, including but not limited to cardiovascular deconditioning, demineralization of bones, and general muscular atrophy. While these issues are often cited as reasons to postpone manned space exploration beyond LEO in favor of continuing zero-g health research, in 40 years the only means by which many such risks can truly be circumvented is the only one not yet investigated in space: specifically, the generation of simulated gravity via centrifugal force.

Specified here as an optional component of the focus mission, artificial gravity for crewed Mars-bound spacecraft may be generated after TMI by deploying the final burnt-out propulsion stage on a 1500 meter tether, then using it as a counterweight and rotating the crewed vehicle about a centre of gravity 100 meters from the cabin at 2 RPM; this would result in the crew experiencing an approximately Mars-equivalent artificial gravity of 0.38g. While perhaps not sufficient to completely eliminate the adverse physiological effects of non-Earth gravity levels, this technique would nevertheless circumvent the need for what may otherwise prove a difficult acclimatization period for astronauts once on the Martian surface.

While neither the complete dynamics nor physiological effects of such an artificial gravity system have yet been ascertained, it is nevertheless noteworthy that, with the set of hardware specified for the focus mission, flight testing of this system could be achieved with only one 20-tonne launch to low orbit (stripped down crew cabin plus empty upper stage) – a simple and informative test, the costs of which would be “in the noise” of overall mission development. Since all Mars-bound spacecraft in this architecture must be designed to operate in both zero- and Mars equivalent-gravity regardless of whether this option is implemented, flight testing this system is highly recommended, even if not employed in the overall mission architecture.



13. RISK ASSESSMENT DISCUSSION

The principal benefits of the Mars for Less mission design are in its anticipated reduction in development costs: with no need for new launch technology, the resources required to initiate this architecture are already at hand – and thus, the price of beginning manned Mars exploration can be reduced by at least an order of magnitude over prevailing HLLV-based proposals.
However, there nevertheless remain apparent drawbacks which must be addressed. The key disadvantages of this approach surround the need for multiple launches: a need which carries with it the associated risks of multiple delays and multiple failures in both spacecraft assembly and operation. While deeper consideration of these issues permits different interpretations as to their overall significance, it is nevertheless acknowledged that this mission plan represents a generally more complex method of undertaking piloted Mars expeditions than single- or dual-launch approaches which have dominated the majority of relevant analysis to date.

Multiple Launches

In terms of failure probability alone, the need for multiple launches is greatly to the detriment of the focus mission. Assuming a reasonable success rate of 98% for each candidate medium-lift launch system, the probability of losing a component of each Mars-bound payload due to launch failure would be approximately 11% per spacecraft, and about 22% per complete mission.

Yet perhaps the issue of failure in multi-launch mission designs is not, in and of itself, as critical an issue as detractors contend. Indeed, in a political context, dividing mission mass into multiple components and launches may actually be regarded as a great strength: while multiple launches certainly increase the likelihood of losing a component because of launch failure, any such loss would represent only a small percentage of the total mission – and so, with the exception of the booster delivering the crew to orbit (which would only be one out of every 12 launches in the Mars for Less mission design), failure in any single launch could be offset by delivering a replacement component to orbit; and while a failing launch system may be shut down for investigation, a program that uses not just multiple launches – but also multiple types of launchers – needn't suffer the same fate. Conversely, a program of Mars exploration predicated on the use of a single, dedicated heavy lift booster may find itself indefinitely delayed – or even permanently grounded – as a result of only one failed launch, which is all but certain to happen at some point during the operation of any vehicle. For a program based on deploying entire missions with a single booster, losing that booster would mean losing:

The crew; *The spacecraft;* *The mission; and* *Any chance of flying again in the near future.*

Literally and figuratively, a heavy-lift booster keeps all the mission eggs in one basket; but launch failure in a program using smaller boosters is, in short, less likely to be either mission or program critical – an important level of flexibility for a program of manned Mars exploration to have, and something that heavy-lift launch vehicles simply can't offer.

An additional benefit of using a larger number of smaller launch vehicles is the increased viability of undertaking an international mission. The use of existing rockets flying discrete, compartmentalized payloads would permit simplified, more predictable costs per launch, mitigating to some extent the financial uncertainty for potentially interested but reticent nations. Using today's launch vehicles – while cumulatively more risk intensive – avoids the otherwise nebulous development cost of new launch technology, and may thus prove to be a more viable method for undertaking an internationally cooperative mission.

Launch Vehicle Availability

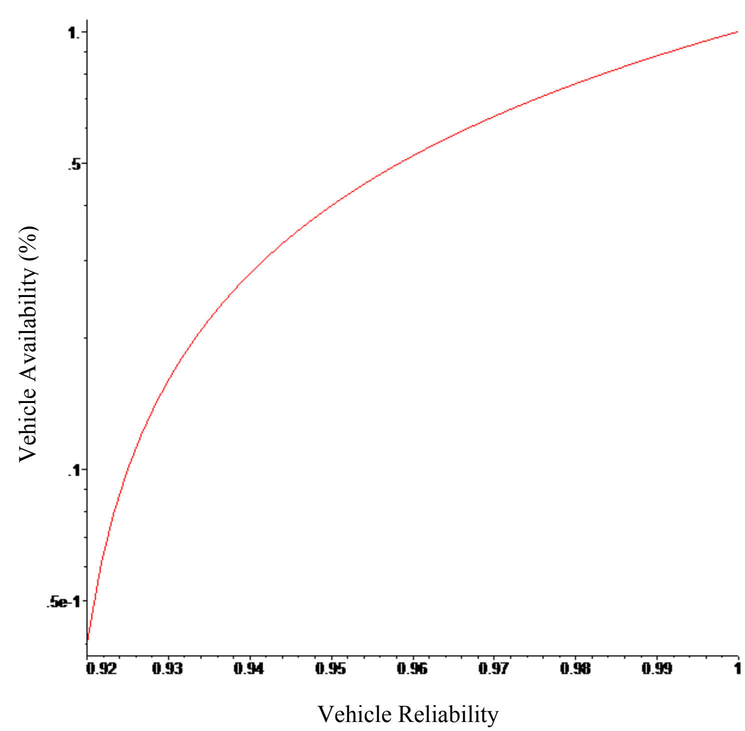
The availability of any given launch system (as a percentage of time throughout a year) can be estimated from its predicted reliability; production capacity; the ability of the launch operations system to support the desired launch rate; existing launch commitments; and its demonstrated stand-down time following failure. The relationship:

$$A = 1 - L\left(\frac{(1-R)t_d}{1-\frac{1}{S}}\right)$$

Can be used to estimate the expected launch availability (A) based on the vehicle's reliability R, nominal launch rate L (which, for the Mars for Less mission would be 6 per year), the estimated or demonstrated stand-down time td following launch failure, and the surge rate capacity S, representing the ability of a given launch vehicle to achieve a higher flight rate than planned [5]. For the Mars for Less mission design, we can plot A as a function of R; letting S=1.33 (i.e. a vehicle which can handle 8 launches per year, or 2 more than planned) and td = 0.5 years (estimated), we can generate the curve shown in Figure 3.)

While it is important to exercise caution with this method of analysis (the availability equation encounters a singularity for surge rates approaching 0), it nevertheless allows us to narrow the field of potential launch vehicles. For example, for a launch vehicle with a reliability of approximately 98% as discussed in Section 6.1, we can expect it to be available for approximately 77% of the time, suggesting that we would want to have at least two individual systems to launch candidate payloads.

Figure 3: *Launch Vehicle Availability as a Function of Reliability*



Propulsion Stage Failure

The issue of TMI stage failure is in a sense more complicated than launch failure, frankly because it is far less decisive. Several different, entirely circumstantial scenarios for backup or abort exist for spacecraft experiencing this variety of malfunction, depending on which particular stage fails and at what point in the overall trans-Mars injection maneuver. While piloted spacecraft in this architecture are designed with the ability for Earth return in the event of stage failure between escape and minimum-energy TMI (from where the mission most likely cannot be recovered), the issue of backup versus abort is less absolute while still in orbit, and requires further analysis.

However, depending on the specific design of each TMI stage, the probability of injection failure would represent a much lesser portion of mission risk than initial launch failure. Assuming each propulsion stage would have a single engine reliability on the order of 99% for required burn durations, the likelihood of TMI failure would be approximately 4% only – and this in turn assumes that the loss of one engine would be sufficient to spoil the entire maneuver. Reference propulsion stages are designed with three parallel-configured engines, 2 outboard and 1 inboard; consequently, 2 of the motors would need to fail (and not just any 2, but the wrong 2, outboard and inboard) per stage to constitute a mission critical, irreparable malfunction. Such 2-engine failure is highly improbable (on the order of 1 chance in 10,000) and is thus considered a negligible component of overall mission risk.

Launch Delays and LEO Wait Time

Delays in this or any other mission design are both inevitable and problematic, particularly when orbital assembly of a cryogenic propulsion system is required. Lengthy delays result in longer wait times in low-Earth orbit, which increase the amount of propellant lost from boil-off and reduce overall performance. Yet it has been shown that, for both spacecraft in this architecture, optimal trans-Mars injections can still be accomplished for propulsion assembly times up to 6 months in duration (which does not even include the time needed for assembling initial, non-cryogenic components).

In fact, closer examination of the impact which launch delays would have on reference propulsion systems shows that, for a fixed interval of time, the net performance available for trans-Mars injection actually increases with launch delays, since less total time is spent by the entire propulsion assembly in LEO. While this assumes a fixed total assembly time, exceeding any such allowance by a substantial margin would introduce the more serious problem of a missed launch window to Mars. Budgeting extra time overall to account for launch and assembly delays is thus recommended, and would not, as shown, be critically detrimental to candidate propulsion systems.

The duration of wait time on orbit also increases the risk of impact from orbital debris; but for time periods of less than 1 year at an altitude below 300 km, the probability of encountering even the smallest particles (~1 mm diameter) is on the order of 0.1% at worst, and decreases exponentially for larger (and thus potentially more dangerous) collisions [4]. While debris impact on orbit is not considered a significant factor in assessing overall mission risk at this stage, such issues would nevertheless require further study with more specific space environment models for candidate spacecraft and assembly orbits.

13. Conclusions and the Next Step

The Mars for Less mission architecture represents an alternative method by which manned Mars missions can be initiated presently by either private or non-U.S. initiatives. By circumventing the need for heavy-lift launch vehicles and dividing mission mass into components that can be placed in orbit with boosters flying today, the cost of developing piloted expeditions can be reduced by an order of magnitude over prevailing design studies – and the task of opening a new planet to humanity can potentially be realized by a larger number of interested parties.

While many arguments have been presented in favor of using medium-lift launch systems instead of heavy-lift ones, it is not the objective of this paper to suggest that heavy-lift launch vehicles are either completely ineffective or unnecessary; however, to a large extent, basing future expeditions to Mars on their use will limit the degree to which entities without comparable launch technology can be involved. For a healthy, cost-sustainable space program to develop, the private sector must play a significant role – and the launch industry must be encouraged to grow. The use of smaller launch vehicles in initial missions is far more likely to promote such growth than a single heavy-lift booster.

Heavy-lift launch vehicles will represent the ideal technology when a demand exists which equals their potential – but such a demand does not yet exist. If the true purpose of President Bush's Vision for Space Exploration is to open the inner solar system to mankind, then undertaking actual missions beyond Earth orbit should be the highest priority. Heavy lift launch technology doesn't currently exist, and its re-development will require several years – years in which no space exploration will occur at all; and with our future in space hinging on the reliability of a single vehicle, the ability of NASA to persevere through setback or tragedy is also called into question.

Launch system redundancy, flexibility, and cost-effectiveness are the real keys to space exploration – especially if such exploration is to last, and the private sector is to play a significant role. For this reason, a mission design using a larger number of more modest, more attainable launch vehicles for human Mars exploration has been made the reference mission design basis for the MarsDrive Consortium.

13. REFERENCES AND CREDIT

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