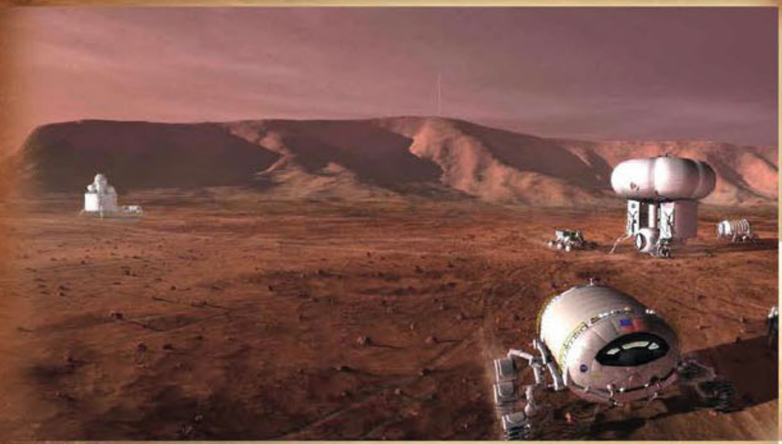
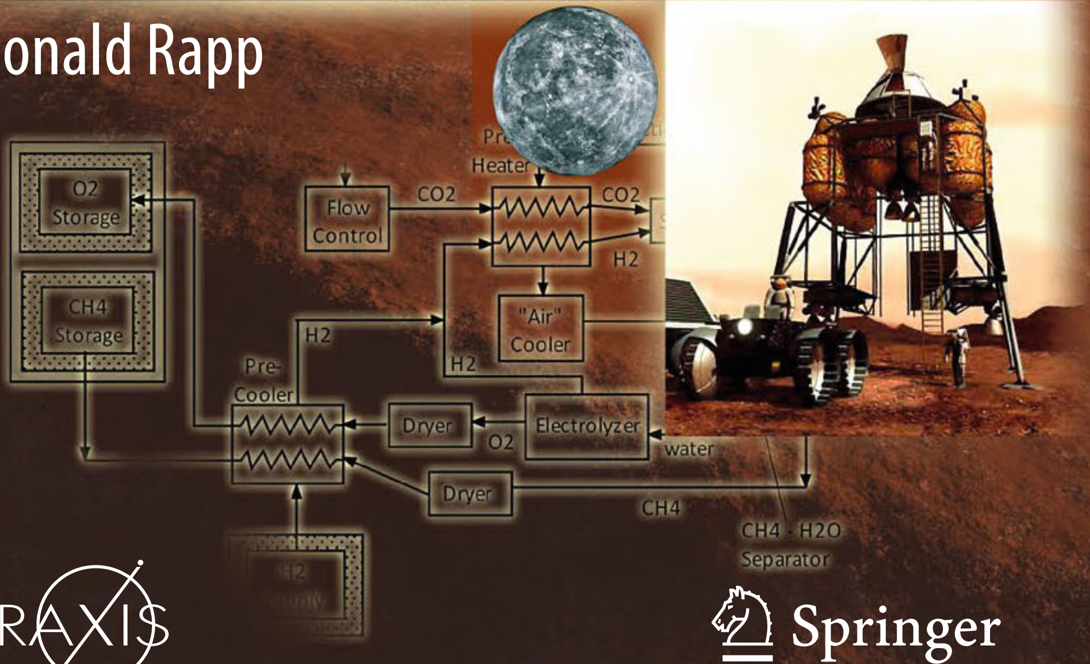
Use of Extraterrestrial Resources for Human Space Missions to Moon or Mars

Second Edition



Donald Rapp



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Preface

Since the earliest expeditions of humans into space, visionaries have contemplated the possibility that extraterrestrial resources could be developed and civilization could eventually move into space. An important early paper (Ash et al. 1978) essentially opened up the realm of ISRU. They proposed that propellants for ascent be produced on Mars. Thus, the term *In Situ Propellant Production* (ISPP) was coined, and this provided a focus for a couple of decades. ISPP on Mars was the most obvious choice for the utilization of extraterrestrial resources because it provided very high leverage and it appeared to be more technically feasible than most other possibilities.

As time went by, visionaries looked beyond the near term and imagined the transfer of the industrial revolution and the electronic revolution to planetary bodies. Metals would be produced and fabricated into objects, concrete building blocks would be assembled into structures, and electronics would be created from indigenous materials. Eventually, ISPP became an obsolete term and it was replaced by *In Situ Resource Utilization* (ISRU) to allow for a wider range of applications than mere propellant production.

Robert Zubrin is a prominent Mars technologist and advocate of Mars exploration and is Founder and President of the Mars Society. His book *Entering Space* provides an impressive road map for humans to settle in space.

Zubrin contemplated finding "fossils of past life on its surface," as well as using "drilling rigs to reach underground water where Martian life may yet persist." He believed that there is great social value in the inspiration resulting from a Mars venture. He also said:

> The most important reason to go to Mars is the doorway it opens to the future. Uniquely among the extraterrestrial bodies of the inner solar system, Mars is endowed with all the resources needed to support not only life, but the development of a technological civilization… In establishing our first foothold on Mars, we will begin humanity's career as a multi-planet species.

Zubrin has support from a good many Mars enthusiasts. (The goal of the *Mars Society* is "to further the goal of the exploration and settlement of the Red Planet.") More than 10 years ago, it was claimed that we could send humans to Mars "in ten years" and begin long-term settlements. Each year, the *International Space Development Conference* hosts a number of futurists who lay out detailed plans for long-term settlements on Mars. The *Mars Society* often describes settlements on Mars as the next step in the history of "colonization" and warns not to make the same mistakes that were made in colonizing on Earth. For example, the Oregon Chapter of the *Mars Society* said:

> When the initial settlements are set up, there will most likely be a few clusters of small settlements. As time goes on, they should spread out. The more spread out the developing townships are, the more likely they will develop their own culture. In the beginning, townships will be dependant [sic] upon each other for shared resources, such as food, water, fuel, and air. Once a more stable infrastructure is set up on Mars, then people should be encouraged to set up more isolated townships. In any area were colonization or expansion has occurred, one important item that cannot be ignored is the law. Some form of law will be needed on Mars. Looking at the system that was used in the old west, we can see that whoever enforces the law can have difficulty completing his job. The 'sheriffs' on Mars must be trustworthy individuals that the majority of people agree on. They should not be selected by the current form of politically interested members of society; this only encourages corruption. Instead, some sort of lottery system of volunteers should be allowed. As for the law itself, it should be set in place to guarantee all of the basic rights of everyone, from speech to privacy.

While these zealots are already concerned with establishing law and order on Mars, and spend time laying out townships for the Mars surface, this humble writer is merely concerned with getting there and back safely and affordably.

ISRU visionaries know no bounds. Imaginative proposals abound for all sorts of futuristic systems. One example is a sort of Zamboni vehicle that rolls along the surface of the Moon or Mars, imbibing silica-rich regolith, processing it into silicon in real time, and leaving in its wake a roadway covered by a carpet of silicon solar cells that stretches out for miles behind the Zamboni.

NASA is not a monolithic organization. Imbedded within NASA is a small cadre of ISRU advocates who have urged NASA to support Mars ISRU technology because of the very significant mission benefits. They have sought support from the greater NASA for further development of ISRU, but such support has been intermittent and inconsistent. Since the 1990s, ISRU advocates have developed elaborate plans for the development of ISRU technology but NASA funding has been concentrated into a few relatively expensive demonstrations while technology funding has been limited and intermittent.

Higher NASA management has provided vacillating leadership over the years, with programs and initiatives sometimes starting with great fanfare and ending abruptly without warning.[1] Budgets rise and fall, and continuity from year to year is difficult to achieve. The greater theme of NASA technology has evolved from *unprecedented*, to *world shaking*, to *revolutionary*, to *game changing,* to *disruptive*.[2] The focus of

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[1] This brings to mind the six stages in a NASA project: (1) wild enthusiasm, (2) great expectations, (3) massive disillusionment, (4) search for the guilty, (5) punish the innocent, and (6) promotion for the non-participants.

[2] As a result, the NASA technology programs have often been *disrupted* because the *game has changed* so frequently.

technology has always been on seeking incredible breakthroughs, and therefore, funding to do the engineering necessary to make evolutionary systems practical has not usually been forthcoming. The focus of human exploration has been to occasionally fund a Mars demonstration project. Visionaries tend to look beyond the best near-term prospects. In this environment, at each juncture when a new technology opportunity arises, the tendency is for NASA ISRU managers to ask NASA HQ for far more funding than can reasonably be expected, and hope to get some fraction of what was asked for. Inevitably, the long-range plan is so over-bloated with ambitions that the divergence between actuality and the plan becomes embarrassing. In 2005, when the NASA *Vision for Space Exploration* was announced, the ISRU enthusiasts wrote plans for extensive robotic and human precursors to validate ISRU on the Moon and Mars, none of which were ever funded, nor was there any serious reason to believe they would be funded. The entire exercise, like most planning activities for ISRU, was basically fiction and fantasy. When the whole NASA enterprise was diverted to lunar mission planning, the small amount of work attributable to Mars ISRU was canceled and new funds were allocated solely for lunar ISRU research.

Unfortunately, lunar ISRU in any form does not seem to make much economic sense to this writer. Furthermore, the technical challenges involved in implementing lunar ISRU are immense. None of the lunar ISRU schemes appear to have a practical financial advantage and it appears to be better, cheaper, and simpler to bring resources from Earth to the Moon—at least in the short run. By comparison, some forms of Mars ISRU have the potential for great logistic and financial benefit for human missions to Mars. Yet funding for Mars ISRU technology has vacillated wildly, and funding for Mars ISRU was essentially zero for the many years while funds poured in for lunar ISRU. This situation was changed remarkably in late 2013 when NASA announced an opportunity to land an ISRU prototype system on the Mars 2020 rover. This program will be reviewed in some detail in this book. Although this new sizable investment represented an important technological advance, it is not clear how this step fits into any presumed long-range, master plan.

In this book, I review the resources available for ISRU on the Moon and Mars, and the technologies that have been proposed for implementation. I also discuss how ISRU would be implemented within human mission scenarios, and I compare the missions with and without ISRU as well as can be done considering the limited available data. As one might expect, the most likely possibility for ISRU to become a viable benefit to a human mission is in providing ascent propellants for the return trip to Earth. While this makes good sense on Mars, unfortunately there are great difficulties on the Moon. None of the processes for producing oxygen from lunar regolith appear to be economically viable. The process for retrieving water ice from shaded lunar craters presents great difficulties. Further to add to these impediments, late lunar mission plans from the Griffin era called for use of space storable ascent propellants on the Moon, thus eliminating any demand for oxygen (produced by ISRU) as an ascent propellant. If that were not enough, safety considerations require that the Moon lander retains ascent propellants to allow for "abort to orbit" during descent in case of abnormal conditions. In which case, the lander would carry its own ascent propellants. Yet, NASA has spent millions of dollars over the past several years developing laboratory prototypes of arcane processes that produce oxygen for lunar ISRU that are very unlikely to be used.

Use of ISRU to produce ascent propellants on Mars appears to be viable and cost effective, but there are hurdles to be overcome. It appears certain that oxygen (and probably methane as well) will be used for ascent from Mars. This assures that propellants produced by ISRU on Mars are applicable to missions. There are two potential resources on Mars: CO_2 in the atmosphere and H_2O in the near-surface regolith. Two processes have been proposed for the utilization of only the CO_2 in the atmosphere to produce oxygen. Solid oxide electrolysis has been advanced to a fairly mature state with the implementation of the MOXIE Project. Alternatively, the so-called reverse water gas shift (RWGS) process may be worthwhile. Unfortunately, after funding an initial innovative RWGS breadboard study by Zubrin and co-workers that generated some optimistic results in 1997, NASA turned a cold shoulder on this technology and did not fund it for the next 15 years while they spent millions on impractical schemes for lunar ISRU.

A well-studied, practical Sabatier–Electrolysis process exists for producing CH_4 and O_2 from CO_2 and H_2. The problem for this process on Mars is obtaining hydrogen. Early NASA mission plans hypothesized bringing the hydrogen from Earth, but they seem to have underestimated the technical difficulty in doing this. Even more important is the fact that storing hydrogen on Mars is very difficult. There are indications of widespread deposits of near-surface H_2O on Mars, even in some near-equatorial regions. If this were accessible, it would provide an extensive source of hydrogen. Thus, the main problem for this form of ISRU on Mars is not process development, but rather, prospecting to locate best sources of near-surface H_2O.[3] What is needed is long-range, near-surface observations with a neutron spectrometer in the regions of Mars identified from orbit as endowed with near-surface H_2O. This might involve balloons, airplanes or gliders, network landers, or possibly an orbiter that dips down to low altitudes for brief periods. None of these technologies seem to be high on NASA's priority list.

The most immediate and feasible application of ISRU is to produce ascent propellants on Mars. Crew size determines the amount of ascent propellants needed and thus determines the leverage gained by using ISRU. Thus, crew size is one of the most critical factors in determining the feasibility and cost of a human mission to Mars.

Hence, I have concluded the following:

- None of the lunar ISRU technologies appear to be economically viable.
- The Mars RWGS process might be a viable option, but NASA's non-funding of this technology after an initial somewhat successful study leaves a great deal of uncertainty.

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[3] We use the term H_2O rather than water here because it is not known whether the H_2O exists as water ice or mineral hydration.

- The MOXIE Project is demonstrating the viability and maturity of solid-state electrolysis for producing oxygen from Mars CO_2. Oxygen-only ISRU appears to be eminently practical.
- The Sabatier–Electrolysis process for Mars ISRU is technically and economically viable if a source of hydrogen can be provided. Bringing hydrogen from Earth and storing it on Mars is problematic. Prospecting for near-surface H_2O on Mars requires a costly campaign, yet the payoff is great.
- Depending on the availability of near-surface gypsum deposits at viable landing sites, utilizing near-surface H_2O on Mars might turn out to be the most cost-effective and technically practical way to utilize ISRU to enhance human missions in space.
- Crew size is one of the most critical factors in determining the feasibility and cost of a human mission to Mars. Crew size determines the leverage from using ISRU. The optimum crew size for a human mission to Mars has yet to be determined.

In the longer run, the optimal path for ISRU might possibly be to retrieve water from Near-Earth Objects and store this water in the cislunar region of space. This water would be convertible into hydrogen and oxygen propellants that could be used for departure from LEO and any other space mission transfers. To validate and implement such a scheme will require considerable dedication and up-front funding, neither of which seems to be readily forthcoming.

South Pasadena, USA Donald Rapp

What's New in the Second Edition

1. Human Missions to Mars and Ascent from Mars Surface

In the first edition, I did not include a description of human missions to Mars, but rather, I simply referred to my book "Human Missions to Mars". However, as I show in this book, by far the most important application of *In Situ Resource Utilization* "ISRU" is to produce 30–40 metric tons of propellants for ascent from the Mars surface. To properly understand the value of Mars ISRU, one must see how ISRU fits into the bigger picture of the Mars mission. To that end, I now provide in this second edition a short synopsis of the Mars mission. In addition to that, I now provide for the first time, a detailed description of the process of ascent from Mars based on new NASA publications since the publication of the second edition of my Mars book. This, for the first time, clarifies the requirement for how much ascent propellants are needed. In doing this, I concluded that this critical figure is sensitively dependent on crew size. Therefore, I provided for the first time, a review and analysis of pros and cons for various crew sizes relevant to ISRU.

2. Solid Oxide Electrolysis of CO_2

In the first edition, the only information available was early, relatively trivial experiments on the laboratory bench in the 1990s. However, starting in 2014 (and continuing today) NASA funded a major new development to demonstrate this technology on Mars with a 2020 launch. That project is called "MOXIE". (see: https://mars.nasa.gov/mars2020/mission/instruments/moxie/).

I am a co-investigator on this project, so I have inside access to data and progress. I have included a lengthy section on solid oxide electrolysis that promises to be an important part of the Mars ISRU picture.

3. Ancillary Needs for Mars ISRU

   (a) It is not enough to produce propellants for ascent from Mars. The propellants produced in a chemical plant must be transferred to the Mars Ascent Vehicle and maintained cryogenically. I included a discussion of this based on recent NASA studies.

(b) Power: ISRU systems are power hungry. There has been new research on nuclear versus solar power systems on Mars, and I have summarized this relevant to ISRU.

4. Obtaining Water on Mars

If water can be obtained on Mars (not yet proven), that would have a major impact on the optimum approach for ISRU. I have upgraded this section based on new data and analysis by NASA.

5. Value of ISRU

I have totally revamped and rewritten this section, and I think it is now much more accurate and clear.

6. Recent NASA Plans

This section is new.

7. In addition, I went over every paragraph, sentence, and word and made a large number of minor changes for accuracy and clarity.

Contents

Nomenclature

AC	Ascent capsule
ALS	Advanced life support
ASR	Area specific resistance
CAC	Cryogenic accumulation chamber
COTS	Commercial off-the-shelf
DRA	Design Reference Architecture
DRM	Design Reference Mission
ECLSS	Environmental Control and Life Support System
EDL	Entry, descent, and landing
ERV	Earth return vehicle
ESAS	Exploration Systems Architecture Study
ESM	Equivalent system mass
EVA	Extra vehicle activity
FSP	Fission space power
HEO	Human Exploration and Operations
HEPA	High-efficiency particulate air
IMLEO	Initial mass in low Earth orbit
ISPP	In Situ Propellant Production
ISRU	In Situ Resource Utilization
ISS	International Space Station
JSC	NASA Johnson Space Center
LDRO	Lunar Distant Retrograde Orbit
LEO	Low Earth orbit
LL1	Lunar Lagrange Point #1
LLO	Low lunar orbit
LLT	LL1-to-LEO Tanker
LM	Landed mass
LMA	Lockheed Martin Astronautics
LOX	Liquid oxygen
LSS	Life support system

LWT	Lunar water tanker
MAAC	Mars atmosphere adsorption compressor
MAV	Mars Ascent Vehicle
MIP	Mars ISRU precursor
MMG	Mars mixture gas
MOXIE	Mars oxygen ISRU experiment
MSL	Mars Science Laboratory
NEO	Near-Earth Object
NERVA	Nuclear Engine for Rocket Vehicle Application
NTP	Nuclear thermal propulsion
NTR	Nuclear thermal rocket
RCS	Reaction control system
RESOLVE	Regolith and Environment Science and Oxygen and Lunar Volatile Extraction
RTG	Radioisotope thermoelectric generator
RWGS	Reverse water gas system
S/E	Sabatier/Electrolysis system
SEP	Solar electric propulsion
SH	Surface habitat
SOXE	Solid oxide electrolysis
SS	Space shuttle
ST	Space technology
TMH	Trans-Mars habitat
TMI	Trans-Mars injection
TPS	Thermal protection system
WAVAR	Water vapor adsorption reactor
YSZ	Yttria-stabilized zirconia

List of Figures

List of Tables

Mars ISRU

1

1.1 Human Missions to Mars

1.1.1 Background

Portree (2001) wrote a superb history of mission planning for sending humans to Mars as of year 2000.

According to Portree:

> More than 1000 piloted Mars mission studies were conducted inside and outside NASA between about 1950 and 2000. Many were the product of NASA and industry study teams, while others were the work of committed individuals or private organizations.

Starting with von Braun's vision of the 1950s, many attempts were made to define a feasible human mission to Mars. Development of nuclear thermal propulsion (NTP) began in the 1950s and 1960s. In 1968, Boeing published a fairly detailed design of a human mission to Mars making extensive use of NTP. The Boeing 1968 study set a high bar for extraordinary detail in analysis of the many subsystems and components needed for a human mission to Mars. The lengthy report is replete with detailed tables and illustrations. It is unfortunate that many subsequent studies failed to come close to clearing that bar. Mission concepts continued to appear through the 1970s and 1980s. In the 1990s, NASA produced *Design Reference Missions* DRM-1 and DRM-3 that became the original standard bearers for Mars mission planning. These DRMs introduced ISRU, and continued to rely on NTP. In the same time frame, Zubrin developed the *Mars Direct* concept and a group at Caltech developed the *Mars Society Mission* concept. In 2005, NASA published a summary of an extensive mission study known as DRA-5, but detailed backup for this summary does not seem to be available. In 2014, NASA announced the *Evolvable Mars Campaign* (EMC). However the EMC seems to be based on vague and ephemeral plans, with a lack of detailed engineering calculations. It will likely end up being scrapped

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for good reasons, as NASA moves on to its next long-range plan. After 60+ years of planning, we still don't have a credible plan for a human mission to Mars. Meanwhile, Elon Musk continues to put out nonsensical dreams of Mars "colonization" to a gullible media in his periodic press releases.

Rapp (2015) amplified and updated Portree's history of planning for human missions to Mars. In this chapter, I will not reiterate that entire history, but instead I will proceed to more recent studies with particular emphasis on the role of In Situ *Resource Utilization* (ISRU).

One of the major factors that will determine the cost and logistic feasibility of a human mission to Mars is the number of heavy-lift launches of materiel will be required, as well as the complexity of logistics of on-orbit assembly, if needed. This is characterized in terms of the *Initial Mass in Low Earth Orbit* (IMLEO). Oddly enough, the way to estimate IMLEO begins at the end points of the mission:

1. How much mass must be lifted from the Mars surface to rendezvous in Mars orbit?
2. How much mass must be delivered from LEO to the Mars surface?
3. How much mass must be delivered from LEO to Mars orbit?
4. How much mass must be returned from Mars orbit to Earth orbit?
5. How much mass must be returned from Earth orbit to Earth?

The contribution to IMLEO from each of the above mass transfers is the mass transferred, multiplied by its appropriate "gear ratio". The total IMLEO is a sum of these contributions. A gear ratio is the ratio of the initial mass at the starting point to the final delivered mass for any transfer of payload. For example, if it requires say, 4 initial mass units to transfer one mass unit to its destination, the gear ratio for that transfer is four. My rough estimate for the gear ratio for M_1 is roughly 56. That is, it takes 56 mass units on the surface to deliver 1 mass unit of payload to rendezvous in elliptical Mars orbit.[1] The gear ratio M_2 for dry cargo is approximately 10. For crew, it is undoubtedly much larger. For cryogenic propellants it is anyone's guess. My wild guess is that to deliver 1 mass unit of cryogenic propellant from LEO to the Mars surface, the gear ratio is something like 16:1. The overall gear ratio from LEO to the surface of Mars, and from the Mars surface to Mars orbit is thus at least 500. It is evident that minimizing the total mass delivered to the Mars surface is important. Even more important is minimizing the mass of the ascent system from Mars to rendezvous in orbit since it has such a large gear ratio. That is why ISRU is so valuable, since it produces ascent propellants on Mars. The masses delivered to Mars and lifted from the Mars surface are strongly dependent on the crew size. That is why crew size is the most important single factor in determining the scale of a human mission to Mars.

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[1] See paragraphs toward end of Sect. 1.1.4.

1.1.2 The Likely Mars Mission Scenario

Any mission to Mars is constrained by the following:

- The Earth and Mars go around the Sun at different speeds.
- The Mars year is roughly 22.57 Earth months. The Earth year is 12 months.

Starting at any given time when the Earth and Mars are juxtaposed in some relative position, we can fast-forward approximately 25.62 months.

- During this period of time, the Earth has made two transits around the Sun and is now 1.62 months further along its orbit than it was at the start.
- Mars made one transit around the Sun and is now 3.05 months further along its orbit.
- But 1.62 Earth months is about 48.6° along its orbit while 3.08 Mars months is 48.6° along its orbit.
- Thus the relative positions repeat themselves roughly every 25.6 months, but the actual positions have moved roughly 49° forward along the orbits.

Thus we conclude that the position of Mars relative to the Earth is at a propitious distance for transfer from Earth to Mars roughly once every 25.6 months.

If a spacecraft leaves Earth and takes say, 7 months to get to Mars, by the time it arrives at Mars, the Earth has moved halfway around the Sun and no return is feasible.

The Earth moves back into a position for transfer from Mars to Earth about 24 months after the initial transfer from Earth to Mars.

Thus a Mars mission time line might be something like:

- Month 1: Send spacecraft toward Mars
- Month 7: Arrive at Mars
- Months 8–23: Remain at Mars
- Month 24: Depart Mars for Earth
- Month 30: Return to Earth.

Thus the crew must remain on Mars for about 16 months. There is no way to abort the mission.

Returning from Mars imposes stringent requirements. The crew must be housed in a suitable habitat for about seven months, life support must be provided without interruption, and large amounts of propellant are needed for transfers. Liftoff from the surface of Mars requires a large mass of propellants, proportional to the liftoff mass. If the mission plan was to rise off the surface of Mars and go directly back to Earth, the entire mass of habitat plus life support would have to be lifted from Mars and sufficient impulse applied to send it on its way toward Earth. The amount of propellants required would exceed 100 metric tons (mT). The scale of the propulsion system for the return vehicle would be huge. The volume of the propellants would exceed 120 m^3, requiring more than 27 tanks of 2-m diameter. Instead, a sizable Earth Return Vehicle (ERV) is placed in Mars orbit containing the habitat for the seven-month journey back to Earth, along with the life support system. A very minimal capsule is used to transport the crew from the surface of Mars to rendezvous and transfer to the ERV in a couple of days. Even with this minimal capsule, the requirement for ascent propellants will be at least 30 mT.

The likely Mars mission strategy was laid down in the 1990s by a NASA study referred to as “DRM-1”.

The strategy chosen for the DRM-1, generally known as a “split mission” strategy, breaks mission elements into pieces that can be launched from Earth with very large launch vehicles, preferably without rendezvous or assembly in low Earth orbit (LEO). The strategy has these pieces rendezvous on the surface of Mars, which will require both accurate landing and mobility of major elements on the surface to allow them to be connected or to be moved into close proximity. Another attribute of the split mission strategy is that it allows cargo to be sent to Mars without a crew at one or more opportunities prior to crew departure. This allows cargo to be transferred on low energy, longer transit time trajectories and the crew to be sent on a higher energy, shorter transit time trajectory. Dividing each mission into two launch windows allows much of the infrastructure to be emplaced and checked out before committing a crew to the mission, and also provides a robust capability, with duplicate launches on subsequent missions providing either backup for the earlier launches or growth of initial capability. Of supreme importance, the *Earth Return Vehicle* (ERV) will be emplaced in Mars orbit, and the propellant tanks of the *Mars Ascent Vehicle* (MAV) on the Mars surface will be filled (using ISRU), prior to launch of the crew.

In DRM-1, the first three launches will not involve a crew but will send infrastructure elements to low Mars orbit and the surface of Mars for later use (see Fig. 1.1).

Whether subsequent missions would go to the same location as the first mission, or to different locations on Mars is still being debated.

Three cargo vehicles depart Earth about 26 months before the astronauts, on minimum energy trajectories direct to Mars (that is, without assembly or fueling in LEO). After the

Fig. 1.1 Mission sequence for first mission to Mars in DRM-1