SMALL VEHICLES FOR A ROBUST MISSION TO MARS

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ABSTRACT

In 2011, a new scenario has been proposed for a human mission to Mars. It is based on the reduction of the crew size to two astronauts per vehicle and the entire duplication of the mission. In 2012, a modification of the scenario has been suggested with the use of several smaller vehicles instead of a big one in order to reduce the risks of the entry descent and landing phase (EDL). The smallness of the vehicle (33 tons maximum according to our calculation) allows the use of rigid 70° cone heat shields, provided that the diameter of the base is 12 meters large. Interestingly, the 33 tons constraint might be met only if the crew is limited to 2 or 3 astronauts. There are many advantages. First, rigid 70° cone heat shields are much simpler and more robust than other EDL technologies. Second, thanks to their smallness, it is possible to send all vehicles to Mars without LEO assembly using a Saturn V class launcher and chemical propulsion. Following these recommendations, several scenarios are proposed and presented. The 2-4-2 scenario is the preferred one because its redundancy allows important backup strategies during the interplanetary transit, in Mars orbit and on the planetary surface. The smallness of the habitat also enables the option of sending it back to Mars orbit at the end of the stay on the surface. This strategy reduces the mass and size of the Earth return vehicle, which can also be sent to Mars using the same class of launcher. Smallness and redundancy might well be the keys for a simple, robust and affordable mission to Mars.

1. INTRODUCTION

This work is a contribution to a study of the International Academy of Astronautics in which the author is involved. Human missions to Mars haven been studied for a long time [8,9,12-15,18-21,24-29]. Despite this large number of proposals, many difficulties remain to be overcome and there is no consensus on the best strategy. Several important options are still debated:

- chemical, nuclear thermal or electric propulsion for interplanetary transit [9]
- LEO assembly of one or several big vehicles, or no LEO assembly at all
- Mars orbit insertion with aerocapture for one or several vehicles
- number of astronauts
- EDL (Entry, Descent and Landing) strategy: rigid/inflatable heat shields, blunt bodies / lifting bodies, etc. [3]
- in situ resource utilization: O2 only, O2 and CH4 with Earth H2, O2 and CH4 with Mars H2O,etc.
- power plants on the Martian surface: nuclear / solar [5]
- backup options: entire duplication of mission, overlap of missions, partial redundancy

In a recent work, it was suggested that small vehicles with small crews could simplify the mission [19,20]. Is smallness a key idea for the design of a manned mission to Mars? Important issues are addressed in this paper. In section 2, the basic requirements for a robust mission to Mars are presented. In section 3, problems linked with the EDL phase are addressed and some recommendations are given. The needs for an assembly in LEO are discussed in section 4. Then, based on the recommendations made in the previous sections, several scenarios are proposed and presented in section 5. The preferred one is described with more details in section 6. Finally, a summary of the most important recommendations conclude the paper.

2. ROBUSTNESS REQUIREMENTS

A robust mission to Mars should minimize the complexity and risks of the mission and at the same time provide numerous backup strategies to come up with the eventuality of systems failures at every stage of the mission. According to several authors, the main risks are tightly linked to astronautical maneuvers [9,12, 21]:

- Launch from the Earth
- LEO (low Earth orbit) rendezvous
- TMI (Trans-Mars injection)
- Aerocapture or propulsive braking
- EDL (Entry, descent and landing)
- Launch from Mars
- Mars orbit rendezvous
- TEI (Trans-Earth injection)

Several reasons explain these risks. First, propulsion involves gigantic mechanical forces with intense vibrations during several minutes, which may cause damages or systems failures to other systems of the space vehicle. Second, because of their mass, the duplication of the entire propulsion system with tanks and propellant is unpractical. As a consequence, backup strategies are rather limited. For instance, after TMI (Trans-Mars Injection), it is impossible to come back to Earth in a short delay. As it was the case for the Apollo 13 mission, the fastest come back procedure consists in a free return trajectory using the gravitational field of the targeted planet [29]. Unfortunately, astronautical maneuvers are unavoidable. However, there are several solutions to reduce the risks and the complexity associated to these phases:

- The first idea is to reduce the number of things and the overall mass of what has to be sent to Mars. The size and capacity of a launcher are limited by physical constraints. The number of launches is therefore linked to the initial mass that has to be sent to LEO (IMLEO). If there are options to reduce that mass, they have to be considered with high priority.
- The second is to reduce the size of the vehicles. Several small robotic landers have successfully landed on Mars [1,3]. For small vehicles, the technology readiness level (TRL) is high. However, giant space vehicles require the conception and design of multiple giant engines at the limit of what is technologically feasible. The smaller the space vehicle, the simpler the propulsion systems. In addition, EDL constraints suggest that the reduction of the size of the vehicle might also be very important to simplify the complexity and risks of that particular phase (see Section 3).
- The last idea is to increase the efficiency of the propulsion systems (especially the specific impulse) in order to reduce the amount of propellant, which is the first contributor to the IMLEO [24]. However, it should not be forgotten that the TRL of such propulsion systems is rather low and that the complexity of the entire mission might be impacted. For instance, if a nuclear power plant has to be used, it might have to be sent to a higher orbit before start, it might require large radiators that would make an aerocapture maneuver more complicated and it might also require additional radiation shielding to protect the astronauts.

The robustness of a scenario can also be evaluated according to the number and the quality of backup solutions. A simple solution is to duplicate the entire mission and to enable rendezvous in deep space or on the surface of Mars for a possible transshipment of the crew in the safe vehicle. Another solution is to provide safe havens with other elements of the mission. For instance, the Earth reentry capsule can play the role of a safe haven if the main module of the habitat becomes unsafe; going back to Mars orbit and joining the Earth return vehicle can also be a backup solution if the surface habitat becomes unsafe. Eventually, if the second manned mission to Mars overlaps with the first one, some assets of the second mission can be used as backup assets for the first one.

3. ENTRY, DESCENT AND LANDING

As already explained in previous papers, the size, shape and mass of the landing vehicle have important impacts on the complexity of the EDL technologies and procedures [1,3,6,7,17]. Fundamentally, the ballistic coefficient is the key parameter. If its value is small enough, the Martian atmosphere provides sufficient drag for a natural braking without the use of any complex technology at least until the velocity has decreased to about Mach one. This is typically the case of all robotic landers that have been sent to Mars up to now. However, for higher values of the ballistic coefficient, it is necessary to make adaptations and to control the descent in a different way. There are basically four options:

- The first is to perform an all propulsive descent. This option is rather simple but the required amount of propellant would have a significant impact on IMLEO and the needs for a LEO assembly, which is not desirable (see next section).
- The second is to add another structural element in order to increase the ballistic coefficient. It could be for instance an inflatable heat shield. That solution could bring a lot of complexity because the constraints are not the same at hypersonic and supersonic velocities, the complementary heat shield would have to be positioned and jettisoned accurately and the control of the attitude could be more difficult [3].
- The third idea is to increase the lift. However, when the lift to drag ratio is high, as it was the case for the NASA space shuttle, the control of the descent is complex because the vehicle has to be continuously and accurately oriented in a specific direction. Furthermore, when the velocity has decreased to about Mach one, the vehicle must be quickly reoriented such that the engines of the propulsion system are correctly positioned below the lander.
- Last but not least, it should not be forgotten that the ballistic coefficient is also proportional to the mass of the vehicle. Therefore, another option is to split the payload in several parts and to land with several smaller vehicles with a lower ballistic coefficient.

The last option might have an important impact on the architecture of the mission, the size of the habitable module, the size of the crew, etc. but it should be clearly investigated in the design of the mission because it could really help a lot in the reduction of the complexity of the mission, the reduction of the needs for research and development of new technologies and their qualification in the Martian environment. According to a previous work, which is based on several technical papers dealing with the sizing of EDL systems, 33 tons at Mars entry could be the limit for the use of vehicles with rigid heat shields and simple biconic shapes, for which the TRL is relatively high [3,6,21]. This recommendation has to be taken into account in the design of any mission to Mars architecture.

4. LEO ASSEMBLY

In the last NASA design reference architecture for a human mission to Mars, the assembly of huge vehicles in LEO has been identified as one of the riskiest phase of the mission [9]. As been experienced with the international space station, numerous delays can be observed for many different reasons. A heavy launcher may have a failure and may require new developments and qualifications and some equipment may have to be changed or adapted. In addition, assembling several modules in LEO is a complex task that usually requires the presence of astronauts, which in turn requires the presence of a habitable module. Moreover, it the operation lasts several years, there is a need to control and periodically reposition all modules on an appropriate orbit by means of a wet propulsion system, which also has to be sent to LEO. The mass of the reboost modules has been estimated to a hundred tons in the NASA reference mission [9]. For all these reasons, an evident recommendation for any realistic mission to Mars is that the assembling of huge vehicles in LEO should be avoided or at least made as simple as possible so that all space operations can be performed in less than a few months with very simple tools and a small number of resources. There probably exists only one strategy to overcome the difficulty. The idea is to divide the payload in several parts and to use small vehicles that can be directly sent to Mars. An important question is the maximum payload that can be directly sent to Mars? Let us make some simplifications and assume the following parameters:

- ΔV = 3.6 km/s from LEO to Mars
- ISP = 450s for the propulsion system (chemical)
- M_u is the payload mass (useful) and M_p is the mass of propellant
- r, the structural mass to propellant mass ratio of the propulsion system, is set to 12%
- Two stages for the TMI propulsion systems (1.8 km/s for each stage)

Tsiolkovski's equation allows us to estimate, in a first order approximation, the mass of the propellant for TMI according to the payload mass:

$$\Delta V = ISP \cdot g \cdot \ln\left(\frac{M_u + (1+r)M_p}{M_u + rM_p}\right) \quad (1)$$

Let $K = e^{\frac{\Delta V}{ISP \cdot g}}$, we get: $M_p = \frac{K-1}{(1+r) - rK} M_u$ (2)

Let us assume that the maximum LEO capability is 130 metric tons (NASA Space Launch Systems specifications) and that there is an increase of 10% for fairing and integration. Then according to our calculations, the maximum payload for a direct TMI maneuver is 46 tons. To conclude this part, the recommendation is to design interplanetary vehicles lighter than this mass.

5. POSSIBLE SCENARIOS

In the previous sections, some important recommendations have been made for the architecture of the mission. The main ones are:

- to reduce the IMLEO as much as possible
- to send small vehicles to Mars (< 46 tons) in order to avoid a long and complex LEO assembly
- to land small vehicles on Mars (< 33 tons at Mars entry)

Several scenarios are presented thereafter to show that it is possible to take them into account and to achieve interesting mission architectures. There are all based on a reduction of the crew to 3 or 4 astronauts, which is assumed to be manageable [4,6,16,19].

- Scenario A: 2-4-2

This scenario has already been described with great details [21]. The idea is to reduce the crew size to only two astronauts per habitable module and to duplicate the entire mission in order to provide numerous backup situations. The total number of vehicles is six but the mission campaign is divided in two parts. Two years in advance, two cargo vehicles are sent to the surface of Mars. Then, two manned vehicles and two Earth return vehicles are sent to Mars.

The manned vehicles land on Mars close to their cargo while the two others wait in Mars orbit. At the end of their stay, the two MAV (Mars ascent vehicles) perform a rendezvous in Mars orbit with their Earth return vehicle, which are finally used for the return to Earth. The strength of this scenario is the availability of another backup vehicle for the interplanetary transits, on the surface of Mars and for the launch from Mars. It also respects the recommendations of using small vehicles that can directly be sent to Mars. All vehicles use aerocapture for Mars orbit insertion and are small enough for standard EDL as it is suggested in section 3. The Mars ascent vehicle is fueled thanks to an in situ propellant production unit (ISPP).

- Scenario B:

In this scenario, there are four vehicles. The first is a cargo with a MAV and an ISPP unit that is sent to the surface of Mars two years prior to the manned vehicle. The second is a manned vehicle with a dual use habitable module for a crew of three astronauts. The habitable module is used during the first interplanetary transit and on the surface of Mars. The two last vehicles have to be assembled in LEO. The first is the wet propulsion system of the Earth return vehicle and the second is the habitable module of the same vehicle. They can be already assembled as a payload of a heavy launcher. However, a second launch is required to send to LEO and assemble that vehicle with the propulsion system required for the trans-Mars injection maneuver. Another option is to send the two vehicles separately and to perform the junction in Mars orbit. This last option might be preferable and not risky for the crew if the junction is performed prior to the launch of the manned vehicle. The feasibility of this scenario remains to be assessed but one way or the other it seems to be manageable.

- Scenario C:

This scenario is similar to scenario B in the number and size of the vehicles. The first vehicle is also a cargo that sends a MAV and an ISPP unit to the surface of Mars. The second vehicle includes the surface habitat. It is unmanned during the interplanetary transit. The third vehicle includes the habitable module that has to be used for both interplanetary transits. Finally, the fourth vehicle brings the propulsion systems of the ERV to Mars orbit. As for scenario B, there is a crew of three astronauts. In Mars orbit, there are two junctions. First, the two parts of the ERV are assembled, propulsion system and interplanetary habitat. Then another junction is needed to transfer the crew from the interplanetary habitat to the surface habitat. After landing, exploration of Mars and fueling of the MAV, the crew comes back to Mars orbit and join the ERV for the return to Earth.

- Scenario D:

Scenario D is similar to scenario C but the interplanetary vehicle is changed into a nuclear thermal rocket. This scenario is also a reduced version of the last NASA reference mission. The reduction of the crew from 6 to 3 astronauts allows important mass savings. The smallness of the habitable module and the reduction of the consumables play an important role but there also are important impacts on the mass of EDL systems, the mass of the ascent vehicle, the mass of the ISPP unit and the mass of the Earth reentry capsule. This scenario is interesting if the mass of the interplanetary vehicle is small enough to avoid one launch and one junction in Mars orbit. An in-depth analysis has to be made to check its feasibility.

- Scenario E:

Scenario E corresponds to the well-known Mars Direct scenario with a reduction of the crew to three astronauts [27]. According to previous calculations, the feasibility of the scenario remains uncertain because of the mass and size of the ERV [19]. However, it would be by far the simplest scenario. If some reductions on the mass of EDL and life support systems can be expected without compromising the safety of the crew, it should be seriously considered.

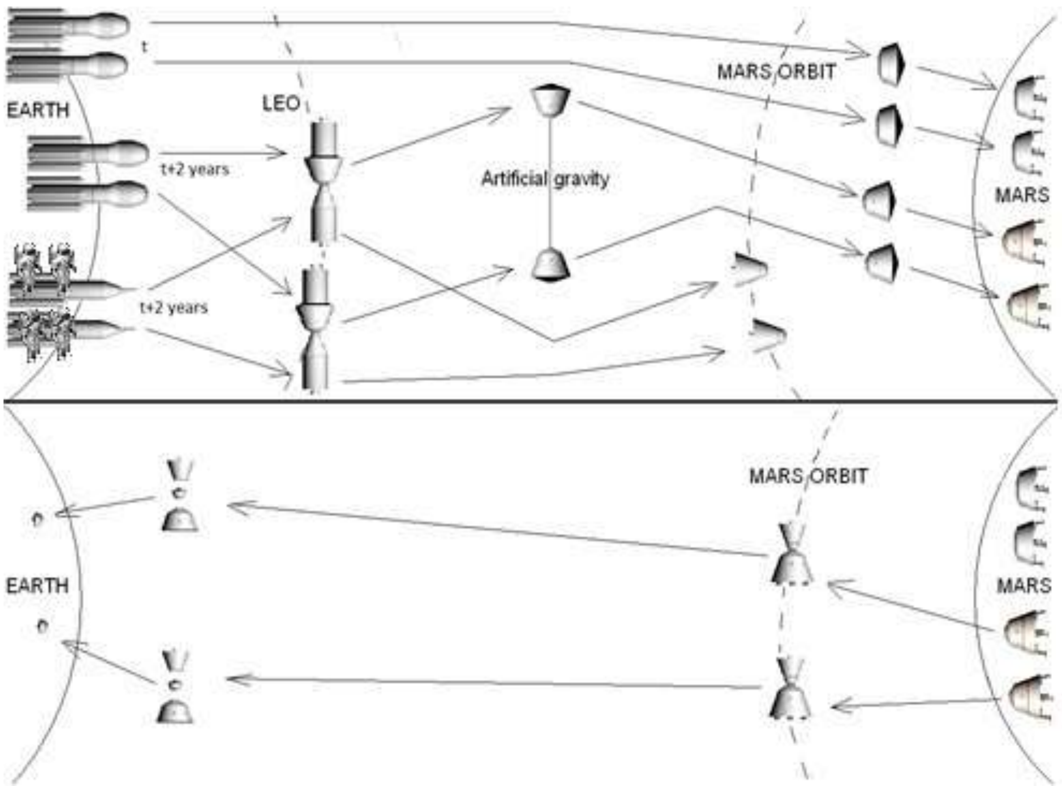

Figure 1: Illustration of the 2-4-2 scenario.

6. PREFERRED SCENARIO

Considering the risks of the mission and especially the availability of backup options, the preferred scenario is the first one. It is indeed the only one that provides simple backup strategies during interplanetary transits and on the surface of Mars. An overlap of two consecutive missions can add numerous backup strategies to the other scenarios. However, it also adds important constraints on the program and on the choice of the landing sites. A synthetic view of the 2-4-2 scenario is presented Figure 1 and the details of the payload for each vehicle are given in Table 1, 2 and 3. The sizing of the habitable modules, EDL and ISRU systems are based on previous studies [3,6,9,21].

Table 1: Earth return vehicle.

Command module	Command module dry mass (Earth re-entry capsule)	4200
	Consumables for the return	3100
Subtotal command module (margin not included)		**7300**
Service module	Propulsion system, engines and tanks (kg)	2900
	Propellant (kg)	24000
	Heat shield for aerocapture (kg)	2000
Subtotal service module		**28900**
Subtotal (kg)		**36200**
Margin 20%		**7240**
Total for TMI, rounded (kg)		**43400**
Transfer in LEO (exchange between the astronauts and the return consumables)		-3100
Launch escape system		1000
Total at launch from Earth (kg)		**41300**

Table 2: Cargo vehicle

Payload	Excavation systems (kg)	3000
	Water extraction systems (kg)	1100
	Sabatier reactor and electrolysis unit (kg)	2810
	Power systems (kg)	3850
	Structure and packaging (kg)	1000
	Backup consumables (kg)	3100
	Science equipment (kg)	600
	Total payload, margin included (kg)	**15460**
EDL systems	Propulsion system, 1.5 MN engines (kg)	1500
	Propellant, 15% of entry mass (kg)	4600
	Structure, tanks and other systems, 10% (kg)	3100
	Heat shield, 12% of entry mass (kg)	3700
	Subtotal (kg)	**12900**
	Margin 20% (kg)	2580
	Total EDL (kg)	**15480**
Total at Mars entry, rounded (kg)		**31000**

Table 3: Habitat lander.

	Subsystem		**Mass estimation (kg)**
Habitat	Life Support System (kg)		3500
	EVA equipment (kg)		200
	Comm/info management (kg)		320
	Power prod. 30 kWe P.V.A. (kg)		1200
	Thermal control system (kg)		400
	Structure (kg)		2000
	Consumables for Mars surface (kg) (3100 kg also in cargo)		3100
	Small rovers (x2) (kg)		380
	EVA consumables (kg)		400
	Subtotal for Mars surface (kg)		**11500**
	Margin 20%		2300
	Total for Mars surface (kg)		**13800**
EDL systems	Propulsion system, engines (kg)		2000
	Propellant, 15% of entry mass (kg)		4500
	Structure, tanks and other systems (kg)		4000
	Heat shield, 12% of entry mass (kg)		3600
	Subtotal (kg)		**14100**
	Margin 20% (kg)		2820
	Total EDL (kg)		**16920**
Total at Mars entry, rounded (kg)			**31000**
LEO		Consumables for outbound	3100
		Total LEO	**34100**
Launch		Transfer in LEO	3100
		Total, rounded (kg)	**37000**

An important problem linked with most Mars mission scenarios is that a launch escape system is required on top of the launcher for safety reasons. Such a system can be associated to a small capsule but not to a heavy habitable module. As a consequence, another manned vehicle is usually needed to send the crew to LEO and make the junction with the interplanetary vehicle. In the 2-4-2 scenario, another strategy is possible. The astronauts are sent to LEO in the Earth return vehicle (ERV) because it includes the re-entry

capsule that can also be used in association with the launch escape system. In LEO, a junction is carried out with the manned interplanetary vehicle for an exchange. The astronauts are transferred in that vehicle for the interplanetary transit while the consumables for the return are stored in the ERV.
Other details of the scenario are presented in a previous paper [21].

7. CONCLUSION

The main conclusion of this study is that it is possible to avoid LEO assembly and to reduce the complexity of EDL systems and procedures, which are two important difficulties of manned missions to Mars. In order to avoid LEO assembly, the recommendation is to design interplanetary vehicles lighter than 46 tons. In order to reduce the complexity of the EDL systems, the recommendation is to design landers lighter than 33 tons at Mars entry. The smallness of the vehicles is therefore an important issue. The 2-4-2 scenario, which is one possible solution among several others, respects these two constraints thanks to the following choices:

- A reduction of the crew to 2 astronauts per vehicle.
- Aerocapture for all vehicles.
- Optimization of ISPP [22].

The final recommendation is to look at the exact requirements of the first human mission to Mars and to determine a sustainable roadmap.

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