

SPACE MISSIONS TO MARS: PAST, PRESENT AND FUTURE

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This paper presents an overview over the history, the current status and the future of Mars exploration missions. After a physical description of Mars and its moons, the first section deals with robotic missions to the red planet. All successful missions are listed, along with most of the failed ones. The names, categories, launch dates and mission purposes are given. Missions presently under preparation are described extensively. The subsequent section gives an overview over generic mission segments and calculates individual and total required velocity increments. Elements of the Mars Pathfinder mission are used as examples where appropriate. The final two sections present the current concept for manned Mars missions and an outlook at the challenges and opportunities linked to human exploration of our neighboring planet.

Introduction

NO other celestial body evokes as many associations as Mars. From its role in ancient mythology to its phantasmal description in “War of the Worlds” [1] to the recent discovery of remainders of organic life (Figure 1), Mars always succeeds in attracting intense public interest. Partly because of that and partly for more objective reasons, Mars is also one of the main targets for scientific exploration of space.

Over the last decades, many probes have entered Mars’ sphere of influence, and many more will during the years to come. Now, investigations are underway for the establishment of a permanent human outpost on our neighboring planet.

The manned exploration of Mars will be an endeavor that – if successful – confirms that the human race can leave its home planet and make its way into the cosmos. Though going to Mars is just a small step compared to the vast distances of space, it will again be a significant one for mankind, because the astronauts will leave Earth behind with a very limited return capability [3].

Thus, since the perils involved in an enterprise like this

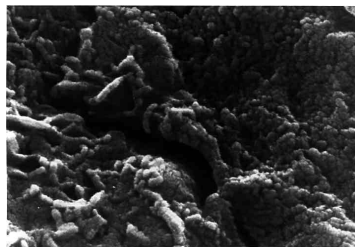


Figure 1: Martian Microfossils [2]

are quite numerous and grave, careful planning is of exceptional importance. Robotic precursor missions are needed to set the stage and deliver information about the target, while implementation and operation of a permanently manned asset in LEO – like the International Space Station – is vital to understand the long-term effects of space on human beings.

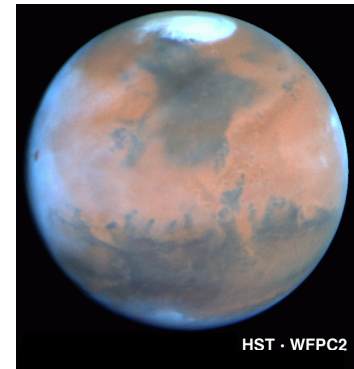


Figure 2: Mars [4]

This paper will present an outline of the steps taken to reach the goal of sending men to Mars. After a brief compilation of facts about Mars and its environment, a description of past and present probe missions is included as an overview of what has already been achieved. To give an impression of the propulsion needs, the subsequent section deals with generic mission segments to be performed by every spacecraft on its way to Mars. Next, manned exploration based on the results of previous robotic efforts is introduced. The final section presents a short outlook into relevant future topics of interest, such as new technologies and commercialization.

Mars

Our neighboring planet (Figure 2) has always attracted special interest. Distinctly reddish in the night sky, and located in the vicinity of the solar path, it is easily recognized even by the occasional stargazer.

Mars' name is the Roman name for the Greek god of war, Αρης (Ares). Due to the planet's blood-red color, it is no surprise that the planet was seen as the herald of destruction and combat.

Physical Description

Mars belongs to the inner planets. A multitude of probes as well as earth-based observations has yielded plenty of data about Mars and its environment. Its diameter is about half that of the earth. Although protected by a thin atmosphere composed mainly of carbon dioxide, its rocky face is covered with impact craters.

The reddish color of Mars is caused by iron oxide dust which covers the underlying rock (Figure 3). Planet-wide dust storms can envelope the surface for months at a time.

Volcanoes also contribute to the shaping of the surface. Amongst them is Olympus Mons, with a height of 25 km, the largest known in the solar system (Figure 4).

Although Mars, due to its tilted axis, knows seasons as the Earth does, earlier hopes of discovering flourishing life were spoiled by the data transmitted by the first planetary probes. As we know today, Mars has no water on its surface, and the chemistry of the covering layers of rocks and dust – in combination with the unfiltered UV radiation – is best described as self-sterilizing.

Table 1 gives an overview of more Mars data.

Moons

Mars has two natural satellites, Deimos ("panic") and Phobos ("fear"); named after two attendants of the Roman god of war, they were discovered in 1877. They are of irregular shape, and only several kilometers each in diameter. Their low density of approximately 2000



Figure 3: Mars Surface [5]

Table 1: Mars Data [6]

Mass (kg)	6.42 * 10 ²³
Equatorial Radius (km)	3397.2
Mean density (kg/m ³)	3940
Escape Velocity (m/sec)	5020
Average distance from Sun (AU)	1.524
Rotation period (length of day in Earth days)	1.026
Revolution period (Length of Year in Earth days)	686.98
Obliquity (tilt of axis in degrees)	25.19
Orbit inclination (degrees)	1.85
Orbit eccentricity (deviation from circular)	0.0934
Maximum surface temperature (K)	293
Minimum surface temperature (K)	130
Visual geometric albedo (reflectivity)	0.15
Highest point on surface	Olympus Mons (about 24 km above surrounding lava plains)
Atmospheric pressure (mbar)	7 to 10
Atmospheric components	CO ₂ : 95.32% N ₂ : 2.7% Ar: 1.6% O ₂ : 0.13% CO: 0.07% H ₂ O: 0.03%
Surface materials	Basaltic rock and altered materials, covered with iron oxide

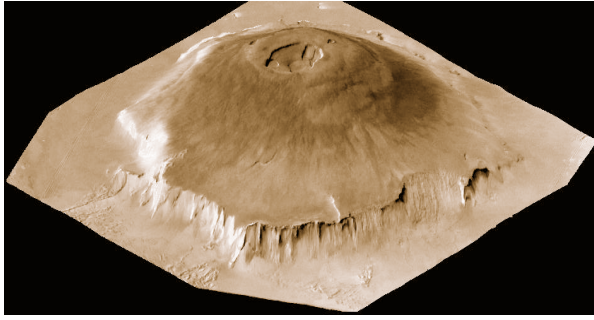


Figure 4: Olympus Mons [7]

kg/m³ suggests that they are trapped asteroids rather than remains of Martian matter. Orbiting Mars at distances of approximately 20000 km and 10000 km, respectively, they may, at a later stage of exploration, provide valuable natural observation platforms.

Exploring Mars

Sending spacecraft to explore distant planets is a challenge of the highest level. To understand the difficulties encountered, one should look at a chronology of Mars missions.

A first examination shows that the initial attempts to study this planet from up close were quite unsuccessful; the missions were doomed by technical failures. But after the first experiences, several spacecraft arrived at Mars over the course of some years, the information gathering of which greatly enhanced our understanding of this planet.

Figure 5 shows the first spacecraft ever to enter Mars' sphere of influence. Mariner 4 was launched on 28 November 1964 and reached Mars on 14 July 1965. Although it was only a flyby, it gave scientists the first close-up look at our neighboring planet.

Following these initial achievements, Mars was left alone for two decades, mainly due to lack of funding. NASA's budget was tied up with the Space Shuttle, and the lack of life on Mars reported by those first probes led to a certain lack of interest in further exploration. Additionally, the analysis of the gathered data had to be completed before the next missions could be suggested.

Two new attempts, in 1988 and 1992, were again foiled by technical failure. It is just recently that two new spacecraft have been scheduled for launch at the end of 1996. They will start off a new sequence of planetary probes aimed at filling the holes left by the pioneering missions, and at preparing the field for the next big step, human exploration.

The following subsections give a more detailed overview over the various missions. All of the successful and most of the failed attempts were included in order to present a complete picture. Stated are the names of the spacecraft or missions, the types, and the launch dates for failed attempts and the arrival date at Mars for successful, as well as a short description.

The First Missions [9]

- ✧ Mars 1960A, B - Mars Probes (October 1960): Failed to reach Earth orbit.
- ✧ Mars 1962A - Mars Flyby (October 1962): Spacecraft failed to leave Earth orbit after the final rocket stage exploded.
- ✧ Mars 1 - Mars Flyby (November 1962): Communications failed en route.
- ✧ Mars 1962B - Mars Lander (November 1962): Failed to leave Earth orbit.
- ✧ Mariner 3 - Mars Flyby (November 1964): Mars flyby attempt; solar panels did not open.
- ✧ Mariner 4 (July 1965), 6 (February 1969), 7 (August 1969): Flybys; measurement of surface and atmospheric temperature, surface molecular composition, and pressure of the atmosphere; in addition, over 400 pictures were taken.
- ✧ Mariner 8 - Mars Flyby (May 1971): Failed to reach Earth orbit.
- ✧ Kosmos 419 - Mars Probe (May 1971): Failed to leave Earth orbit.
- ✧ Mars 2 - Mars Orbiter/Soft Lander (November 1971): The lander crashed-landed; no data was returned and the first human artifact was created on Mars. The orbiter returned data until 1972.



Figure 5: Mariner 4 [8]

- ✧ Mars 3 - Mars Orbiter/Soft Lander (May 1971): First successful landing on Mars; return of surface video data; the orbiter made measurements of surface temperature and atmospheric composition until 1972.
- ✧ Mariner 9 - Mars Orbiter (November 1971): First successful US attempt. Complete mapping of surface; analyzing Martian atmosphere and surface. First close-up photos of moons Phobos and Deimos. Orbited over one year.
- ✧ Mars 5 - Mars Orbiter (July 1973): Imaging data acquisition.
- ✧ Mars 6, 7 - Mars Orbiters/Soft Landers (March 1974): Mars 6 lander failed; Mars 7 missed orbit.
- ✧ Viking 1, 2 - Orbiter / Lander combinations (June / July 1976): Mapping, imagery (Figure 6), biological experiments (search for life), chemical analysis of soil; the Vikings present the most thorough exploration of Mars up-to-date. The on-site analysis performed by the lander combined with the mapping and atmospheric studies done by the orbiter made a major contribution to our present knowledge of the Red Planet.

Recent Efforts [11]

- ✧ Phobos 1, 2 - Mars Orbiter/Lander (July 1988): Sent to additionally investigate moon Phobos. Phobos 1 lost en-route due to command error, Phobos 2 failed on Phobos approach.
- ✧ Mars Observer - Orbiter (September 1992): Communication lost on Mars orbit insertion.

On the Launchpad

- ✧ Mars Global Surveyor - Orbiter (November 1996): Replacement for Mars Observer; will return high resolution imaging of the surface, will support studies of the topography and gravity, the role of water

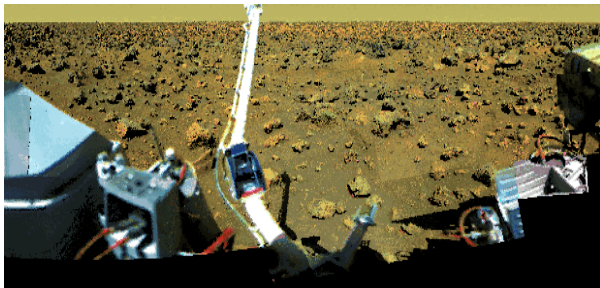


Figure 6: View of Mars from Viking Lander [10]

and dust on the surface and in the atmosphere of Mars, the weather and climate of Mars, the composition of the surface and atmosphere, and the existence and evolution of the Martian magnetic field [12].

- ✧ Mars 96 - Orbiter and four landers (two soft landers and two surface penetrators) (November 1996): Study the evolution of Mars, with special emphasis on studying the atmosphere, surface and interior. Create a high-resolution map of the surface and conduct measurements that will identify mineral deposits, surface composition, and crust structure. Measure seismic activity, magnetic fields, and heat flow while searching for active volcanoes [13].
- ✧ Mars Pathfinder - Lander & surface rover (December 1996): The primary objective is to demonstrate the feasibility of low-cost landings on and exploration of the Martian surface. The scientific objectives include atmospheric entry science, long-range and close-up surface imaging [14].

Planned Probes

More probe missions to Mars are being planned which will result in better comprehension of Mars' environment today as well as an understanding of its evolution in the past. Even sample-return missions are scheduled, to provide Earth-based scientists with specimens for definitive analysis. Such missions may even result in the discovery of new ways to produce propellants on Mars from in-situ resources and to reduce the amount of fuel for the return flight that has to be "imported" from Earth [15].

Each mission will improve our insight into the Martian atmosphere and surface. By means of orbiters and an array of landers, even using surface rovers, penetrators and drifting balloons, they will fulfill the scientific objectives identified in the Space Exploration Initiative [16]: to accomplish global characterization of Mars. Even more important is the fact that they will contribute toward the selection of landing sites and help to prove the technology being employed when men start making trips to Mars.

Examples of these new probes include:

- ✧ Planet B (1998): Will be the first Japanese spacecraft to reach another planet [17].
- ✧ Mars Surveyor Orbiter (1998) and Lander (1999): Will be studying the planet from a polar orbit, with emphasis on the south polar region [18].

- ✧ Mars Surveyor 2001 (2001): Mars Probe; part of NASA's effort to launch a probe every time Mars and Earth are in a favorable position (every 26 months).
- ✧ Mars Surveyor 2003 (2003): Mars Probe.
- ✧ Mars Surveyor 2005 (2005): Will for the first time return soil samples from another planet, for analysis on Earth [19].

Common Mission Segments

A major concern with every space mission is the needed amount of propellant. As this is highly dependent on the actual spacecraft mass, the total required velocity increment Δv is used when determining generic mission requirements. This is calculated by adding the Δv 's of the individual mission segments which can be calculated using rather straightforward equations.

In this section, the total Δv is calculated for a return trip to Mars. These calculations are useful for all kinds of missions to Mars, from simple flyby to manned expedition. The Pathfinder mission [20] is used as an example to illustrate some of the concepts employed. In all cases, elliptical Hohmann trajectories are assumed. Where appropriate, Oberth transfers are calculated additionally.

The following astronomical parameters are used in the trajectory calculations in this section [21]:

Body	Radius r [m]	Mass M [kg]	Distance From Sun R [m]
Sun	$695 \cdot 10^6$	$1989 \cdot 10^{30}$	–
Earth	$6378 \cdot 10^3$	$5976 \cdot 10^{24}$	$149.6 \cdot 10^9$
Mars	$3397 \cdot 10^3$	$6.422 \cdot 10^{23}$	$227.9 \cdot 10^9$

In the equations below, G represents the gravitational constant defined as [22]:

$$G = 6.6732 \cdot 10^{-11} \frac{\text{m}^3}{\text{kg s}^2}$$

The mission itself is divided into the following sub-tasks which will be treated below:

- ✧ Launch and Earth escape
- ✧ Interplanetary Segment

- ✧ Entering Mars orbit
- ✧ Mars landing
- ✧ Mars surface transport
- ✧ Mars Ascent and escape
- ✧ Return to Earth

Launch and Escape from Earth

To inject an object into an Earth orbit of arbitrary height $h = 500$ km, two impulses are required:

$$\Delta v_1 = \sqrt{GM_E \left(\frac{2}{r_E} - \frac{1}{a_1} \right)} = 8053 \frac{\text{m}}{\text{s}}$$

$$\begin{aligned} \Delta v_2 &= \sqrt{\frac{GM_E}{r_E + h}} - \sqrt{GM_E \left(\frac{2}{r_E + h} - \frac{1}{a_1} \right)} \\ &= 145 \frac{\text{m}}{\text{s}} \end{aligned}$$

with the major semi-axis of the transfer ellipse as:

$$a_1 = \frac{2r_E + h}{2} = 6628 \text{ km}$$

Note that in case of an eastward equatorial launch, Δv_1 is reduced by the rotational velocity of the Earth at the equator:

$$\Delta v_1^* = \Delta v_1 - 464 \frac{\text{m}}{\text{s}}$$

To escape from LEO, the following velocity increment is required:

$$\Delta v_3 = (\sqrt{2} - 1) \sqrt{\frac{GM_E}{r_E + h}} = 3153 \frac{\text{m}}{\text{s}}$$

The total velocity increment needed to escape from Earth is thus:

$$\Delta v_4 = \Delta v_1 + \Delta v_2 + \Delta v_3 = 11351 \frac{\text{m}}{\text{s}}$$

Interplanetary Segment

To inject a spacecraft into a transfer orbit once it has escaped the influence of Earth's gravitational field, the required Δv is:

$$\begin{aligned}\Delta v_5 &= \sqrt{GM_S \left(\frac{2}{R_E} - \frac{1}{a_2} \right)} - \sqrt{\frac{GM_S}{R_E}} \\ &= 2944 \frac{\text{m}}{\text{s}}\end{aligned}$$

with the major semi-axis of the transfer ellipse as:

$$a_2 = \frac{R_E + R_M}{2} = 188.77 \cdot 10^6 \text{ km}$$

To save total impulse, the injection into transfer orbit can be combined with the escape from the Earth by using only one impulse for both (Oberth injection). The required Δv for this is:

$$\Delta v_6 = \sqrt{(\Delta v_4)^2 + (\Delta v_5)^2} = 11727 \frac{\text{m}}{\text{s}}$$

After injection into the transfer orbit to Mars, only trajectory control maneuvers are usually executed. Figure 7 shows a plot of the Pathfinder probe trajectory as an example.

Note that different trajectories are possible by trading off required transfer time versus required Δv . The elliptical Hohmann transfers used for all calculations are most time-consuming, but also most efficient.

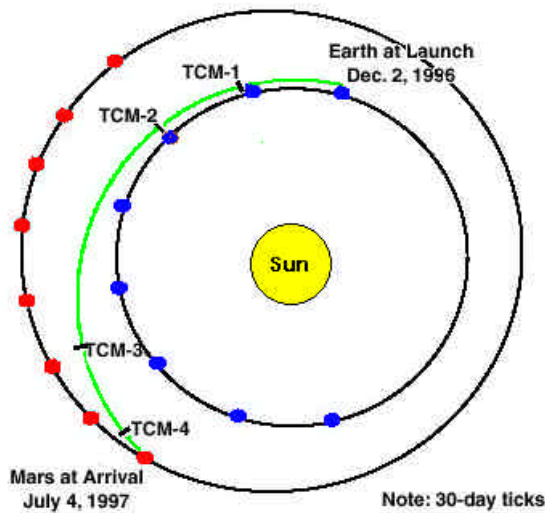


Figure 7: Pathfinder Trajectory [23]

To put the spacecraft from its transfer ellipse into Mars' circular trajectory around the sun, an additional velocity increment is necessary:

$$\begin{aligned}\Delta v_7 &= \sqrt{\frac{GM_S}{R_M}} - \sqrt{GM_S \left(\frac{2}{R_M} - \frac{1}{a_2} \right)} \\ &= 2648 \frac{\text{m}}{\text{s}}\end{aligned}$$

Entering Mars Orbit

The use of planetary atmospheres as a spacecraft deceleration mechanism has passed its trial of fire when the Magellan spacecraft aerobraked into a low circular orbit about Venus. As a fuel-efficient technique, aerobraking will be used to help circularizing the orbit of the Mars Global Surveyor mission at Mars in 1996 [24].

Nevertheless, to present an upper limit for the required Δv , the following equation assumes no aerobassist effects when the spacecraft is decelerated from escape velocity to enter into an arbitrary orbit of 1000 km above Mars' surface:

$$\Delta v_8 = (\sqrt{2} - 1) \sqrt{\frac{GM_M}{r_M + 1000 \text{ km}}} = 1293 \frac{\text{m}}{\text{s}}$$

Soft Landing

To give an impression of the maximum required Δv for landing on Mars, we also perform the following calculations assuming no aerodynamic assistance. The Δv for decelerating from the circular orbit given above into an elliptical transfer orbit with perigee on the Martian surface is:

$$\begin{aligned}\Delta v_9 &= \sqrt{\frac{GM_M}{r_M + 1000 \text{ km}}} - \\ &\quad - \sqrt{GM_M \left(\frac{2}{r_M + 1000 \text{ km}} - \frac{1}{a_3} \right)} \\ &= 207 \frac{\text{m}}{\text{s}}\end{aligned}$$

with the major semi-axis of the transfer ellipse as:

$$a_3 = \frac{2r_M + 1000 \text{ km}}{2} = 3897 \text{ km}$$

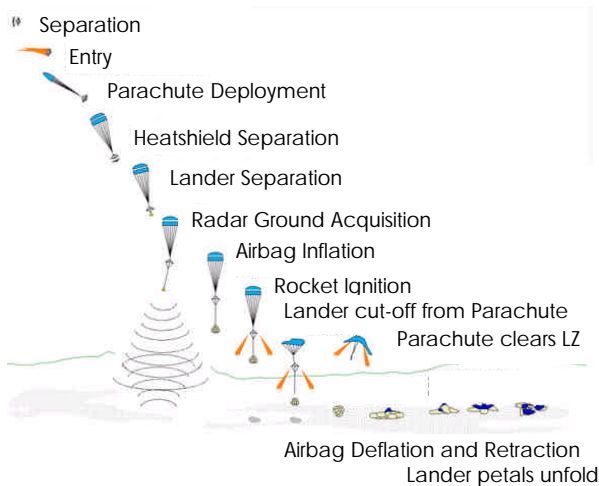


Figure 8: Pathfinder Landing Sequence [26]

Finally, the spacecraft has to lose all remaining velocity at perigee in order to come to a soft landing on the surface*:

$$\Delta v_{10} = \sqrt{GM_M \left(\frac{2}{r_M} - \frac{1}{a_3} \right)} = 3772 \frac{\text{m}}{\text{s}}$$

The total Δv needed to land on Mars from a solar orbit is:

$$\Delta v_{11} = \Delta v_8 + \Delta v_9 + \Delta v_{10} = 5272 \frac{\text{m}}{\text{s}}$$

Again, using the Oberth maneuver to leave the transfer orbit and land on Mars' surface in the same turn, we can reduce the required Δv to:

$$\Delta v_{12} = \sqrt{(\Delta v_7)^2 + (\Delta v_{11})^2} = 5900 \frac{\text{m}}{\text{s}}$$

The Pathfinder mission serves as an example for re-entry using atmospheric aids [25]. Figure 7 depicts the phases of the lander's reentry. After separation of the lander from the orbiter, it enters the Martian atmosphere behind a protective shield which slows down the vehicle (peak deceleration of 20 g occurs at 30 km altitude). At about 6-10 km altitude, after a sufficient amount of kinetic energy has been transformed into heat, parachutes deploy, and the shield is jettisoned.

* The rotation of Mars was neglected in this calculation, as its effect depends on the latitude of the landing site.

During descent on the parachute, the lander is lowered about 20 m beneath the parachute assembly. Once the lander has reached an altitude of 50 m above ground, a radar altimeter initiates the firing of three small solid rockets, reducing the vertical component of velocity to near zero. Simultaneously, large six-lobed airbags inflate around each face of the lander. Finally, the lander is cut off from the parachute, and it falls down to the surface while a final thrust of the braking rockets propels the parachute away from the landing zone. The airbags are not vented during landing; they provide energy absorption and protection of the landing craft during impact.

Peak decelerations of 40 g's will be experienced as the lander makes several bounces on the airbags before coming to its final rest. The random nature of these bounces will likely carry the lander to a location uncontaminated by solid rocket exhaust. Deflation of the airbags and the unfolding of the three petal-shaped side panels conclude the landing sequence.

Surface Transport

The scientific value of an expedition is increased many times if the exploration is not limited to the immediate vicinity of the lander.

On board the Pathfinder craft, a low-cost robot vehicle (Figure 9) extends the reach of the investigations beyond the landing site by providing a few days' worth of mobility.

The rover, which has been named "Sojourner", is a 630 mm long six-wheeled vehicle with a ground clearance of 130 mm [28]. The rover is stowed on the lander



Figure 9: Pathfinder Rover [27]

during flight; it will be controlled by an Earth-based “driver” based on images from rover and lander cameras. Communications with the rover are relayed through the lander. As the time delay between Earth and Mars can be up to 41 minutes, semi-autonomous control is required.

The vehicle’s energy sources are designed to support a minimum seven-day mission using either solar power from its own solar arrays or battery power provided from its internal primary (non-rechargeable) battery.

Ascent and Mars Escape

Leaving the surface of Mars and entering a low orbit takes the same nominal Δv as needed for a landing without use of any aerodynamic techniques. Nevertheless, the return vehicle will almost certainly be much smaller and thus more lightweight than the original lander, which reduces propellant mass. This concept has been successfully employed with the Moon return vehicle, consisting only of the upper portion of the Lunar Module [29].

Leaving the orbit and escaping Mars also requires the same velocity increment. Thus, the necessary overall Δv to go from Mars’ surface into a solar orbit is again:

Table 3

Segment	Symbol	Δv [m/s]
Injection to Mars	Δv_6	11727
Mars landing	Δv_{12}	5900
Injection to Earth	Δv_{15}	5900
Earth landing	–	0
TOTAL		23527

$$\Delta v_{13} = \Delta v_{11} = 5272 \frac{\text{m}}{\text{s}}$$

Back to Earth

For the injection from Mars’ orbit around the sun into a trajectory that leads back to Earth, the necessary velocity increment is the same as on the outbound flight:

$$\Delta v_{14} = \Delta v_7 = 2648 \frac{\text{m}}{\text{s}}$$

Again, Mars escape and interplanetary transfer orbit injection can be combined using Oberth’s approach:

$$\Delta v_{15} = \sqrt{(\Delta v_{13})^2 + (\Delta v_{14})^2} = 5900 \frac{\text{m}}{\text{s}}$$

For Earth capture and reentry, aerobraking will definitely be used, as the concept has been proven by the Apollo missions. Thus, no additional Δv is necessary.

Total Mission Δv

For a return mission to Mars, Table 2 compiles the results of the individual calculations above and adds the total required Δv : 30135 m/s. This assumes pure Hohmann maneuvers, no aerobraking on Mars and full use of aerobraking on Earth return.

Using the optimal Oberth maneuvers, the total required velocity is calculated in Table 3 as 23527 m/s. The use of Oberth maneuvers thus results in a savings of 22% compared to standard Hohmann transfers, which allows significant fuel savings.

Table 2

Segment	Symbol	Δv [m/s]
Earth to LEO 500 km	$\Delta v_1 + \Delta v_2$	8198
Escape from LEO	Δv_3	3153
Transfer injection	Δv_5	2944
Mars injection	Δv_7	2648
Decelerating into 1000 km Mars Orbit	Δv_8	1293
Landing on Mars	$\Delta v_9 + \Delta v_{10}$	3979
Mars Escape	Δv_{13}	5272
Transfer injection	Δv_{14}	2648
Earth landing	–	0
TOTAL		!Syntaxfehler,)

Sending Men to Mars

Motivation

In 1988, President Reagan declared that the goal of US national space policy was, ‘to expand human presence and activity beyond Earth orbit into the Solar System’ [30]. The current efforts of planetary exploration, especially the drive towards Mars, are clearly based on that vision. What are the reasons behind such a long-term perspective regarding the use of space assets?

On the one hand, manned space effort is tied to the belief that, “new lands create new opportunities” [31]. In history, discovery and exploration of new territories and subsequent migration have been stimulated by a diversity of factors, from exhaustion of resources “back home” to the search for economic freedom and opportunity. Also, there have always been people who were adventurous enough to make a newly-found territory their home. Most of these settlements have eventually become self-sufficient, and have enlarged the genetic, cultural and economic diversity of humanity. Settlement of the planets can once again enlarge the sphere of human action and life.

On the other hand, establishing a base on Mars can be supported even without permanent colonization in mind. It is the nature of the human mind to strive for more knowledge, to leave behind old limitations, and to go where no-one has gone before. The struggle to meet challenges like setting up an outpost of mankind on a barren planet will provide an enormous boost not only to technology and international cooperation, but also to the human spirit in general, with all its advantageous effects on economy and culture [32].

In addition to the arguments presented above, a study by the Johnson Space Center has shown that manned exploration of Mars is also technically feasible within the near future, and that such an effort could be, to a large extent, self sufficient within ten years [33].

Special Problems

The most radical difference between this and all previous manned endeavors is that once committed to a journey to Mars, astronauts will not be able to return until the alignment of the planets in combination with the capacity of their spaceship’s propulsion system allows it [34]. Unlike during a trip to LEO or even to the Moon, there is a very narrow window within which return is feasible. Basically, the commitment to launch is a commitment to several years in space.

The NASA Office of Exploration identified five “key prerequisites” [35] needed in order to master the complexity of such a mission:

- ✧ Pathfinder (“cheap and fast”) Technology,
- ✧ Life Sciences Research,
- ✧ Robotic Precursor Missions,
- ✧ Earth-to-Orbit Transportation,
- ✧ and a space station.

A exemplary look at Life Sciences as one of the items mentioned shows the complexity of related topics. The area includes

- ✧ radiation protection,
- ✧ medical care for extended periods of time,
- ✧ human behavior and performance considerations,
- ✧ life support in space habitats and space vehicles,
- ✧ countermeasures to reduce the influence of micro-gravity,
- ✧ and special problems connected to unavoidable extravehicular activity.

An important challenge is to minimize the biological risk caused by heavy ion impacts resulting from solar activity and the cosmic ray background. The latter, negligible during LEO operations under the protective shield of the Earth’s magnetic field, becomes an important factor when long transit times and open interplanetary space are combined for missions from Earth to Mars. Although the radiation hazard should not be impossible to master [36], it must nevertheless be the subject of thorough investigations during the spacecraft design of a spacecraft for a manned mission.

Medical support is made more difficult by the fact that there is no rapid-return capability from Mars. Even the round-trip time for communications can be as long as 40 minutes, which makes telemedicine worthless in emergencies and for complicated procedures. From today’s point of view, the only way to deal with these issues is a highly autonomous medical care system, including the capability for major surgery [37], operated by a physician on the crew.

Psychology presents another difficult problem. An expected mission duration of more than one year, given the confined space and the constantly impeding perils of space travel, will place the crew in stressful circumstances that have never been encountered before. However, experience on the research bases in Antarctica as

well as operational practice with both MIR and the future International Space Station will offer important insights into human behavior [38].

Proposed Mission Approach

Maybe the most substantial failure in NASA's plan of putting men on the Moon was the lack of commitment towards establishing a permanent base. Thus, once the initial excitement about the first landing faded, the general interest of the population as well as that of the funding political bodies soon abated. The result was a drastic decrease in space funding, and NASA plunged into its worst period of recession. Even much of the corporate knowledge which the agency assembled during the dash for the Moon has disappeared.

To apply the lessons learned, NASA is now focusing its mission planning on establishing a robust surface capability on Mars. Current scenarios outline the mission elements as follows [39]:

- ✧ In the launch window before the manned mission starts, an unmanned cargo vehicle is launched.
- ✧ The cargo vehicle puts its payload onto the Martian surface. The payload includes a nuclear-powered propellant generation facility to produce the return fuel for the manned mission (methane and oxygen) from Martian CO₂ and "imported" hydrogen at a mass ratio of 18 kg of propellant produced for each kg of hydrogen brought from Earth [40]. Additionally, it generates water, oxygen, and buffer gases for life support.
- ✧ Satellites deployed by the cargo vehicle continue to orbit Mars, providing communications relay, gathering physical data and serving as a navigational aid for the soon-to-arrive human explorers.
- ✧ After telemetry indicates that the supplies are in place and enough fuel has been produced, the manned mission is launched on a fast trajectory at the next launch window, 26 months later. Due to the pre-positioning of supplies and fuel, the spaceship can be comparatively small. The fast trip to Mars – 120 to 180 days – ensures a minimized exposure of the crew to deep-space radiation hazards and prolonged microgravity.
- ✧ The manned lander, aided by beacons, touches down next to the cargo vehicle lander. A self-sustaining habitat, designed with commonality with the transfer habitat on the spaceship in mind, provides a base for the manned exploration (Figure 10). The nuclear re-

actor, no longer needed to produce fuel, provides an ample source of energy, backed up with solar generators. A rover, equipped with a pressurized cabin and fueled by some of the produced methane and oxygen, provides long-distance surface mobility.

- ✧ After the crew has finished their exploration and returns home using the fuel generated on-site, the base as well as the orbital assets stay in place, prepared to provide support to the next mission.

As an additional advantage, this new approach requires 30% less delivery of mass to low Earth orbit, and it allows 50% more metric tons of usable exploration payload. It also allows a stay time of 500 days on the surface of Mars, as opposed to 30 days for previous mission concepts [41].

The new approach to human Mars exploration emphasizes surface technologies that will be of long-term use for a permanently manned base. Physical, chemical and bioregenerative life support systems will make important contributions to the direct efficiency of the mission, and will also decrease the cost of subsequent efforts drastically. The single base will then be improved over the following years with the addition of modules similar to the original systems [42].

This new strategy enhances the scientific return by providing a continuous stream of data, improves crew safety by speeding up the space portion of the mission and providing a pre-positioned base if an "Abort to Mars" has to be executed. On top of that, it prepares the ground for a permanently manned human outpost on another planet.

The Shape of Things to Come

Advances in many different fields of space technology may make it easier one day for humans to venture to Mars and establish permanent presence there.

New Propulsion Concepts

Chemical propulsion is the technology of choice for the next decades. It is mature and readily available. But differing concepts offer significant advantages concerning propulsive power.

Nuclear propulsion, for example, would allow for the decrease of transit time to as little as 100 days [43]. Solid-core fusion engines with specific impulses over 700s have already been tested on the ground [44] and are thus available for the design of manned missions.



Figure 10: Manned Mars Base [45]

On the lower end of the power spectrum, solar sails provide a slow but steady mode of transport for ferrying supplies back and forth, with minimal expenses.

Extended Operations

The basic strategy given for manned exploration is very adaptable. If interest and funding allow, the concept of pre-positioning a cargo vehicle, producing the return fuel in-situ and manning the base 26 months later can be applied to different sites of interest. Thus, a network of research outposts would gradually be developed on the Martian surface, each capable of sustaining human occupants and sending them safely back to Earth.

At a later stage, the Martian moons Deimos and Phobos (see page 2) may as well be developed into observation and relay bases, as they orbit the planet in 30

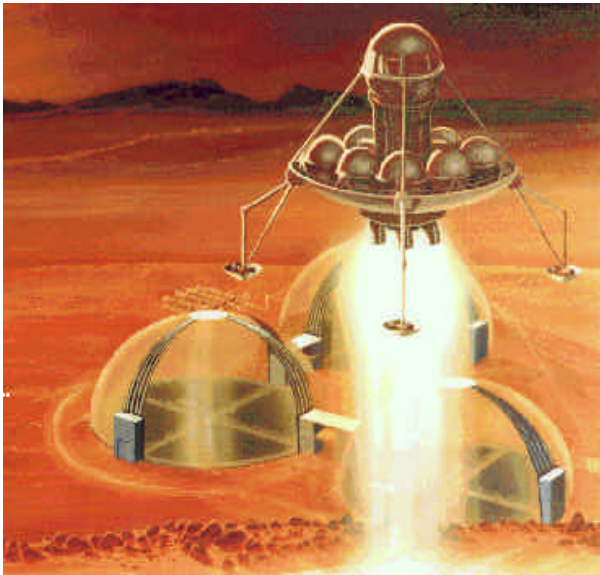


Figure 11: Advanced Base [46]

and 7.5 hours respectively. Their size results in escape velocities of 6 and 10 m/s, respectively, which is high enough for safe manned surface operations and is still low enough to provide all the amenities of microgravity.

Finally, more elaborate surface bases will be erected, providing long-term habitability and increasing independence from support flights (Figure 11). This stage of operations will prepare Mars for the first “colonization-style” missions, securing mankind’s foothold on Mars for generations.

Commercial Exploration and Exploitation

The key to long-term affordability of human presence on Mars - and space in general - is economical usefulness. Although the establishment of an outpost of mankind is in itself of immense cultural and historical value, government-controlled space policy has proven itself to be very dependent on transient moods of politicians and the general public. Thus, after proof-of-concept by government-sponsored expeditions has been achieved, the most ardent support for a human colony on Mars will come from companies who see profitable business opportunities stemming from it.

Once the technology is available on a sufficiently broad basis, many possibilities arise for commercial use of Mars and its environment:

- ✧ Exploitation of Mars minerals,
- ✧ Base for asteroid mining,
- ✧ Communications platform for deep-space probes,
- ✧ Replenishment base for manned space missions,
- ✧ “Safe haven” for documents/technology/knowledge in case of major catastrophe on Earth,
- ✧ Proving ground for self-sufficient technologies,
- ✧ Tourism,
- ✧ ... and many other ideas which will inevitably spring up. Who would have thought that GPS receivers would today be installed on every yacht when Sputnik was launched only three decades ago?

The “commercialization” of Mars exploration and exploitation may seem a little far-fetched. But several years ago, sending satellites into Earth orbit was a major, government-only undertaking which was criticized by many “earth-bound” scientists and politicians as a waste of money and effort. Nowadays, no one could possibly negate the beneficial influence of space efforts on everyday life, such as communications and naviga-

tion satellites, and their operation has become a very profitable business.

If the right decisions for establishing human presence on Mars are made now, the scenarios outlined above may very well represent the shape of things to come.

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