

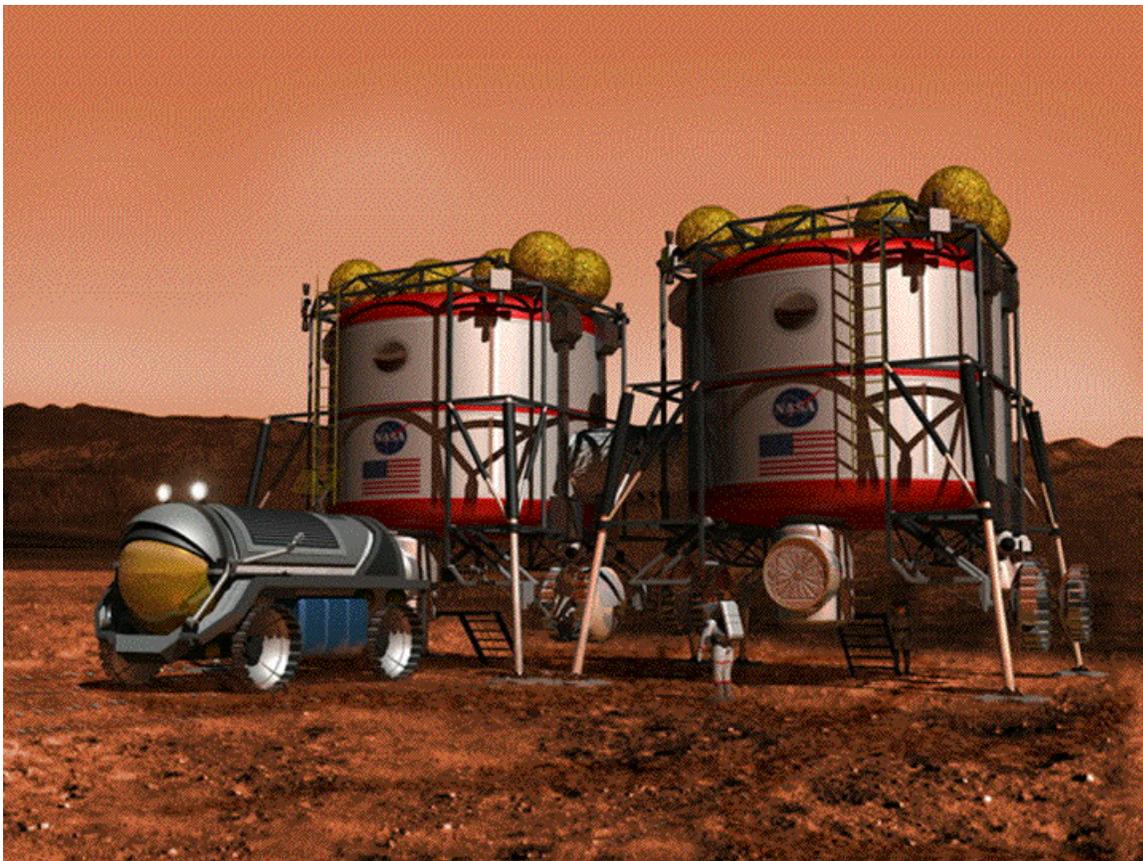


Resource Utilization and Site Selection for a Self-Sufficient Martian Outpost

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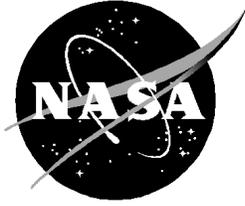
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Contents

	<i>Page</i>
1. Introduction	1
1.1 Motivation.....	1
1.2 Mission Strategy	2
1.3 Assumptions and Constraints.....	3
2. Consumables & Materials.....	4
2.1 Resource Requirements.....	4
2.2 Atmospheric Resources.....	6
2.2.1 The Martian Atmosphere.....	6
2.2.2 Atmospheric Research.....	8
2.2.3 Atmospheric Resource Utilization	8
2.2.4 Geographical Distribution	10
2.3 Surface Material Resources	11
2.3.1 The Martian Surface	11
2.3.2 Material Resource Utilization.....	12
2.3.3 Geographical Distribution	14
3. Water	14
3.1 Water Evolution: Signs and History	14
3.1.1 Atmosphere and Volatile Evolution	15
3.1.2 Atmosphere and Volatile Depletion	17
3.1.3 Geomorphology—Cratered Uplands at High Latitudes	19
3.1.4 Geomorphology—Cratered Uplands at Low Latitudes.....	21
3.1.5 Geomorphology—Planes and Poles	24
3.2 Resource Acquisition and Exploration.....	26
3.3 The Future of Water on Mars.....	27
4. Energy.....	28
4.1 Energy Requirements.....	28
4.2 Nuclear Resources.....	28
4.2.1 Feasibility	28
4.2.2 Advantages	29
4.2.3 Disadvantages.....	29
4.2.4 Site Selection.....	29
4.3 Geothermal Resources	29
4.3.1 Feasibility	29
4.3.2 Advantages	30
4.3.3 Disadvantages.....	30
4.3.4 Site Selection.....	31
4.4 Solar Resources.....	31
4.4.1 Feasibility	31

Contents

(continued)

	<i>Page</i>
4.4.2 Advantages	32
4.4.3 Disadvantages.....	32
4.4.4 Site Selection.....	33
4.5 Wind Resources	33
4.5.1 Feasibility	33
4.5.2 Advantages	33
4.5.3 Disadvantages.....	33
4.5.4 Site Selection.....	34
4.6 Energy Summary.....	34
5. Site Selection	34
6. Conclusion	39
7. References	39

Tables

Table 2.1	Consumables Per Person Per Day.....	4
Table 2.2	Waste Products Per Person Per Day	4
Table 2.3	In Situ Resource Utilization Priorities	6
Table 2.4	Atmospheric Composition – Mars and Earth	7
Table 2.5	Useful Materials From the Martian Atmosphere	8
Table 2.6	Chemical Composition of Regolith Components	11
Table 2.7	Useful Materials From the Martian Soil	12
Table 3.1	Observations Needed to Improve our Understanding of the Inventory and Distribution of Water	15
Table 4.1	Depth of Mars Geothermal Reserves as a Function of Years Since Last Volcanic Activity	30

Contents (continued)

	<i>Page</i>
Figures	
Figure 3.1 Phase equilibrium diagram for water.....	16
Figure 3.2 Pressure and temperature versus time on early Mars based on simple climate model presented in the text	18
Figure 3.3 Schematic representation of the Mars climate system, showing exchange of volatiles among the surface, bulk atmosphere, and upper atmosphere.	18
Figure 3.4 Regions in the regolith showing where water ice might be stable, based on subsurface temperatures and an average atmospheric water vapor abundance.	20
Figure 3.5 Two categories of rampart craters: those possessing a single continuous ejecta deposit and those surrounded by two concentrically lain deposits	20
Figure 3.6 Images showing unsoftened and softened cratered terrain	21
Figure 3.7 Valley system morphology demonstrating erosion.....	22
Figure 3.8 Outflow channels.	23
Figure 3.9 Outflow channels.	23
Figure 3.10 Erosion through release of water.	24
Figure 3.11 Waterflow-induced erosion.....	24
Figure 3.12 North pole of mars showing perennial water ice circumscribed by terraced aeolian deposits.	25
Figure 5.1 Map showing areas believed to contain subsurface ices or permafrost.	35
Figure 5-2 Map showing high amounts of atmospheric pressure in Hellas basin.	35
Figure 5.3 Regions of low thermal inertia, indicating fine-grained top soil.	36
Figure 5.4 Possible locations for geothermal energy sources	37
Figure 5.5 Outflow channels and valley networks	38
Figure 5.6 Circled areas indicate possible landing sites.....	38

Acronyms

bya	billion years ago
D	deuterium
e	production energy
ERV	earth return vehicle
G	mass gain factor
IR	infrared
ISRU	in situ resource utilization
mya	million years ago

Abstract

As a planet with striking similarities to Earth, Mars is an important focus for scientific research aimed at understanding the processes of planetary evolution and the formation of our solar system. Fortunately, Mars is also a planet with abundant natural resources, including accessible materials that can be used to support human life and to sustain a self-sufficient martian outpost. Resources required include water, breathable air, food, shelter, energy, and fuel. Through a mission design based on in situ resource utilization, it becomes possible to establish a permanent outpost on Mars beginning with the first manned mission. This paper examines the potential for supporting the first manned mission with the objective of achieving self-sufficiency through well understood resource development and a program of rigorous scientific research aimed at extending that capability. The potential for initially extracting critical resources from the martian environment is examined, and the scientific investigations required to identify additional resources in the atmosphere, on the surface, and within the subsurface are discussed. The current state of knowledge regarding the planet's geomorphology is examined, particularly as it pertains to the question of finding the most valuable resource, water. The questions of scientific practicality, necessity, and feasibility are examined with respect to the concepts of resource utilization and habitability. Unmanned precursor missions, such as the Pathfinder and Mars Global Surveyor, are discussed in the context of supporting the selection of an initial landing site. Considerations are presented for determining the optimal landing site based on the best combination of the known and potential existence and accessibility of martian resources. The primary goal of achieving self-sufficiency on Mars would accelerate the development of Human colonization beyond Earth, while providing a robust and permanent martian base from which humans can explore and conduct long-term research on planetary evolution, the solar system, and life itself.

1. Introduction

1.1 Motivation

One of the most profound and compelling objectives for the exploration and development of space is to ensure the ultimate survival of the human species. Science and technology have now reached a point where an awareness of our vulnerability within a delicately balanced biosphere coexists with the knowledge and tools to establish permanent settlements beyond Earth. The fundamental purpose of the mission chosen for this study is to develop the capability for establishing and sustaining a human presence on the planet Mars. This mission is designed to be humankind's first fully self-sufficient and operational settlement on the surface of another terrestrial body within our solar system. As such, the scientific research conducted on this mission will be targeted toward developing an understanding of the availability and distribution of martian natural resources that can be utilized for the survival and growth of a human outpost. Although it is beyond the scope of this paper, this may eventually lead to a martian colony with permanent families of residents, service and export industries, and a locally driven economy.

There are several key advantages to taking a self-sufficient approach to the first human mission to Mars. Given our current launch capabilities and costs, this approach provides an economically feasible plan to achieve the most science for the least expense. As few as two initial launches may be required to deliver the necessary habitation module, life support systems, food, surface vehicles, power generators, science equipment, and an emergency return vehicle. The mission goal to remain indefinitely, and to establish the use of local resources, will result in immeasurable long-term economic savings. An emphasis on long-term visits and survival-oriented research will quickly reduce the life support logistics required from Earth for follow-on missions and future inhabitants. It will also provide the necessary framework for

long-term exploration, research, and continuity of scientific investigations. Ultimately, this approach would lead to the achievement of more reliable science and eventually more humans living on Mars in the shortest amount of time, when compared with other mission strategies.

The establishment of a long-term autonomous outpost on the planet Mars will require surface-based, human-tended research to gain a scientific understanding of the current state of local resources. This research must identify the abundance, distribution, and accessibility of resources that can be used to provide water, food, air, energy, and construction materials. These survival-based requirements provide the guidance and impetus for defining short-term research priorities. Such investigations will naturally lead toward related topics of scientific interest and, as survival needs are met, more time will be available for fundamental research. These secondary and more fundamental scientific objectives will therefore be identified as potential outcomes of the primary research or as natural follow-on studies.

1.2 Mission Strategy

This paper, in general, assumes that a first mission to Mars will be based on a slightly modified version of the transportation and habitation concepts proposed by Zubrin in his Mars Direct plan (Zubrin, 1996; Zubrin et al., 1991). This plan calls for all flights to Mars to take place every two years on low-energy conjunction missions. At conjunction the Earth and Mars are on opposite sides of the Sun and at the greatest distance – 400 million km. Low-energy, conjunction class orbits such as these take only about 6 months to travel between the Earth and Mars. The first step in the Mars Direct plan has an unmanned earth return vehicle (ERV) leave the Earth two years before the crew, using either a modified STS launch system, or other heavy lift vehicle such as Energia. In addition, our modification of the plan calls for the launch of an additional modified ERV platform which contains spare parts, cryogenic storage tanks, drilling facilities, and wind energy generation equipment. After a 6-month flight the two vehicles aerobrake into martian orbit and then deorbit for a landing guided by a previously placed transponder beacon. Both vehicles are virtually unfueled at this point. In fact, the ERV contains only 6 metric tonnes of liquid hydrogen. This will be used as feedstock for the production of some 96 metric tonnes of methane and oxygen for the return trip and 12 tonnes of fuel for martian rovers. The ERV also carries a couple of these surface rovers. One rover is carrying a 100 kW nuclear reactor, which would be robotically emplaced in a nearby crater to provide initial power. If either more fuel or energy stocks need to be created, it is only necessary to slightly increase the initial amount of hydrogen stock from Earth. A series of “low-tech” chemical reactors are on board the ERV and, upon receiving power from the reactor, the process of creating methane and oxygen is initiated. Six months after the processing commenced, the ERV is fully fueled using the hydrogen feedstock and the martian atmosphere, thereby priming the site for human habitation and emergency return. It is important to note that the production process for these vehicles should be designed in an assembly line format, thereby reducing costs and improving system redundancy. The same type of vehicle, with minor alterations, could also be used for lunar missions.

About one year after the arrival of the first unmanned habitat module and the first ERV is fully fueled, a piloted habitat vehicle and an ERV again leave Earth (compared to Zubrin's plan, one more initial vehicle launch is assumed). The crewed vehicle is a habitat module that will land and remain on the martian surface. The second ERV is the return vehicle for the next crew and the backup for the first crew. Artificial gravity may be induced using a tether attached to the final stage of the launch vehicle, thereby alleviating many of the aversive long-term biophysiological changes that occur in a microgravity environment. En route, the crew can also spend a significant amount of time remotely exploring the area around their upcoming landing site using teleoperated rovers from a previous unmanned mission. After a 6-month trip, four to six astronauts land on Mars, and spend 500 days on the surface before returning on the first fully fueled ERV. The second ERV, which landed at the same time as the crew, begins processing fuel from the martian atmosphere and becomes the backup for the next crew.

The habitat assumed in the Mars Direct plan is 5 meters high and 8 meters in diameter. Twice the habitable size of the ERV, it has two decks with 8 feet of headroom and 1000 square feet of floor area. Closed-loop or semi-closed-loop oxygen and water systems will be used. A pressurized rover, which operates on methane and oxygen, is on board as well as an ample supply of food (for about three years). The loaded hab module weighs approximately 25 metric tonnes. The crew will live in this habitat for the outbound and surface portions of the mission. The Mars Direct plan only allows for a small experimental inflatable greenhouse to be provided on this flight. Although not integrated into the Mars Direct plan, other studies have suggested an EVA port. This would allow pressurized rovers and EVA suits to be “docked” and entered directly from the pressurized environment. This would limit the loss of life support gasses and dust contamination.

1.3 Assumptions and Constraints

This section details the initial conditions and constraints that are assumed in this study.

- First, the following currently planned missions to Mars are undertaken and successful: Mars Pathfinder (1996), Mars Global Surveyor (1996), Mars Surveyor – Orbiter and Lander (1998), Japanese Planet B Orbiter (1999), Mars Surveyor – Orbiter and Lander (2001). From these flights, it will be assumed that general information on potential landing sites, and some detailed information on surface soil composition and global surface resources is obtained. Also, further information on the availability of solar and wind energy resources will be obtained. This paper assumes that the current plans for the 2003 (Mars Surveyor – 2 landers) and 2005 (Mars Surveyor – Sample Return) missions are modified. The 2003 launch opportunity is modified to include the 2005 sample return using in situ propellant manufacturing as described by Kaplan (1996). This allows a return of material that could fully characterize the martian soil for mineralogical age, its usefulness as a resource, possible levels of toxicity, and shielding characteristics. Thus, engineering evaluations of in situ propellant manufacturing and quarantine procedures could be assessed. The 2003 launches will be further modified to include microprobes that will visit three to five candidate landing sites. These probes will perform final determinations of surface conditions and immediate resource availability. Landing beacons will also be robotically emplaced using micro-rovers from these missions. It would then be possible to send the first ERV in 2005.
- Second, the economic and political conditions are such that a science and technology development program for the design and construction of mission hardware can be sustained. Recent increases in the awareness of the media, and the Internet, due to the success of the Pathfinder landing mission, have highlighted – and heightened the public interest and commitment to – the possibility of a manned mission to Mars. A recent announcement by NASA Director Dan Goldin substantiates this assumption that NASA is seriously considering the Mars Direct plan as a viable option for the first decade of the 21st century (Anselmo, 1997). The economic benefits of this approach, which are mainly derived through martian resource utilization, might allow NASA to go forward with a first manned mission to Mars.
- Third, it is assumed that the overall mission objective is to establish a permanent base on Mars from which high-value scientific research can be performed. While the Zubrin plan includes a return vehicle and a limited surface time, the mission is extendible on the basis of the performance of in situ resource utilization (ISRU). The mission design would include essential goals, primary mission objectives, and discretionary objectives. Survival and the capability for safe return to Earth are essential goals. Primary mission objectives include basic ISRU development and demonstration as well as fundamental planetary science. Discretionary objectives would allow for the development of

additional ISRU activities that increase the self-sufficiency of the outpost and allow the mission to be extended.

- Finally, it is assumed that the specific mission design is a function of information obtained during the precursor robotic missions. This paper separates the Earth-Mars transportation problem from the problem of living on Mars. Furthermore, this paper is focused on defining the most promising ISRU objectives and identifying the scientific investigations on Mars that would lead toward greater self-sufficiency. It is not intended to propose a specific mission design.

2. Consumables & Materials

2.1 Resource Requirements

The essential requirements to support human life include water, food, air, and shelter. Additional requirements for a Mars mission include energy and fuel. While none of these currently exist in directly useable form on Mars, all of the elements required to derive potable water, grow plants, mix breathable air, and construct pressurized and protective habitats are available and accessible on the surface. Potential sources of energy include wind, solar, and geothermal activity. Numerous fuel and oxidizer combinations can be derived from the atmosphere itself. The utilization of these local resources will translate directly into the reduction of transportation costs from Earth. In addition, ISRU provides a measure of mission self-sufficiency, which could ultimately evolve to the stage of a fully independent martian base or colony.

Various studies have been performed to quantitatively assess the daily requirements of an average person. Caloric requirements depend on physical activity as well as psychological condition (e.g. stress) and there are uncertainties with respect to operating in different gravitational environments. Boston (1996) provides a summary of multiple studies on human consumption. Representative requirements are given in Table 2.1 below.

Table 2.1: Consumables Per Person Per Day

Material Consumed	Mass
Air (O ₂)	0.8 kg-0.9 kg
Drinking Water (H ₂ O)	2.3 kg-4.6 kg
Washing Water (H ₂ O)	1.1 kg-5.4 kg
Food	1.5 kg-2.5 kg

Depending upon the degree of recycling that can be achieved by the life support system, these requirements can be reduced by careful use of waste products, which are given in Table 2.2.

Table 2.2: Waste Products Per Person Per Day

Waste Material	Mass
CO ₂	0.8 kg-1.1 kg
Water (H ₂ O)	1.8 kg-2.5 kg
Solid Waste	0.13 kg-0.2kg

Meyer (1996) points out that humans are fundamentally a net source of water as well as CO₂. This is a result of the metabolism of food to provide energy. Therefore, it is theoretically possible to recycle all of the required water. Meyer estimates that if only 77% of the human waste water were recycled then human life support requirements for additional water would be zero. Efficiencies of 90-95% will be likely requirements for a first Mars mission to ensure that this resource is not a limiting factor. Additional water, however, will be required for many other uses besides life support. Carbon dioxide can similarly be recycled to produce oxygen either by photosynthesis or chemical means. Solid waste can be used to produce fertilizer to provide nutrients required for plant growth. These mechanisms will be discussed further in later sections.

Fuel and oxidizer production is a critical requirement for both the return vehicle and for surface mobility. In the Mars Direct plan, a total of 96 metric tonnes of methane and oxygen are required for returning four crew members to Earth. An additional 12 tonnes are allocated for surface exploration. Self-sufficiency of a martian base, however, requires the ability to maintain fuel stores and replenish supplies. These supplies can be used to provide heating, lighting, equipment power, and an alternative or emergency energy source for all systems, including life support, recycling, resource development, science and exploration. While nuclear, solar, or wind energy might provide the baseline energy resources, fuel stores are a safe and effective way of stockpiling energy.

A self-sufficiency trade study described in Boston (1996) identifies the mission duration at which the development of local life support resources becomes advantageous. Within 30 days, without recycling, or with the equivalent leakage, it becomes advantageous to derive oxygen from local resources. The time constants for water and food are about 6 months and 3 years, respectively. Therefore, the first Mars mission will likely carry sufficient food supplies for the first 3 years, at which point food production must be fully established on Mars to support a continued human presence without additional supplies launched from Earth. Initially, hydroponics and artificial lighting may provide the means to grow supplements of fresh vegetables. However, research on radiation protection, or resistant strains, and nutrient vitalization of the martian soil will be required to establish reliable self-sufficient food production. Water, nitrogen, and CO₂ will be required in large quantities to support this development.

Another requirement for successful human inhabitation on Mars is shelter, both in terms of living and working space as well as environmental (radiation) protection. Current spaceflight experience provides little for determining the minimum adequate space for maintaining crew morale when mission durations are measured in years. The Russian *Mir* complex or the *International Space Station* place a lower bound on habitable space requirements for a Mars base. Boston (1996) presents a range of space requirements from a minimum of 17 cubic meters to 1335 cubic meters per person. The latter value was the actual habitable volume for Biosphere 2, a closed ecological system that supported a crew of 8 for two years (Nelson, 1996). While a habitat of this size cannot be established on Mars with the first flight, numerous options exist to extend the habitable volume with inflatable structures and in situ construction using martian soil. Radiation hazards can also be mitigated by construction of subsurface habitats or by covering structures with martian regolith.

Energy is the final requirement for all martian base operations. This resource is the cornerstone for all ISRU activities and is an essential requirement for mission success and a sustained human presence on Mars. Utilization of solar, wind, and geothermal energy resources are discussed in detail in a later chapter. It is assumed that the first Mars mission includes redundant nuclear power generators with 100 kW continuous output capability. This is consistent with the approximate requirements for numerous mission design studies, including the Mars Direct plan.

Developing the capabilities to access various local resources, and the probable order in which these capabilities are achieved, depends on the cost-to-benefit trade-off for launching resources from Earth as compared to launching the equipment and power reserves for extraction. Meyer (1996) uses two figures of merit to characterize the advantage of developing a particular resource on Mars: the mass gain factor (G) is the ratio of the total mass of a resource that can be produced to the mass of the equipment required (for the equipment life cycle). The mass gain should be large to justify the risk and expense of ISRU development, and Meyer suggests that a factor of at least $G=100$ is desirable for initial ISRU systems. The production energy (e) is the energy to produce one kg of the resource, and a desirable range of 10kW-hr/kg or less is desirable to make ISRU a practical option for early missions. This is based on rough estimates of the various resources required and the expected available power. These criteria can be used to rank the priority in which ISRU systems should be developed and utilized. Qualitatively, the order of priority for major resource categories is shown in Table 2.3 along with characteristic time scales.

Table 2.3: In Situ Resource Utilization Priorities

Priority	Resource	Time Scale
1	Propellant	- Mission baseline supply established before crew departs from Earth - Continuous production
2	Gases - O ₂ , N ₂ , CO ₂ , Ar, etc.	- 30 days or equivalent loss
3	Water	- 6 months or equivalent loss
4	Energy	- 1 year
5	Shelter and radiation protection	- 2 years
6	Food	- 3 years

Longer-term requirements include new supplies of specific chemicals and materials that will be required to maintain and construct recycling systems, equipment, and new facilities. Ceramics, glass, metals, cement, and organic compounds are the building blocks from which an extended martian base and operational facilities can be built. The capability to develop these resources will depend on martian-based science to identify the availability and distribution of particular materials. The technology to extract such materials on Mars will be an evolving process with martian-based and Earth-based research and development.

2.2 Atmospheric Resources

2.2.1 The Martian Atmosphere

By Earth standards, the atmosphere on Mars is very thin, cold, and dry. Nevertheless, it is known to contain the critical resources that could enable the first manned Mars mission to remain on the surface indefinitely. Fortunately, the current state of the martian atmosphere is reasonably well understood. Earth-based observations, remote sensing from the Mariner missions, and actual measurements from the two Viking landers and Mars Pathfinder have provided enough information to characterize major compositional and meteorological features. The atmosphere is primarily composed of CO₂ (95.3%), and the remaining constituents are listed in Table 2.4 with a comparison to Earth's atmosphere.

Table 2.4: Atmospheric Composition – Mars and Earth (Meyer, 1996)

Gas	Mars	Earth
CO ₂	95.3%	0.03%
N ₂	2.7%	78.08%
Ar	1.6%	0.93%
O ₂	0.13%	20.9%
H ₂ O	0.03%	~2%
CO	0.07%	0.12 ppm
Ne	2.5 ppm	18 ppm
Kr	0.3 ppm	1.1 ppm
Xe	0.08 ppm	0.09 ppm
O ₃	0.03 ppm	40 ppb
Other	—	< 7 ppm
Dust	~10 ppm	—

Total pressure at the surface is in the range of 7-10 millibars (or the equivalent pressure at 99 000 feet above the Earth's surface). Seasonal lows in pressure are correlated with the condensation of CO₂ at the South pole during the southern winter, and the highs occur during the northern fall and winter when CO₂ sublimates from the southern polar cap. This cyclic exchange of about 25% of the atmospheric mass, between the atmosphere and the surface, is the dominant characteristic of martian weather (a result of the planet's larger orbital eccentricity). It is driven mainly by the variation in insolation at the poles, and is responsible for the observed global dust storms that can shroud the planet for months at a time.

The total amount of water in the martian atmosphere is only about 1.3 km³. This corresponds to approximately 100 micrometers if precipitated out over the entire planet. Precipitation and evaporation of water varies with season and latitude, but the surface regolith can act as a sink or source for water vapor (frost) depending on temperature and conditions near the surface (Kieffer, 1992). The distribution of water vapor in the atmosphere favors the high latitudes (>60 degrees) and lower elevations. Hellas Basin, for example, at more than 4 km below the planetary reference level, can have up to twice as much water as anywhere else on the planet.

The mean atmospheric temperature on Mars is 215 K, but variations with time of day, season, and latitude are significant. At the equator, temperatures range from 160 K at night to 290 K during the day. At the Viking lander sites, peaks ranged from 190 K to 240 K. Despite the high concentration of atmospheric CO₂, low-altitude surface pressures and densities are not high enough to provide a sufficient greenhouse effect to trap infrared (IR) radiation from the cooling surface at night or sustain the presence of liquid water.

2.2.2 Atmospheric Research

While the current composition of the martian atmosphere is essentially known, much remains to be determined about its origin and evolution. As suggested by Carr (1996), most of the volatile elements that formed the early atmosphere were probably outgassed from the planet during the stages of accretion and differentiation. The amounts of volatiles present at this time and their subsequent history are highly uncertain over two orders of magnitude. Thus, reconstruction of the climatic history of Mars is very speculative at present. An understanding of this history is important in determining the amount of volatiles that were likely to be retained by the planet. The resources to support extraterrestrial life on Mars in the past, or human life in the future, is largely dictated by this history. Outgassing and atmospheric interactions with the surface over time directly relate to the formation of carbonates, nitrates, and the maintenance of temperatures and pressures that are conducive to life (and liquid water). Atmospheric research on Mars would consist of detailed chemical analysis of the current atmosphere, and careful analysis of the surface and subsurface composition at sites that can be correlated to a wide range of historical periods in the formation of Mars.

2.2.3 Atmospheric Resource Utilization

The martian atmosphere can be used to generate a variety of fuels, oxidizers, liquids and gases to support a wide range of requirements for transportation, life support, agriculture, science, and other ISRU processes. Table 2.5 is a partial list of useful materials that can be obtained directly from the atmosphere using well-established processes.

Table 2.5: Useful Materials From the Martian Atmosphere (Meyer, 1996)

Material	Representative Process
H ₂ O	Dehumidification of martian air
O ₂	Reduction of CO ₂ , Sabatier process
N ₂ , Ar	Liquefaction, fractional distillation
CO	Reduction of CO ₂ , Sabatier process
H ₂ O ₂	Auto-oxidation, electrolysis
NH ₃	Electrosynthesis
N ₂ H ₄	Raschig process
HNO ₃	Oswald process
N ₂ O ₄	Produced from HNO ₃
HCOOH	Electrochemical reduction of CO ₂
CH ₄	Catalytic hydrogenation of CO

Mining the atmosphere for essential materials has significant advantages over other potential resources. There is no requirement for resource exploration, excavation, or material handling. The availability and composition of the atmosphere is well known. The techniques for material extraction are also well developed and based on common chemical processes used by industry on Earth. Furthermore, the logistics of deploying and operating atmospheric processing equipment are simple and could be performed autonomously (Meyer, 1996). These properties are used to their full advantage by Zubrin (1996) in the Mars Direct plan to ensure that robotic missions have processed adequate supplies of essential resources (fuel and oxidizer) on the martian surface before the crew departs from Earth.

One disadvantage of atmospheric processing is that the energy requirements for processing certain materials in Table 2.5 are very high and possibly prohibitive. In particular, obtaining 1 kg of H₂O from the atmosphere would require processing a volume of 106 m³ with a requirement for 103 kW-hr of energy. Aside from the equipment needed to move this much air in a reasonable amount of time, this would use the entire energy budget for an initial base for one hour. Despite this cost, a small amount of water could probably be extracted from the atmosphere over time during the process of obtaining other materials. Since hydrogen is a required component of many essential materials, an initial supply will have to be transported from Earth. This would be replaced by local resources once a local supply of water is identified.

Breathable air can be obtained from the atmosphere by the extraction of oxygen at a cost of 12 kW-hr per kg. At this rate, oxygen could easily be produced for replenishing losses due to leakage, as well as for oxidizing materials to be used in combustion processes. The detailed design of an oxygen processing unit for Mars is presented in Ash (1989). One issue for producing breathable air is the need for buffer gas. Pure O₂ is not only toxic, but presents a fire hazard as well. Nitrogen is the main inert buffer gas in the Earth's atmosphere, where it has an abundance of 78%. On Mars this is reduced to only 2.7%. Argon is another useful buffer gas that is available on Mars in small concentrations. The best known method to extract buffer gas from the martian atmosphere was developed by Meyer and McKay (1984): Martian air would be compressed to 5.1 atm, at which point most of the CO₂ condenses out. A Joule-Thompson expansion back to 2 atm solidifies the remaining CO₂, leaving N₂ and Ar as the main constituent gases. This process requires 9.4 kW-hr per kg, which is a reasonable cost to cover losses due to recycling leakage. This process would also be used as the basis for producing nitrogen needed for other applications, such as ammonia for refrigeration and nitrates for the fertilization of soil (Meyer, 1996).

The ability to produce fuel and oxidizer materials from the martian atmosphere is by far the most dramatic advantage of ISRU. The weight penalties associated with the transportation of return vehicle propellant from Earth is the single most dominating factor in overall mission capability. For every ton of propellant produced on Mars, a savings of 300 tons of fuel at launch from Earth is attained (Zubrin, 1996). This amounts to 30,000 tons of fuel for a four-person Mars mission. Without ISRU processes to produce rocket propellant on Mars, the goal of establishing a permanent presence on Mars would have to wait for more efficient propulsion technology and far better economic conditions!

A variety of fuels can be produced on Mars and each has advantages and disadvantages. Given that a local source of water has been found, it would be possible to produce liquid hydrogen/oxygen fuel by electrolysis ($2H_2O \rightarrow 2H_2 + O_2 + 571\text{kJ/mol}O_2$). While this combination has the greatest specific impulse (Isp) of all chemical fuels (=460), the hydrogen and oxygen must be stored cryogenically (even on Mars). Another disadvantage is that hydrogen would initially have to be transported from Earth. Other potential fuels provide a higher hydrogen leverage. At the other extreme is carbon monoxide and oxygen, which can be produced easily by the Sabatier process ($2CO_2 \rightarrow 2CO + O_2 + 566\text{kJ/mol}O_2$). This fuel has a much lower Isp (=259), but the lower gravity on Mars means that its use is possible for a two stage Earth return vehicle. Other hydrocarbon fuels with a high hydrogen leverage, have much higher Isp values, and can propel a single stage fully reusable vehicle from Mars. Three such fuels are

methane, methanol, and acetylene. Of these acetylene has the highest Isp (=410), but is also highly explosive and therefore a dangerous material for martian use. Methane can be produced via the reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O - 164.8\text{kJ/mol}CH_4$). The addition of two more steps, to recover the hydrogen from water and recombine oxygen to form CO_2 , allows for the full utilization of hydrogen and a stoichiometric production of O_2 for combustion. Methane is the propellant of choice for the Mars Direct plan due to its high Isp (=380) and high propellant to hydrogen mass ratio of 18:1. Since methane requires cryogenic storage, however, methanol might be a preferable fuel for surface vehicles and other equipment that can be operated by typical combustion engines. With a slightly lower Isp (=315), methanol can be stored as a liquid at ambient temperatures and pressures on the martian surface.

Another very useful fuel on Mars is hydrogen peroxide (H_2O_2). This monopropellant can be used to power surface vehicles or even launch vehicles, but its principal advantage is as a convenient energy storage medium. H_2O_2 could be synthesized electrochemically, and if necessary is quickly decomposed into H_2O and O_2 for critical drinking and breathing supplies. Numerous other processes that depend upon water or oxygen could also utilize these products. This reaction also produces energy that can be used for heating, powering equipment, or transportation. H_2O_2 can also be used as an explosive, a disinfectant, and a bleaching agent (Clark, 1989).

Research and development for greenhouse food production will require large amounts of water and CO_2 , as well as nitrogen in the form of the nutrients required for plant growth and soil fertilization. The extraction of CO_2 from the atmosphere is simply a matter of compression, and the extraction of N_2 was discussed earlier. Since most plants tend to exhibit favorable growth in rich CO_2 environments, the composition of the martian atmosphere for greenhouse air requires only slight adjustments. The partial pressure of nitrogen is required to be greater than about 10 hPa to allow for biological nitrogen fixation, and some small amount of O_2 is required by most plants for aerobic mitochondrial respiration. Greenhouse gases must be heated to maintain a temperature of about 10°C , which is mainly to ensure that water remains in a liquid state. In general, plants are surprisingly tolerant to variations in atmospheric pressure, which could result in significantly relaxed power and structural requirements on Mars. The disadvantage of low-pressure greenhouses is that human tending could not be performed without environment suits, and the regenerative interfaces between habitable volume and greenhouse space would be more difficult.

2.2.4 Geographical Distribution

In addition to being a well-characterized resource, the atmosphere is also a relatively ubiquitous source of its major constituents. As a global reservoir it is also self-replenishing. For example, even if a martian base could extract all of the atmospheric water vapor, it would be continually resupplied by sublimation at the poles to maintain equilibrium saturation conditions. Water vapor also happens to be the only important constituent with any significant geographical distribution. High latitudes and low elevations contain more water vapor at the surface. Since the process of extracting water from the atmosphere is expensive, however, this will probably not be an important factor for the first mission to Mars. Obtaining water from hydrated soil or permafrost would be preferable. Otherwise, the ability to perform ISRU with atmospheric resources is available anywhere on the planet, and is not a limiting factor for landing site selection.

2.3 Surface Material Resources

2.3.1 The Martian Surface

Based on the observations of the Viking landers, the surface of Mars seems to be covered by a regolith material that is comprised of a range of elements from fine dust, to indurated clods, vesiculated stones, and boulders. The apparent homogeneity of the regolith at the two distant locations suggests that the global dust storms on Mars serve to distribute this material somewhat ubiquitously over the entire surface of the planet. A salt-cemented crusty material called "duricrust" is also found at both sites. Salts are found in the uncemented fines as well. The composition of the rocks and bedrock is unknown. The chemical composition of the regolith has been inferred, however, by combining Viking data with Earth-based spectral observations and an analysis of the SNC meteorites, which are thought to have originated on Mars. Table 2.6 presents the expected mineralogical composition of the martian soil (Clark, 1989).

Table 2.6: Chemical Composition of Regolith Components (Clark, 1989)

Element (As Oxide)	Concentration		
	Fines	Salt	Rock
SiO ₂	44%	0%	51.4%
Fe ₂ O ₃	17.4%	<2%	19.4%
Al ₂ O ₃	7.3%	<2%	7.1%
SO ₃	7.2%	7.2%	0.2%
MgO	6%	up to 6%	9.3%
CaO	5.7%	<1%	10.0%
Na ₂ O	?	up to 1.4%	1.3%
Cl	0.6%	0.6%	0.01%
TiO ₂	0.58%	0%	0.87%
K ₂ O	<0.5%	0%	0.16%

The most abundant pure elements in the soil by weight are silicon (21%) and iron (13%). Magnesium, aluminum, sulfur, calcium, and titanium were also specifically detected at around the 1% level by Viking experiments. Sulfur is about 10 to 100 times more abundant than in terrestrial soil. Phosphorus is also thought to be present due to a 0.3% concentration by weight in the SNC meteorites. Significant quantities of adsorbed volatiles were also detected by Viking. Oxygen, CO₂, H₂O, and other compounds were released upon heating (Meyer, 1996).

Current theories of the formation of Mars suggest that the once thicker CO₂ and N₂ atmosphere must have formed carbonic and nitrate compounds at a time when significant H₂O existed as a liquid on the martian surface. There may also be significant amounts of H₂O and CO₂ adsorbed in a porous regolith surface layer. There appears to be a global crust of salt enriched materials on the surface, probably in the form of (Mg,Na)SO₄, NaCl, and (Mg,Ca)CO₃ (Meyer, 1996).

The potential for the existence of regional deposits of minerals and ores on Mars is presently speculative. Plate tectonics are responsible for most geological concentrations of these resources on Earth. While the associated uplifting and subduction of the crust has not occurred on Mars (with essentially one plate), geothermal activity is a possible mechanism that can produce similar results, and has done so on Earth. Volcanic processes have also been associated with deposits of copper, lead, zinc, gold, and silver on Earth and might occur on Mars.

2.3.2 Material Resource Utilization

The fact that martian soil (regolith) seems to be relatively consistent in composition and globally distributed is a major advantage with respect to the possibilities for ISRU of this material. In a fashion similar to the development of ISRU for atmospherically derived consumables anywhere on the planet, the regolith is a certain resource that can be utilized at any base location, landing site, or temporary research station. A wide range of materials can be extracted directly from the martian soil as illustrated by Table 2.7.

Table 2.7: Useful Materials From the Martian Soil (Meyer, 1996)

Material	Representative Process
H ₂ O	Evaporation of indigenous ice/permafrost
H ₂ O ₂	Electrolysis of H ₂ SO ₄ , low-pressure evaporation
O ₂	Electrolysis of H ₂ O
S	Sulfides and sulfates
Fe	Fe-oxides
Ti	Titanomagnetite, ilmenate
Al	Molten electrolysis of oxides
Mg	Molten electrolysis of epsomite
Ceramic	Clay – SiO ₂ , Al ₂ O ₃ , H ₂ O
Glass	SiO ₂ , Al ₂ O ₃ , MgO, CaO, K ₂ O
Duricrete	Silicates, salts, iron minerals, CO ₂
Cement	Silicates and H ₂ O
Plaster	Gypsum, calcium sulfate

Any of the materials shown in Table 2.7 can be produced from martian soil using conventional industrial and chemical processing techniques that are already in use on Earth. The required infrastructure and energy requirements, however, determine which processes are feasible for an initial martian outpost. The remainder of this section will focus on the utilization of readily available, low-cost resources that can be applied to the provision of essential requirements at an early stage.

Extraction of H₂O from the soil is a primary objective of ISRU development. Chapter 3 presents a detailed discussion of the likely distribution of water and permafrost entrained in the martian soil. The depth at which permafrost can be found at different latitudes is a fundamental question that would be a focal point of surface science. Its availability, however, cannot be assured except at very high latitudes. The water of hydration in the soil, however, is accessible anywhere on the surface. Extraction requires heating, but the energy required per kg of H₂O is far less than that required to extract H₂O directly from the atmosphere. Meyer (1984) obtained a value of ~100 kW-hr/kg for water from the atmosphere, which is prohibitive given expected power resources of a first mission. Clark (1989) finds that approximately 9 kW-hr is required to obtain 1 kg from the regolith using a conventional heating process and cold plate. A potentially more efficient method has been identified by Meyer (1996), which uses microwave heating to selectively target the dipolar H₂O molecules within the surface material. A disadvantage of this process is that large quantities of soil must be processed or mechanically handled (100 kg per 1 kg of H₂O). This may not be a significant factor if the dehydration of regolith is simply a first step in a sequence to process soil for other applications.

Another immediate and low-cost use for martian soil is for providing radiation-proof inhabitable space. The radiation environment on Mars includes a combination of solar ultraviolet and ionizing radiation from cosmic rays. These sources influx high energy particles including protons, alpha particles, and nuclei of heavy metals. On Earth, the surface is largely protected from cosmic rays by its magnetic field. The absence of a significant magnetic field on Mars, combined with the thin atmosphere, provides little shielding against these radiation sources. Prediction of the radiation flux at the surface of Mars is further hindered because the solar cycle (and solar wind) reduces the influx of cosmic rays to the inner solar system. This reduction is a function of nuclei mass, however, and the distribution of ionizing radiation that will be experienced by astronauts en route and on the surface of Mars itself can be mitigated through a layering of low and high atomic weight materials (Turner, 1992, Townsend 1996, Letaw 1989, and Nachtwey 1989). The stopping power and nuclear adsorption characteristics of the martian soil is difficult to estimate precisely, but an upper bound for the required coverage to shield astronauts on the surface from worst-case solar events or cosmic radiation is about 6 meters.

The expansion of habitable space is another anticipated application for martian soil. When mixed with water, unprocessed regolith may be capable of acting exactly like cement. This is due to the cementing action of sulfate salts, which are known to be present. Through baking the final structures at high temperatures to remove the water of hydration, strong structural elements could be formed. Extended structures could be built over inflatable volumes that ensure an airtight seal. With advanced robotics reconnaissance and sample return missions to Mars prior to the arrival of the first human mission, the ability to construct additional living space from local resources could be assured (McKay, 1996).

Another important but longer-term use of martian soil is to provide the required growth material and nutrients required for the cultivation of greenhouse plants on Mars to supplement and eventually replace food supplies from Earth. Much work has already been done to study the requirements for conditioning lunar regolith into suitable soil for agriculture (Boston, 1996). The basic process of conditioning martian soil would be to remove salts, oxides, and toxins, and then make adjustments for pH and add fertilizing nutrients. Waste products could be used to provide fertilizer, or on a larger scale they can be produced through a series of chemical processes beginning with ammonia. This requires nitrogen, and at present the atmosphere is the only known resource. Fractional distillation of buffer gas, which was discussed earlier, can be used to separate the nitrogen from Argon. The direct reaction of hydrogen and nitrogen can then be used to produce ammonia ($3H_2 + N_2 \rightarrow 2NH_3 - 46\text{kJ/molNH}_3$). Once ammonia is available, numerous fertilizers can be easily produced. Nitric acid, for example, is obtained through the Oswald process combining ammonia and oxygen. From nitric acid and sodium or calcium carbonate, one can produce ammonium, sodium, and calcium nitrates. All of these processes can be developed from well-established Earth-based methods. The final step in preparing the soil is based on the nitrogen cycle,

which requires specific bacteria to produce nitrates and nitrites. These bacteria derive energy by oxidizing ammonia and would be a resource that must come from Earth and be cultivated on Mars (Meyer, 1996).

Numerous other applications for martian surface and subsurface materials have been proposed. Up to 25 kg of magnesium can be extracted from each cubic meter of soil if regolith content estimates are correct. Lightweight metal structures and refractory bricks can be made from magnesium. Due to the availability of salts and water, it is likely that acids, bases, and other reagents can be produced for use in hydrometallurgical treatments similar to the processing of iron ore (Meyer, 1996). Metals can be used to construct parts for equipment, pipes and drilling string, wind turbine blades, and other applications. Ceramics, glass, sealants, alloys, and composites have all been suggested as potential materials for local production. These processes, however, will have to wait for later missions and an expanded martian colony. The development of almost all required materials could eventually be achieved. The key to continued growth in self-sufficiency is a directed plan of ISRU resource development based on the use of established and reliable resources and techniques, while conducting science to expand the knowledge of available local resources.

2.3.3 Geographical Distribution

As discussed earlier, the distribution of martian regolith is sufficiently ubiquitous to ensure that established ISRU processes could be carried out almost anywhere on the martian surface. This is an important advantage for ensuring successful ISRU development for a first martian outpost. Research to further characterize the surface and subsurface materials, and to correlate material properties with geological features, would be a fundamental focus of scientific studies. It is generally assumed that deposits of specific minerals and ores would be associated with regions of potential geothermal, volcanic, tectonic, or erosional activity. Surface investigations of such sites would be required to identify specific new resources. In situ research would also be aimed at developing robust methods for harvesting plants with revitalized martian soil, as well as protecting plants from harmful radiation while providing sunlight. Finally, the development of new techniques to extract new resources efficiently would be a continuing process with both martian- and Earth-based investigations.

3. Water

3.1 Water Evolution: Signs and History

Water is perhaps the most important substance for the sustenance of Earth-based life. Therefore it also becomes one of the most highly prized resources to be exploited in situ on Mars. In space, our reliance on water and its constituents is undeniable. As a biological necessity it provides the basis for the survival of life; when divided it supplies our atmosphere and propels our rockets. Though it is feasible to bring a complete supply of water for a limited mission to Mars, it becomes quite impractical to support a significant outpost with diverse capabilities for any length of time. This section is devoted to the questions concerning water on Mars, including our present understanding of its abundance and distribution, as well as our capability for in situ extraction and utilization. The current state of knowledge concerning the evolution of the martian atmosphere is discussed, followed by an examination of the related geophysical and geochemical evidence.

Adopted from Carr, (1996), the data presented in Tables 3.1 provides a comprehensive outline of scientific data and methods that would be required to judiciously select and establish the first manned landing site.

Table 3.1: Observations Needed to Improve our Understanding of the Inventory and Distribution of Water (Carr, 1996)

Knowledge Needed	Technique	Goals
Global terrain, chemistry, mineralogy: (Orbiter)	Imaging: VIS-IR spectroscopy, γ -ray spectroscopy	To understand water processes. Identify former oceans, lakes, springs. Define erosion rates vs. time.
Atmosphere isotopes: D/H, C, N, O noble gases	Mass spectrometry	To understand water history: original amounts, losses and gains.
Microfeatures, in situ chemistry, mineralogy: (lander with rover)	Micro-imaging, Alpha-proton-X-ray spectrometer, differential scanning calorimeter/evolved gas analyzer	To understand water processes: sediments, precipitants, etc. Depositional conditions. Weathering conditions.
Geophysics/geochemistry profiles: (lander with rover)	γ -ray spectroscopy, neutron spectrometry, electromagnetic sounding	Water at surface, Water near surface (1-2 m), and water at depth.
Soil/rock isotopes: (lander with rover)	Mass Spectrometry	Age of weathering. Composition of past atmospheres.
Definitive trace elements, lithologies, ages, etc.	Sample return	Environmental conditions, fractionation processes, ages, etc.

3.1.1 Atmosphere and Volatile Evolution

The last in the chain of terrestrial worlds to accrete out of the primordial solar nebula, Mars was endowed with nearly the same abundance of volatiles as either the Earth or Venus. During planetary condensation and cooling, some 4.5 billion years ago, Mars began the formation of a complex atmosphere and surface environment. The chief constituents of this early atmosphere were, according to most researchers, CO₂ and H₂O and were assumed to be the result of subsurface outgassing and early volatile-rich planetesimal impacts (Beatty and Chaikin, 1990). The accumulation of volatiles persisted, it is estimated, throughout the period of heavy bombardment (~3.9 billion years ago). Continued volcanism, impact vaporization, and cooling throughout this period provided a means of atmospheric stabilization. This meant that the amount of volatiles being outgassed was greater than the amount of material lost to either surface chemical reactions or space. Evidence suggests that these processes took place over tens of thousands to millions of years for their influences to have an effect. Studies have shown (Pollack et al., 1987; Kahn, 1985) that CO₂ partial pressures in excess of one bar would be required to place a large portion of the martian environment above the freezing point of water (Figure 3.1).

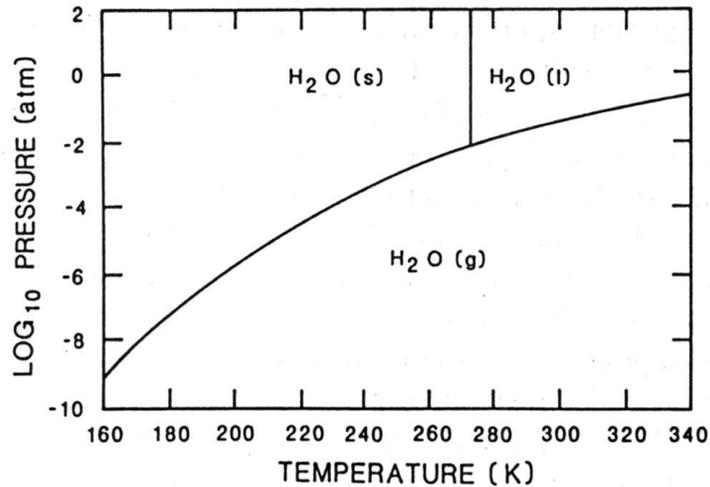


Figure 3.1. Phase equilibrium diagram for water. Adapted from Mutch et al. (1976). (Jakosky, 1985)

Once this point of quasi-steady-state carbon dioxide recycling was reached, liquid or near-liquid water would have been able to flow on the surface. This effect would have been primarily focused in mid and equatorial latitudes. Pollack et al. (1987) and others have concluded that to maintain a steady CO₂ atmosphere, at least 10 bar of carbon dioxide would have to have been supplied to the atmosphere given gravity and surface area.

Clifford (1993) and others provide support to the idea that at least four basic processes were responsible for introducing large quantities of water and other volatiles into the martian atmosphere: volcanism, impacts of volatile rich meteorites and comets, catastrophic flooding, and the sublimation of subsurface equatorial ices. Long-term cyclical changes in martian obliquity would also lead to higher abundances, on the average, of atmospheric water vapor (Kieffer et al., 1992). Estimates for the volume of water outgassed come from either geological evidence, or through chemical isotopic ratios. Research done by Carr (1987) involving channel and outflow volumes estimates that between 6 and 160 meters of water (the equivalent depth of a planet-encircling ocean) have been outgassed throughout the planet's history. Other geographical evidence comes from Greeley (1987) and others who have demonstrated that juvenile water releases from volcanic activity over the last 4 billion years indicate a minimum of 46 meters of water have been released. Measurements of isotopic ratios, alternatively, comes from both the Viking landers and the SNC meteorites (4 Shergohites, 3 Nakhilites, and Chassigny). Many authors currently believe that the SNC meteorites represent a series of low-crystallization-age basalts (~ 130 mya to 1.3 bya) whose composition and encapsulated atomic abundance ratios reflect their origins as being martian as opposed to being from other sources in the solar system (Jakosky, 1991; Dreibus and Wanke, 1987). Jakosky (1991) has determined that 10-20 meters of water were needed for an atmospheric exchange due to oxygen fractionation and heavy isotope buildup over a period of about 108 years.

3.1.2 Atmosphere and Volatile Depletion

Large-scale changes in the martian atmosphere only became prevalent after the period of heavy bombardment (~ 3.8 bya) when Mars began to show signs of a declining rate in large-scale volcanism and volatile outgassing. It is believed that the geothermal activity was confined to localized areas of long-lasting hot-spot volcanism. Such large-scale changes decreased the amount of material outgassed and recycled into the atmosphere, while the amount lost, especially to space, remained constant. Major sources of atmospheric reduction come from surface chemical and weathering reactions or escape processes that operate from the exobase (i.e., the point where the chance of hitting another molecule before speeding away drops 50 percent).

Given the variable ocean hypothesis, carbon dioxide—once absorbed in surface water—will react with minerals in the rocks to form calcite deposits, which results in a net loss of CO₂ from the atmosphere. The continued production of carbonates and nitrates and subsequent CO₂ and H₂O removal would have been capable of continuing as long as liquid water was available or until some form of recycling mechanism existed. On Earth, as opposed to Mars, atmospheric regeneration currently occurs due to crustal recycling, plate tectonics, and biogenic effects. This process would eventually result in a gradual reduction in the mass of the atmosphere, a decrease in any associated greenhouse effects, and initiate a decline in mean global temperatures. Such a decline in temperature and pressure is demonstrated in Figure 3.2 by McKay and Davis (1991).

Pollack et al. (1987) estimate a weathering time scale of about 107 years in order to remove 1-2 bar of CO₂ from the martian atmosphere. This removal process is dependent on water pH and, according to Kahn (1985), could have produced the equivalent of 20 meters or more of calcite. Furthermore, this process would cease in removing atmospheric CO₂ once the temperature declined low enough to preclude the existence of any liquid reservoirs. This would roughly leave CO₂ levels in equilibrium since carbon dioxide itself is fairly resilient to photodissociation, which alone can only account for a 10 mbar or less total loss from photochemical reactions (i.e., energetic carbon atoms at the exobase) in the atmosphere (Kahn, 1985).

Another surface process possibly responsible for volatile reduction would be the presence of metallic iron in surface materials. This could cause the reduction of H₂O into FeO and produce diatomic hydrogen which, as mentioned previously, would later escape to space (Dreibus and Wanke, 1985; Beatty and Chaikin, 1990). A last major volatile relocation process would be in the condensation of H₂O and CO₂ into polar and subsurface ices. At least presently, the polar layered deposits constitute the largest potential sink for water injected into the atmosphere (Kieffer et al., 1992).

On the other hand, there are several mechanisms involved in depleting a planet's atmosphere of its volatile constituents directly into space (see Figure 3.3). One way is through the photochemical dissociation of molecules by ultraviolet radiation (specifically H₂O into H, O, H₂, and OH), and their subsequent heating to escape velocities. This process is known as hydrodynamic escape.

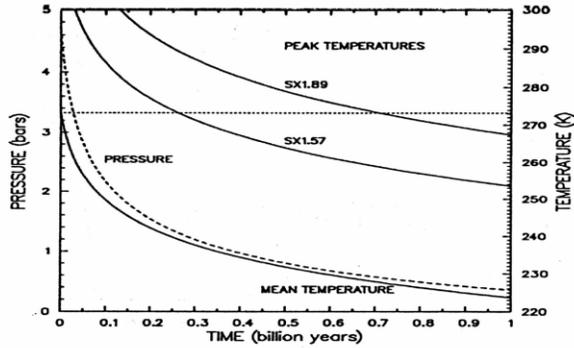


Figure 3.2. Pressure (dashed line) and temperature (solid lines) versus time on early Mars based on simple climate model presented in the text (McKay and Davis, 1991). The solid curve corresponds to the mean temperature on the surface of Mars for the given pressure. Also shown is the perihelion equatorial temperature corresponding to $S_m/S = 1.57$ (middle curve) and $S_m/S = 1.89$ (top curve). As long as peak temperatures exceed freezing, ice-covered lakes can exist. The zero on the time axis was chosen to correspond to the time when mean global conditions on Mars reached the freezing point.

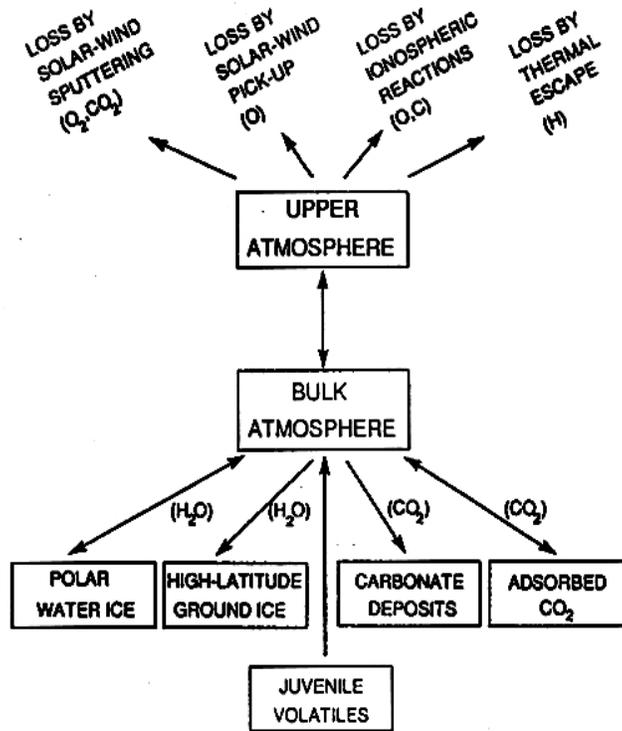


Figure 3.3. Schematic representation of the Mars climate system, showing exchange of volatiles among the surface, bulk atmosphere, and upper atmosphere. Boxes represent volatile reservoirs; arrows represent exchange of volatiles between reservoirs or permanent removal from a reservoir, depending on whether the arrow is mono- or bidirectional (Jakosky, 1991).

Nonthermal escape and sputtering are two more ways whereby dissociated ions, as mentioned above, become trapped within magnetic field lines of the solar wind and are carried off-planet (Jakosky, 1991).

Isotopic differentiation and elemental fractionation (Figure 3.3) occurs during inter-molecular reactions by way of various mass-dependent atmospheric escape or condensation processes (Jakosky, 1991). Lighter isotopes are preferentially removed (i.e., increasing the ratios of $^{18}\text{O}/^{16}\text{O}$, $^{13}\text{C}/^{12}\text{C}$, $^{15}\text{N}/^{14}\text{N}$, and D/H) to the point that current isotopic abundance measurements indicate atmospheric history and evolutionary processes (Jakosky, 1991; Carr, 1987; Pollack et al., 1987). Thermal escape of hydrogen, at its current rate ($6 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ as 2H and O [Stoker et al., 1996]), corresponds to the loss of the equivalent of a layer of water 2.5 meters deep over the entire planet during its 4.5 Gyr history. Carr (1996) estimates, given current climatic conditions throughout martian history, that at least three meters of water have been lost from the upper atmosphere (up to 70 meters if high obliquity periods are accounted for). Hydrogen escape also accounts for the measured enrichment of surface deuterium with respect to terrestrial values (1.5 to 2.0 times greater). Such an enrichment in the levels of deuterium suggest that an estimated 3.4 meters of water have escaped from the surface of the planet (Kieffer et al., 1992). It is also important to note that Dreibus and Wanke (1987) and others have shown that noble gas abundances can be used as indicators of water abundance and gas loss from the primitive martian atmosphere.

Due to its small radius and low gravitational acceleration, another mechanism which probably occurred readily in the first billion or so years was associated with the shock heating of the atmosphere and subsequent impact blowoff due to 10 km-or-larger planetesimal impacts (Dreibus and Wanke, 1985; Beatty and Chaikin, 1990). Kieffer et al. (1992) compiled information showing that the vapor plume created by a sufficiently large projectile is capable of ejecting the entire air mass above the plane tangent to the point of impact. Note that this kind of an event will not fractionate any of the associated constituents and thereby indicates other types of specific evolutionary events (i.e., refuting or confounding current isotopic dependent theories). One of the last and most important atmospheric loss mechanisms is that of the simple diffusion of lighter elements upward to the exobase, where one of the preceding non-impact-related processes removes them to space.

3.1.3 Geomorphology—Cratered Uplands at High Latitudes

It is the cratered uplands at high latitudes that provide some of the most dramatic evidence for past presence of large amounts of water on Mars. Poleward of the 30° latitude bands, Mars is characterized by a host of geophysical forms which preclude the existence of subsurface ice. These conclusions have come from "periglacial" comparisons made on Earth. The features include fretted terrain, debris flows, and degradation due to the viscous creep of ice-saturated materials. Fretted terrain refers to areas with a strong bimodal distribution, by elevation, of flatter lowlands separated from the more heavily cratered uplands through a complex pattern of 1-2 km-high escarpments (Carr, 1987). Commonly found along the northern lowland/southern highland boundary, fretted terrain escarpments are girded by debris flows which extend up to 30 km from their bases. These features are generally limited between the 30° and 55° latitude bands (Carr, 1987; Mendell, 1985). As presented in Figure 3.4, restriction within these bands is understood by noting the instability of ground ice equator-ward of approximately 35° and poleward of about 55° where ground temperatures fall below 180K, and which in turn greatly inhibit creep rates (Carr, 1987; Squyres, 1989). Observational data has also shown that such features are absent at lower latitudes and is in agreement with the former conclusions.

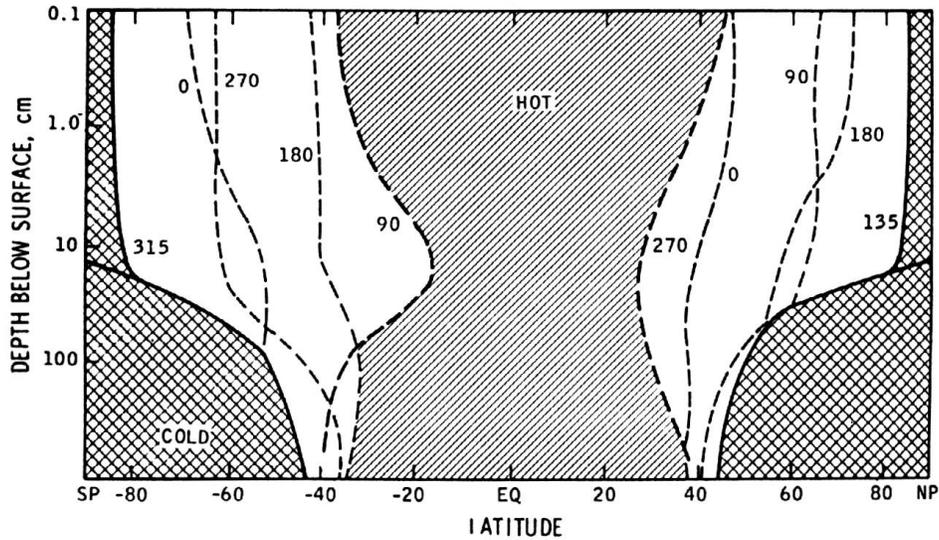


Figure 3.4. Regions in the regolith showing where water ice might be stable, based on subsurface temperatures and an average atmospheric water vapor abundance. The dashed lines mark the calculated stability regions at 90° increments of L ; the hatched region denotes where water ice is not stable at any season; and the cross-hatched region denotes stable ice year-round. From Farmer and Doms (1979) (McKay and Davis, 1991).

Slow, solid-state, viscous creep of subsurface ices is a well-studied and common characteristic of any ice-laden planetary body. Water ice has been shown to undergo ductile deformation at temperatures even lower than those encountered on Mars. Squyres (1989) has provided two classes of landforms that are produced under such conditions. The first category results from materials which have been transported via mass wasting processes away from their associated escarpments. Included here are the fluidized ejecta deposits, which seem to occur planet wide as opposed to the two remaining formations: the lobate debris aprons and concentric crater fill. Mouginis-Mark (1981) has divided these fluidized ejecta curtains, or "rampart" craters, into two categories. Resulting from impacts into water-laden target material, Type 1 craters possess a single continuous ejecta deposit, whereas Type 2 craters are surrounded by two concentrically lain deposits (see Figure 3.5). Both types are emplaced with distal ridges (i.e., "ramparts"), and show morphology which is indicative of ground-flow processes.

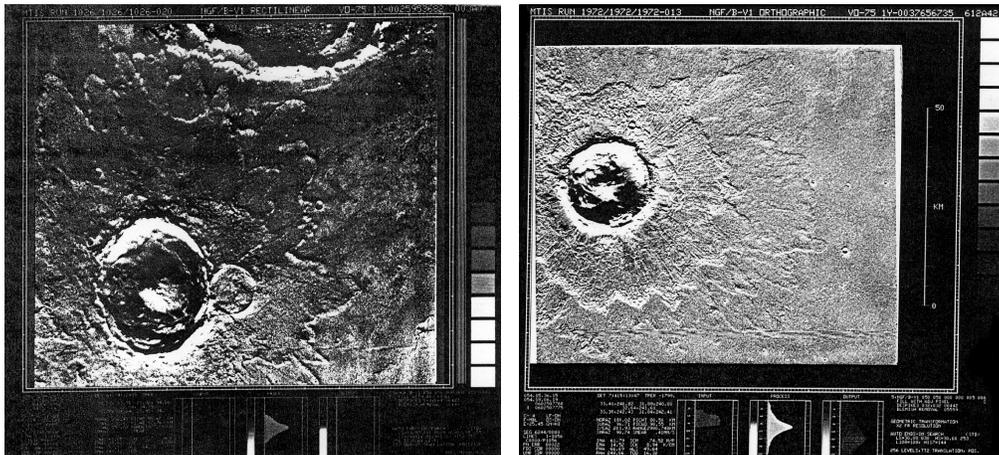


Figure 3.5. Two categories of rampart craters: those possessing a single continuous ejecta deposit (left) and those surrounded by two concentrically lain deposits (right) (Mouginis-Mark, 1981).

On the other hand, lobate debris aprons are thick accumulations of material at the base of escarpments and are similar to glacial debris flows on Earth. They are pronounced by convex topography and show surface lineations parallel to the flow and compressional ridges where obstructions have been encountered (Squyres, 1989; Mendell, 1985).

Concentric crater fill is roughly the same thing, yet it is confined within impact craters and produces concentric ridges due to compressive stresses. These forms are all very similar and fit into thermodynamically expected distributions of mobile near-surface ground ice.

Squyres' (1989) second class of viscous creep features is referred to as terrain-softening (see Figure 3.6 a, b). Located within the same 30°-50° latitude bands, this process shows a distinct muting of topography through the smoothing and rounding out of all associated land features. This process is basically the result of gravity-assisted settling of material that is rich in water ice. Terrain softening and the previously mentioned rheological deformation processes provide the most convincing evidence, both currently and historically, for the presence of water on Mars.

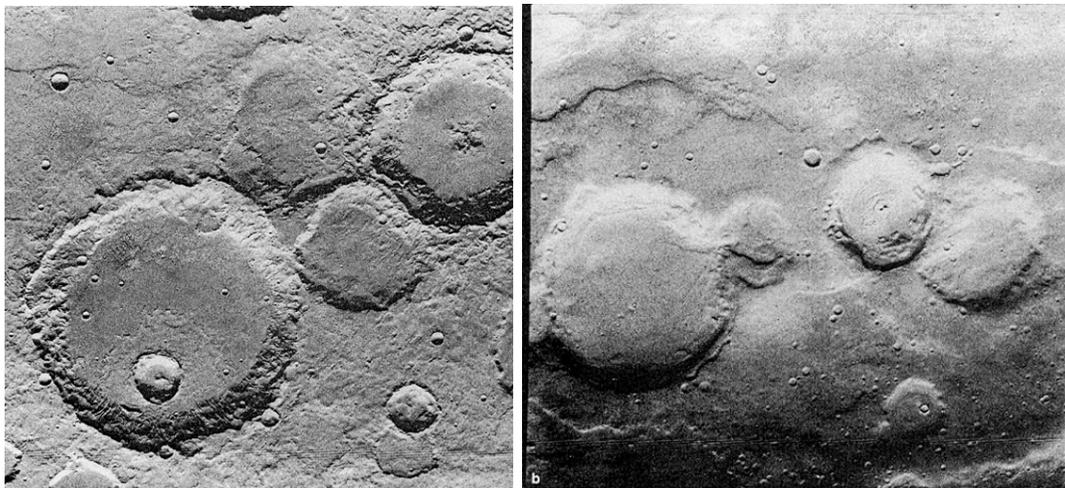


Figure 3.6 a, b. Images showing unsoftened (a) and softened (b) cratered terrain (Viking Orbiter images 42S10, latitude -32°, longitude 227°, scale across frame is about 160 km; and 195S20, latitude 33°, longitude 313°, scale across frame is about 60 km) (Squyres, 1989).

3.1.4 Geomorphology—Cratered Uplands at Low Latitudes

The cratered uplands at low latitudes are degraded predominantly through fluvial-like processes and therefore provide the best support for the theory of a wetter and warmer climate early in martian evolution. Researchers like Carr (1987) have labeled branching valley networks and outflow channels as the two predominant fluvial processes on Mars. Pervasive throughout the low-latitude ancient highlands, the valley networks have similar morphologies to terrestrial drainage systems, yet individual martian valleys contain rectangular or U-shaped cross-sections with flat floors, steep walls, rounded amphitheater terminations to tributaries (Squyres, 1989) and relatively poorly developed dendritic branching patterns. These valley systems were emplaced during the period of heavy bombardment (i.e., over 90% cut the Noachian, ~2.5 bya) as shown through the density of superimposed impact craters (Figure 3.7). For almost 90% of the recorded valleys, the longest path through the network to the most distant tributaries are between 20 and 200 km with an average between 60-70 km and the longest being 1350 km. The Earth itself only has 25 rivers over 1000 km long, with the longest being the Nile (6650 km). Most researchers now believe that these features are a result of sapping, the gradual erosion of material due to the flow of subsurface liquid water, as opposed to runoff erosion due to precipitation (Carr, 1987;

Squyres, 1989; McKay and Davis, 1991). Valley system morphology (Figure 3.7) seems to require a significant amount of time to produce the volumes of erosion presently observed.



Figure 3.7. Valley system morphology demonstrating erosion.

Goldspiel and Squyres (1991) have calculated the volume of water and sediment removed from Ma'adim Vallis, which is the largest ancient valley system on Mars. They have also shown that Ma'adim Vallis empties into the 150-km-diameter crater Gusev, which subsequently supports theories involving lacustrine-type (i.e., lakes or oceans) environments and formations (Squyres, 1989). Estimates for the total volume of material removed from the Ma'adim Vallis system are around $13,000 \text{ km}^3$ and a corresponding layer of deposited sediment in Gusev of 780 meters. The most common and important conclusion for the formation of such valley systems is that they could not have formed under present climatic conditions but during a more clement era early in martian history (Carr, 1992).

Outflow channels, though, provide the best evidence for flowing water throughout martian history. They are most commonly found on the northern lowland/southern highland boundaries, adjacent to the equatorial canyon systems of Vallis Marineris, the Chryse-Acidalia basin, in Elysium Planitia, the eastern part of Hellas basin, and the southwestern margins of Amazonis Planitia. Channels stem from a cratered highland source region and debauch onto the lowland plains (Clifford et al., 1989; Carr, 1987). These channels arise fully born from chaotic regions where there was a rapid removal of subsurface material, and then extend downstream for hundreds of kilometers (Figures 3.8 and 3.9).

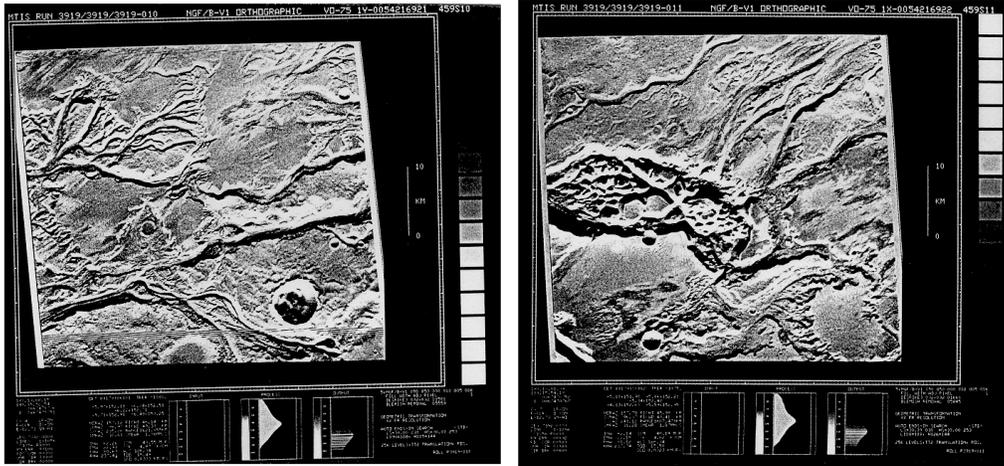


Figure 3.8. Outflow channels.

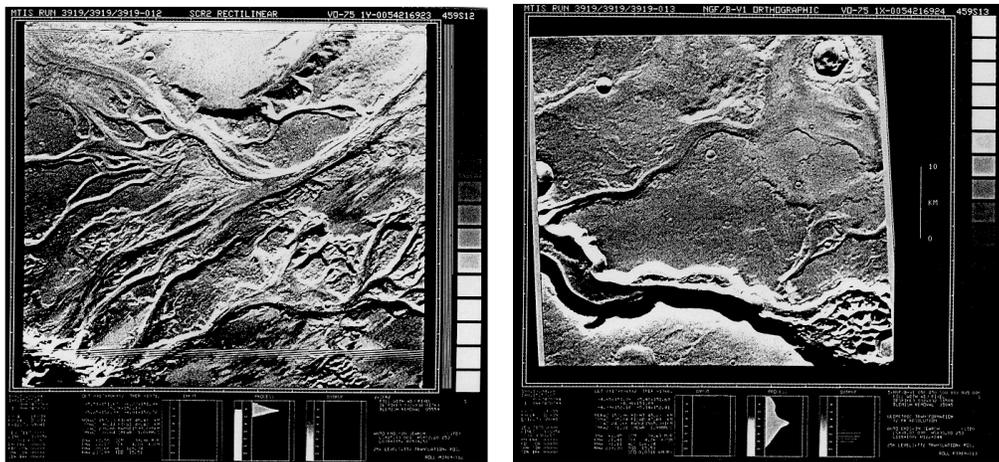


Figure 3.9. Outflow channels.

Channels have bed-forms on their floors which include longitudinal scours, inner channel cataracts, and plucked zones. They are also characterized by sinuous streamlined walls, enclosed teardrop-shaped islands, and tend to be deeper closer to their source (Carr, 1992). Such a massive release of subsurface water (i.e., as high as $3 \times 10^8 \text{ m}^3 \text{ s}^{-1}$ whereas the average Mississippi discharge is $3 \times 10^4 \text{ m}^3 \text{ s}^{-1}$) suggests some form of geothermal heating or tectonic compression of confined aquifers followed by a release of liquid at very high pressures (Squyres, 1989; Carr, 1987). Carr (1987) calculated a minimum volume of eroded material for a single large circum-Chryse channel to be about $5 \times 10^6 \text{ km}^3$. The minimum amount of water required to perform this amount of erosion would have been $7.5 \times 10^6 \text{ km}^3$, based on the assumption that there was a 40% by volume sediment load (i.e., the maximum amount of sediment in suspension for the estimated type of surface material) and a maximum resistance by materials towards erosion. From this, Carr (1987) also determined that such a release would be equivalent to 50 meters of water spread over the entire surface of the planet.

Squyres (1989) and others estimate that such catastrophically enormous floods would retain enough latent heat to be able to flow for many hundreds of kilometers under present climatic conditions before being halted by freezing or sublimation. This line of thought corresponds well with the Mouginis-Marks (1990) observation of young channels (i.e., less than 1 byr B.P.) on the Tharsis Plateau between Olympus Mons and Ceraunius Fossae. Though, to date, the youngest channel flows have been located near both Elysium Planitia and Amazonius Planitia (estimated to have been dug during the Amazonian era, ~2.8 bya, whereas the majority are Hesperian in age, ~3.9 bya).

These features are thought to be the result of intrusive events and geothermal heating of deep-seated cold trapped volatiles. The minimum volume of material removed from the channel in Figure 3.10 is estimated to be 1.15 km³ with an associated water release of about 3 km³ (again using an erosion efficiency of 40%).

Figure 3.11 is another example of a young water release producing raided channels some 400 km long near Olympica Fossae and Olympus Mons (Mouginis-Mark, 1990). The magnitude of these outflow channels tells us that an abundance of water has flowed on Mars; Yet, they provide little evidence, thus far, concerning the specifics of climatic change, history and the overall evolution of the planet.

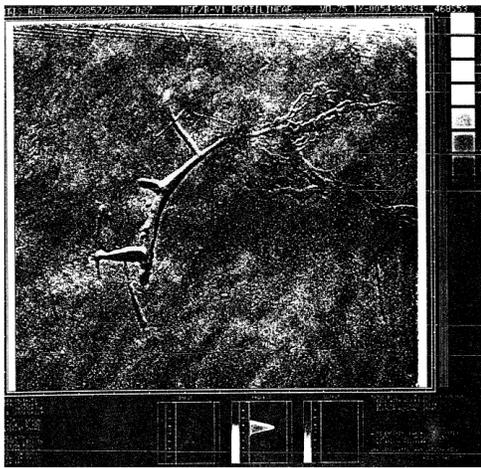


Figure 3.10. Erosion through release of water.

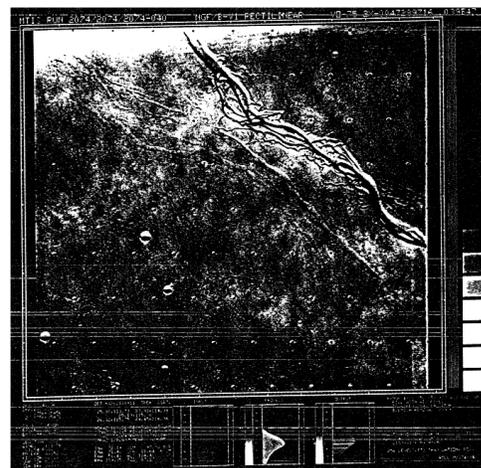


Figure 3.11. Waterflow-induced erosion.

3.1.5 Geomorphology—Plains and Poles

The final two regional features, the plains and poles, clearly demonstrate invisible and visible reservoirs of water, respectively. The plains regions on Mars occur mostly at low latitudes or in low-lying areas at high northern latitudes (Carr, 1987). The low-latitude plains are chiefly the result of volcanic activity and are typically some of the youngest terrain on the planet (i.e., the Tharsis plateau and Elysium Planitia). Some of these plains contain complex patterns that have been associated with lava-ice interactions. This correlates well with the theory that volatile poor lavas covered the more volatile rich megaregolith and basement material. As mentioned in the previous section and shown in Figure 3.8 and 3.9, channel formation has occurred in the Tharsis volcanic plains region due to the blanketing, compression and heating of older units (Mouginis-Mark, 1990). Yet the low-lying, high northern latitude intercrater plains are also of great interest because they are situated downstream and at the termini of several large, highland outflow channels. Carr (1987) has noted several channels northwest of Elysium, some 50° north

latitude, that terminate in fine branching distributaries that have debauched onto the northern plains. Other channels include the large Amazonis channel and the circum-Chryse channels. Large amounts of outflow and mass wasted volatile rich materials, which have probably been mixed with ice, have been interbedded on these plains and result in a complex assortment of terrain features (i.e., polygonally fractured ground, mottled albedo markings, ridges, irregular pits, etc.). The northern plains are also well-categorized as being regions of high thermal inertia, which are indications of a fine (~40 mm or smaller) particulate dust (Keiffer et al., 1992). This fine aeolian deposit is probably a mixture of salts and clays and has been estimated to hold between 3% and 15% water of hydration (Stoker et al., 1996).

The poles, on the other hand, are the only places where substantial amounts of water have been directly observed. The north pole of Mars is comprised of a perennial water ice that is circumscribed by terraced aeolian deposits (Figure 3.12). These deposits gradually warm and melt and then are covered again with wind blown sediments, depending on orbital obliquity and season. During the northern winter, the water ice and frost sheets extend down to at least 80° N latitude and are covered with a CO₂ frost layer. The south pole, though considerably smaller, is also considered to have a water-ice deposit, yet the surface temperature remains cool enough to allow for the condensation of a perennial CO₂ ice layer. Viking data corroborates the existence of these CO₂ reservoirs due to the measured increases in atmospheric CO₂ in the summer hemisphere. At this time, it is the martian poles about which we know the least, and from which we may have the most to gain in the future.

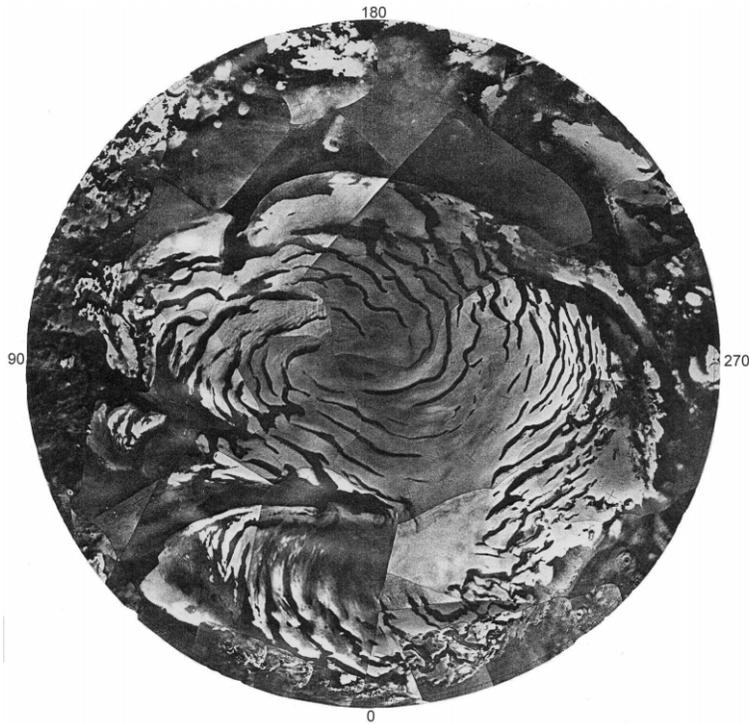


Figure 3.12. North pole of Mars showing perennial water ice circumscribed by terraced aeolian deposits.

3.2 Resource Acquisition and Exploration

Having outlined the current level of understanding concerning the presence of water and related volatiles within the martian environment, the techniques that could be employed in extracting this precious resource are now examined. According to Zubrin (1996) and others, there are currently several techniques that could be employed in the retrieval of martian water. A point of interest is that no new technologies need be considered and several of the ones mentioned have been in existence for a century. Again, note the possible reservoirs of martian water:

- 1) Geothermally heated pools or artesian aquifers
- 2) Subsurface brines (liquid as low as -55°C)
- 3) Polar ice deposits (again the only currently known source of large amounts of water)
- 4) Subsurface ice and permafrost in the regolith (indicated to be poleward of approximately 40° latitude)
- 5) The martian soil
- 6) The atmosphere

Any initial mission will take advantage of many extraction techniques to not only provide the required redundancy inherent in space exploration, but to establish a net gain in supplies that will firmly establish a permanently manned facility.

With regards to the reservoirs one, two and four above, a cautious choice of landing site could place such deposits within the top few meters of the surface, yet even finds within a few hundred meters of the surface could be reached if the proper tools were employed. In this paper we assumed that one of our landing craft would be primarily used as a drilling platform with a maximum depth of penetration of roughly 200 meters (a simple task for any drilling company on Earth). Zubrin (1996) suggested that such drilling may cut reservoirs that are under some form of head pressure. If this were to occur, liquid material would geyser into the thin martian air, freeze and precipitate onto the surface near the well, where it could then be collected. It is also important to note that any drilling equipment of this size will provide invaluable stratigraphic data that can be used to answer questions concerning regional and planetary formation.

For reservoirs three, and again four, it may be necessary to provide crews with blasting equipment in order to free material that is frozen at ambient martian surface temperatures. Once broken into manageable sizes, the material will need to be heated (as mentioned later) to release the frozen water. There may also be other locations where ice outcrops have remained intact (e.g., recent low latitude impacts, north faces of crater rims, lava tubes, etc.).

Analysis of how to extract water from our fifth surface-related reservoir, the soil, has taken many forms. Ash et al. (1978) and others have noted that a batch processing unit which utilizes the excess heat rejected from the power generating equipment suffers no loss in electrical power needed to provide the 500°C temperature required to extract the water. Based on a 2% water by volume analysis, they concluded that roughly 346 l. of soil would need to be processed to extract 9 kg of water. Another technique, as already mentioned, requires heating in a conventional oven (to approximately 500°C). This data and technique, though not planned for, was roughly demonstrated by the Viking gas chromatograph mass spectrometer. As demonstrated in the literature, soil can generally be processed by one of two methods: The first includes the collection and transportation of material to the processing facility (ovens), whereas the second incorporates the ovens/heaters into a roving vehicle. It has been estimated that the energy required and amount of water produced would be: 1) 100 kWh gives 700kg/day for the stationary device (or more if the waste heat from a nuclear thermoelectric generator were employed); 2) about 300W for running the rover-oven making 42 kg H_2O per day (using a radioisotope thermoelectric generator). The

major difference is that the fixed ovens will require trucks to move the feedstock to them, and the ovens themselves will then produce about 120 m³ of slag material (i.e., dried dirt). A mobile oven, on the other hand, will collect, heat, and redeposit soil as it travels. Along the same lines but without the requirement of moving large quantities of martian soil, Zubrin (1996) suggests the use of a mobile microwave oven. A major equipment advantage, this machine would use selected frequencies and a skirted collector to irradiate surface material and collect the resulting steam on cold plates within the cavity of the rover (estimates are 1 kWe-hr per kilogram water). Though less efficient, this machine might prove mechanically simpler. A final method, simplistic as it sounds, may prove to be the most economically feasible. The emplacement of a transparent dome constructed out of a 0.1-mm-thick polyethylene could be used to farm selected soil sites in a systematic manner. Inside the tent, the surface temperature would increase, allowing volatilized water to be captured by an enclosed cold trap device. Zubrin (1996) showed that a 25-meter hemisphere, ringed by reflectors, could obtain an effective power level of 98 kW (e.g., about 700 W/m²). This is enough of a temperature increase to farm about 224 kg of water in an 8-hour day.

Lastly, we look at our sixth source of martian water. Though one of the driest sources (Viking values range from 1 to 90 precipitable microns), the atmosphere could provide an alternative source of water production (beyond that which was produced during return vehicle fuel processing). Two main techniques have been researched in this field. The first entails compressing large quantities of native air to condense out appreciable amounts of water. Though having the extra benefit of producing needed argon and nitrogen, it is almost 30 times more energy intensive than soil extraction. The second process includes moving large quantities, again, of air across a zeolite sorption bed (a desiccant that can absorb up to 20% of its weight in water). Producing a 100-meter-per-second wind flow, this process could produce up to 90 kg of water per day at an expense of about 10 kWe. Again, it will be well within the means of the first manned mission to incorporate several of these techniques in the pursuit of ISRU and the establishment of the first permanently manned outpost.

3.3 The Future of Water on Mars

Without providing fundamental answers to the questions concerning planetary volatile evolution, environmental and climate histories, relevant research as well as efficient and economically viable resource utilization on Mars cannot be conducted. As with many other aspects of this first flight, water acquisition will take into account multiple resources and methods of processing. To finally resolve the issue of where to erect large human habitats on Mars, a multitude of questions will need to be answered by both precursor robotic missions and human prospector missions. Such questions involve the examination of water-formed features such as the valley networks, outflow channel, and lacustrine deposits. It is also important to understand the hydrology of surface and subsurface deposits. Do the high-latitude, low-lying plains contain near-surface ices that contribute to the effects of terrain softening? What is the present state of the martian water cycle? Do carbonate deposits exist that suggest a history of a warmer and wetter Mars? Did life ever evolve on Mars and, if so, does it still survive? In light of these and other questions, mission planning aimed at the identification of material abundances, as well as precursor mission data analysis, will provide the first manned flight with the necessary information to establish a permanent human presence on the planet Mars.

4. Energy

4.1 Energy Requirements

Energy will be a key driver for the establishment of a self-sufficient martian outpost since resource extraction is energy-intensive (Duke, 1985). This section highlights the key advantages and disadvantages of many of the currently proposed Mars power regimes and subsequently ascertains their feasibility in terms of site selection. The energy systems needed generally fall into two categories: mobile and base-load. Mobile power sources are needed for space suits, rovers, robots, and rocket engines. Fuel cells, batteries, and internal combustion are options for these short-term and mobile applications but require a base-load system for recharge. The base-load power is of primary concern in this section and in Mars mission planning in general. There are four potential sources for martian base-load energy systems: imported nuclear, geothermal, solar power, and wind power. It is believed that wind and surface solar power generators are highly variable and of limited use as base-load systems. However, mobile power sources can also be thought of as energy storage systems which enhance wind and solar generating systems. Presently, several Mars exploration scenarios assume in-situ production of energetic mobile energy sources (e.g., rocket fuel). By using these same resources in surface combustion or fuel cell systems, a broader base-load power system will provide for a more robust and efficient energy storage capability for use by any near-term manned Mars mission.

It has been estimated that the power to operate Biosphere 2 was approximately 100 kW per person. However, this did not include the energy required for materials production and pressurization, which would raise such energy requirements. Nor did the Biosphere 2 program include the ability to extract new resources from the environment or to exchange wastes with the outside, which would lower the anticipated energy needs (Meyer, 1996). A Japanese study placed a value of 20 kW to 50 kW per person as the value needed for a 150-person Mars settlement. In another study, Haslach (1989) reported that 400 kW would be needed to support a martian habitat. However, no description of number of people or types of activities to be performed is associated with this estimate. Therefore, it has been ascertained that a power supply system on the order of 100 kW to 500 kW will be needed for the outpost presented in this document.

4.2 Nuclear Resources

4.2.1 Feasibility

Nuclear power is traditionally listed as the baseline power supply for Mars missions (Zubrin 1996, Meyer 1996, Duke 1985). From the late '50s to 1972, a series of analytical and experimental projects were undertaken to produce viable space nuclear power systems (Colston, 1985). One high point of this work was the 1965 flight of the .5 kW SNAP 10A reactor, which operated in space for 40 days. The NASA-sponsored SP-100 project was initiated in 1981 and targeted the production of a 100 kW system with a 7-year lifetime (Colston, 1985). Estimates of the power output of the SP-100 class reactors, as a function of mass, range between 37 W/kg and 17 W/kg (Zubrin 1996, Haslach 1989). Although these projects remain uncompleted, the technological foundation has been laid and no stumbling blocks are seen. The Russians however, continued development of a space nuclear reactor to produce the 6 kW TOPAZ II with a 3-year life (Voss, 1994).

4.2.2 Advantages

Nuclear power is a compact method for generating power in the 100 to 500 kW range. The technology is well understood and at least one space-qualified system has been produced (Voss, 1994).

4.2.3 Disadvantages

Most power plants envisioned would produce radioactive wastes after a 7- to 10-year lifetime that would have to be disposed of (Boston, 1996). The power units could not be recharged in situ without a great deal of high technology and mineralogical support. Also, there is a great deal of political and public resistance to building, launching, and using nuclear reactors at this time. In fact, for the near-term Mars missions, the ability to build and launch a significant reactor could be a long lead-time item when taken in light of the political, legal, and technological hurdles involved.

4.2.4 Site Selection

The only potential site constraint for nuclear power is the availability of a relatively deep crater near the landing site which would contain the reactor and shield the habitable portions of the landing site (Cohen, 1996).

4.3 Geothermal Resources

4.3.1 Feasibility

Geological measurements are required to determine the heat flux on Mars. However, a current estimate suggests that the average value is close to 35 mW/m². This is less than the average terrestrial value of 80 mW/m². On the Earth, the process of plate tectonics typically serves to concentrate this energy (Meyer, 1996). This process is not currently seen or believed to be possible on Mars. However, young volcanic features are also indicative of underground geothermal sources (Zubrin, 1996). Seven percent of the martian surface was geologically emplaced during the Upper Amazonian period (this dating comes from an impact crater count of less than 40 craters larger than 2 km per 10⁶ km²). Of this, about 3.1% is covered with formations resulting from young igneous intrusions or various fluvial processes which are indicative of near-surface volcanic heating. Hence, 4.5 million km² of martian surface area is likely to have experienced volcanism in the last 700 to 250 million years. In fact, it is possible to have had active volcanism until recent times or even ongoing today. These regions are likely candidates to have near-surface resources of geothermal energy (Fogg, 1996). It should be noted that this significant near-surface geothermal energy may not have a surface manifestation. With this in mind, Fogg points out that most Amazonian volcanism (which is less than 2 billion years old) lies on the 28% of the surface (40 million km²) contained between 20° and 220° W and 50° N to 15° S. This area may contain many regions of such cryptovolcanic or subsurface volcanism which may be a result of a huge mantle plume of ascending magma (Fogg, 1996). Therefore, there are many regions of Mars that may possess geothermal resources.

The question of how deep and where these resources are will only be conclusively answered by drilling missions. However, some estimations are possible. Table 4.1 is provided in Zubrin (1996) as a guide to the depth needed to reach geothermal resources given different geological ages. As a point of reference, a single-well geothermal source of 150° would produce 10 MW of power. This assumes that heated fluids are available to directly drive the energy production turbines (Fogg, 1996). Fogg also discusses extraction techniques when lower temperatures are available and when geothermal fluids are not available. Electricity production represents an indirect use of geothermal energy and has a maximum

conversion efficiency of about 20%. On the other hand, direct use of geothermal energy for heating has been demonstrated to attain efficiencies of close to 90% (Fogg, 1996).

Fogg also suggests a 10-km limit of the depth of available resources. This maximum depth is set for two reasons. First, at 10 km most pore spaces in the crust will be closed by compaction and heated fluids would not be available. Also, 10 km is an accepted maximum limit for terrestrial drilling technology (Fogg, 1996). Table 4.1 shows that the capability to drill from 2 to 3 km holds the potential for utilizing significant geothermal resources. However, the early capabilities of a Mars outpost will only allow drilling to a few hundred meters for water exploration or extraction purposes as discussed previously. Unless near-surface sources are found, full-scale (i.e., deep drilling operations) use of geothermal energy will not be feasible until the capability to produce, on planet, material supplies such as pipe and drill rod. Therefore, geothermal energy represents a potential resource for intermediate applications after a martian outpost has grown to significant capabilities (Fogg, 1996). Geothermal prospecting, if not immediately, will turn out to be an important activity to ensure future growth and prosperity of a permanent Mars colony.

Table 4.1: Depth of Mars Geothermal Reserves as a Function of Years Since Last Volcanic Activity (Zubrin, 1996)

Time since activity (Myr)	Depth to 0°C (km)	Depth to 60°C (km)	Depth to 100°C (km)	Depth to 200°C (km)	Depth to 300°C (km)
.5	.29	.62	.84	1.38	1.92
5	.65	1.38	1.87	3.09	4.30
10	.91	1.95	2.64	4.36	6.09
20	1.29	2.76	3.73	6.17	8.61
50	2.04	4.35	5.88	9.73	13
>150	3.53	7.53	10	17	24

4.3.2 Advantages

Geothermal power on the Earth can provide from 1 to 10 MW of power. Also, the energy source would likely be near heated underground aquifers, in which case a useful secondary byproduct of the energy extraction process (water) is produced (Zubrin, 1996). The generators used could be common to wind, solar dynamic, and some nuclear sources.

4.3.3 Disadvantages

The true extent and location of geothermal energy is not known at this time. Hence, the initial mission planning could not rely on a geothermal source (Duke, 1985). Also, geothermal energy extraction will require deep drilling, which could be costly in light of mass, time, and safety considerations. Successful exploitation of geothermal energy will require a long-term buildup of mass intensive components or a martian manufacturing capability.

4.3.4 Site Selection

The youngest volcanic regions on the planet are the most likely regions to drill for geothermal power. The candidate regions suggested in (Fogg, 1996) include the Upper Amazonian regions of Elysium, Arcadia, Amazonia, and Tharsis. The Cerberus Plains in SE Elysium are a young region which potentially erupted with a 1% water content which subsequently produced fluvial features to the west. If the plains are indeed volcanic, then the source was either buried fissures or low-shield volcanoes in the west (Fogg, 1996).

Hecates Tholus is the oldest and northernmost Elysium volcano. However, its western slope is almost completely crater-free which suggests a new surface. The most logical explanation is pyroclastic emplacement, which could have been driven by heated water. If this is the case, then the heat source was between 200 and 4000 meters deep and may very well be active today (Fogg, 1996).

Medusae Fosse is located to the southwest of Olympus Mons, which also suggests a pyroclastic origin due to the lack of lava flow patterns and the ease of wind erosion. This suggests a more silicate source for the magma than the volcanic plains of Amazonia to the north and the Tharsis constructs to the east. The current observations suggest that the region was formed by large eruptions occurring over the last two billion years. The youngest regions are in the center and east. The long life of these eruptions and the thickness of the youngest layers suggests that the processes may not be extinguished (Fogg, 1996).

Northwestern Tharsis contains the youngest terrain of the Tharsis province. Most importantly, this region also shows evidence of recent flooding activity. This suggests that shallow reserves of geothermally heated fluids exist. This greatly enhances the utility of a geothermal source (Fogg, 1996).

There appears to be a series of pyroclastic deposits in the floor of Valles Marineris. These features are coincident with the fault system creating the valley. It is suggested that the rifting and subsequent volcanism are not extinct, especially in and around Coprates Chasma. Also, the pyroclastic nature of the eruptions suggests that volatiles such as heated water are strong possibilities (Fogg, 1996).

4.4 Solar Resources

4.4.1 Feasibility

Martian solar power is available but variable (Zubrin 1996, Meyer 1996, Geels 1989, Meyer 1989). The orbital eccentricity, annual dust storms, and day-night cycles all produce fluctuations in the available power. Orbital eccentricity causes a variation in the solar constant from 718 to 493 Wm^{-2} . On average, the martian surface receives about 50% of the solar flux that the Earth's surface does (mainly due to its distance from the sun). On the Earth, there is an average daily insolation of 75 to 200 Wm^{-2} due to increased absorption by the atmosphere. On Mars, though, global dust storms occur one to two times a year roughly at perihelion and can last for months. Local dust storms may also last for a few days (Meyer, 1996). Martian dust storms do not render solar power ineffective, however, since the dust has a scattering effect rather than a blocking effect. Hence an all-sky, scattered light collector would continue to produce power at a level 15% to 25% of its maximum output (Meyer, 1989). Without the scattered light collection, the output could drop by 95% of typical values (Geels, 1989).

There are three extraction mechanisms for solar power: solar dynamic, photovoltaic, and space-based. Solar dynamic systems utilize collected light to heat a working fluid which drives a turbine. Such systems would convert 15% to 25% of the incident energy into electricity, however, a large amount of thermal heat would be available from such systems as well. The major components of these systems (pipes, boilers, and collectors) are “low tech” and would be amenable to repair and eventual manufacturing on Mars (Zubrin, 1996). However, the solar collectors would generally require a point source of light. Hence dust storms would reduce the output up to 95% of typical levels (Geels, 1989).

Photovoltaic systems do not require a single point source of light and would be less affected by global dust storms. These systems operate at about 12% to 13% efficiency for silicon-based photovoltaic cells and less than 20% for advanced GaAs (gallium arsenide cells), and produce no excess heat (Ramohalli et al., 1987). However, the output would be degraded by dust accumulation on the collector’s surface; yet, this could be easily removed by manual or automated systems (Zubrin, 1996). Current thinking would have crews line the sun-facing walls of a small crater with sheets of solar cells. In addition, the power to mass ratio for photovoltaic solar power to offset the continuous production of a nuclear reactor is estimated to be 3.7 W/kg (Zubrin, 1996). It has also been suggested that in the future, these sheets of solar cells could be manufactured on Mars itself. However, since such production facilities represent a “high tech” endeavor, a mature base or colony would need to be in place (Zubrin, 1996).

Space-based solar energy collection and microwave beaming for base-load power has only recently been studied for martian applications (Mankins, 1997), however, it has received a great deal of attention for Earth-orbiting (Collins, 1996) and lunar surface installations (Criswell, 1996). Space-based collection systems would not be subject to the power reductions brought on by the atmosphere and dust storms. Assuming a .25% conversion efficiency as provided by Criswell, (1996) for a lunar installation providing terrestrial power with 1980s technology, an equivalent martian power density would be $0.0025 \times 590 \text{ W/m}^2$ or 1.48 W/m^2 . Hence it would require a solar array area of 68000 m^2 . This translates into a planar array of solar cells arranged in a $259 \text{ m} \times 259 \text{ m}$ square. This would require a spacecraft roughly the size of the fully assembled *International Space Station*. The Japanese are currently considering producing a technology demonstrator satellite of these dimensions to produce solar energy in Earth orbit and beam the power to Earth (Collins, 1996). The footprint of the ground-based rectenna for the Earth orbiting Solar Power Satellite (SPS) is 1 km^2 . Although the rectenna is “low tech” and could be produced from martian resources, it represents a longer-term investment than this project is considering.

4.4.2 Advantages

Solar production systems would not produce wastes and would be sustainable. Solar dynamic generators would be common to wind, combustion, and some nuclear systems. Much terrestrial and space experience exists for solar energy production systems. Solar systems could function in a hybrid mode with other systems to create a redundant base-load system. A space-based system would provide a constant power source which is unaffected by dust storms.

4.4.3 Disadvantages

Surface solar energy production would be highly variable due to orbital eccentricity and seasonal dust storms. Solar energy systems would require periodic maintenance to service moving parts and clear dust from collection surfaces. A full-up space-based system and associated surface rectenna has yet to be verified and represents an investment beyond that which this project is considering.

4.4.4 Site Selection

The equatorial regions between +/- 40° receive the most annual sunlight (Meyer, 1996). Solar dynamic collectors would be most useful in the northern regions during the spring and summer (Zubrin, 1996). Most of the major global dust storms originate between 20° and 40° in the southern hemisphere (therefore this would be a good region to avoid) (Geels, 1989).

4.5 Wind Resources

4.5.1 Feasibility

Contrary to intuition, martian wind power is a viable option (Zubrin 1996, Meyer 1996, Meyer 1989, Haslach 1989). The atmospheric density is about 100 times less than the Earth. However, Mars has three advantages for successful wind power applications: less gravity (less massive components), large temperature and pressure swings, and tremendous surface relief. The power available from a wind turbine is given by the following (Haslach, 1989):

$$P=1/2 c \rho v^3 A.$$

P is the power produced by the wind turbine, A is the swept area of the wind turbine, v is the wind velocity, ρ is the density of the atmosphere, and c is the power coefficient which provides the amount of power which can be converted to electricity. It can be seen that, although the atmospheric density is 100 times less on Mars, the dominant term is the wind speed. Hence, assuming a ρ of .01665 kg/m³ for Mars, a 30 m/s martian wind will provide the same power as a 6 m/s wind on the Earth (Zubrin, 1996). Using a value of c=.4 as is common on terrestrial turbines, a 200 m² turbine could produce 2 kW in a 14 m/s wind and 12 kW in a 25 m/s wind (Haslach, 1989).

Two studies have been performed on martian wind power, both out of NASA Ames. One of these by Haslach produced a concept which called for a 17.25-meter-tall giromill turbine (vertical axis with straight blades) situated atop a 21.5-meter landing vehicle and which would weigh 175 kg.

4.5.2 Advantages

Wind power produces no wastes and is totally sustainable. Also, it requires “low tech” extraction technology. Hence, it would be easily maintainable and potentially expandable. In fact, most of the mass and volume of a wind turbine are in the blades and tower. These are components that could be manufactured early in a martian outpost’s life from native metallic or composite materials. Terrestrial experience has shown that wind/solar and/or wind/combustion hybrid systems are extremely effective systems which can provide near continuous power. Also the generator systems could be common to solar dynamic, combustion power, and some nuclear systems. The best uses for a wind turbine include powering the extraction of fuels, consumables, and construction materials; manufacturing processes; and remote science stations (Haslach, 1989). The power to mass ratio for wind power generated using a design as suggested by Haslach, (1989) ranges from 7.64 W/kg for 14 m/s winds to 44.1 W/kg for 25 m/s winds.

4.5.3 Disadvantages

Wind power is a variable resource when used alone. It would produce power in lower quantities than a nuclear system would. Also, the extraction system would have to be sited appropriately to make full use of the resource. The most effective winds would be about 25 meters above the surface.

4.5.4 Site Selection

The Viking landers measured an average wind speed of 5 m s^{-1} with a maximum of 10 m s^{-1} . It has been estimated that a well-chosen site could see 14 m s^{-1} . Possible sites include the horseshoe vortices around raised rim craters (as seen by dark streaks). Long, low-angle slopes (as seen on the shield volcanoes or slopes of large basins) may produce winds of 25 to 33 m s^{-1} at 25 meters above the surface. Wind channels due to hills and valleys are natural sites which have been used successfully on the Earth. Also, since Hellas basin has a 44% denser atmosphere (and hence a 44% increase in power), if it is windy then it too would be a favorable site.

4.6 Energy Summary

Three energy sources currently exist which are capable of independently supplying power for a permanent Mars base: nuclear, geothermal, and space-based solar power. Unfortunately, each of the potentially independent systems has some serious issues that will need to be addressed if they are ever to be considered as viable methods for martian energy production: nuclear is currently not accepted by the populace; geothermal reserves are unknown and will require sufficient drilling technology and equipment in place; and space-based solar power has not been sufficiently applied in the estimated magnitude needed.

Hence, the most reliable, efficient, and effective approach is to develop a series of alternative sources and couple them to various energy storage devices. This capability seems to be most readily demonstrated though the use of solar dynamic, photovoltaic, wind, and internal combustion technologies. None of these require development beyond the present state of their respective technologies, and all have been highly demonstrated and accepted.

5. Site Selection

The last major step before implementing a manned mission to Mars will include the process of site selection. This process will take into account, at a minimum, all the knowledge outlined in the previous sections. The purpose here is to highlight a few locations that will afford our mission the greatest access to the resources required to establish a permanent habitat on the surface of Mars, thereby ensuring mission success. The gradual increase in knowledge concerning resource locations and their relative proximity to each other will become evident. Points of interest occur as resources begin to conjoin within a given region. It is at these confluences where real site selection begins. In our discussion we have identified six major resources, and two major geophysical features, which will be used in site selection. The regions in the following figures are approximate and depict information that is relevant in the context of our physical and theoretical understanding as to the present state of the planet Mars. The maps are centered at the 0° meridian and the edges are 180° east and west, respectively.

The resource considered first is water in the form of subsurface ices or permafrost (Figure 5.1). As there is a rather varied set of theoretical responses as to where this boundary might currently lie, we have chosen somewhat conservatively and decided to limit our site to greater than 45° of latitude, north or south. This should give us a reasonable chance of reaching ground ice or perhaps even brines at a depth of approximately 150 meters or less. Soils at this latitude may even contain a greater level of hydration due to proximity of subsurface ices and the possibility of a global water cycle. Also, it is the northern plains regions which show the most conclusive evidence for near-surface ice and permafrost (i.e., fretted terrain, terrain softening, polygonal fractures, etc.).

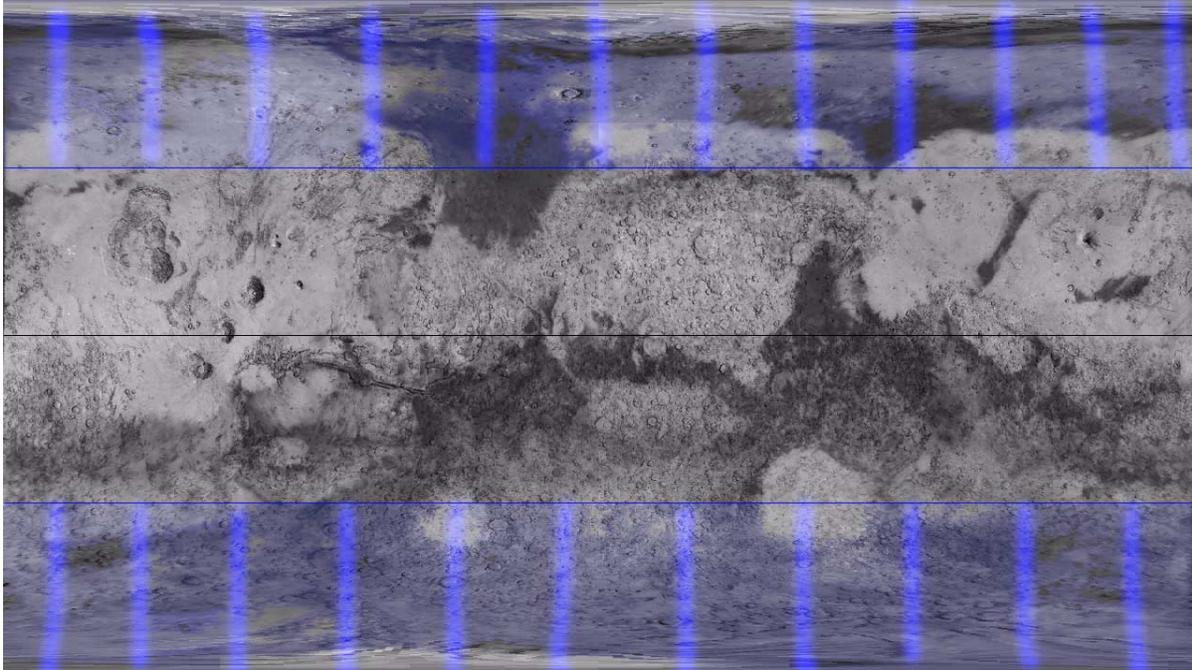


Figure 5.1. Map showing areas believed to contain subsurface ices or permafrost.

Demonstrated next are the regions which are estimated to have a higher amount of atmospheric pressure and therefore water vapor. There are three basic regions where it might be useful to extract water from the air: the northern low land plains (i.e., below the mean surface datum), the deep regions of Vallis Marineris, and Hellas Planatia. In fact, the average atmospheric density within the Hellas basin is 44% greater than the planetary average. As depicted in the following Figure 5.2, these regions are predominantly two or more kilometers below the planetary datum.

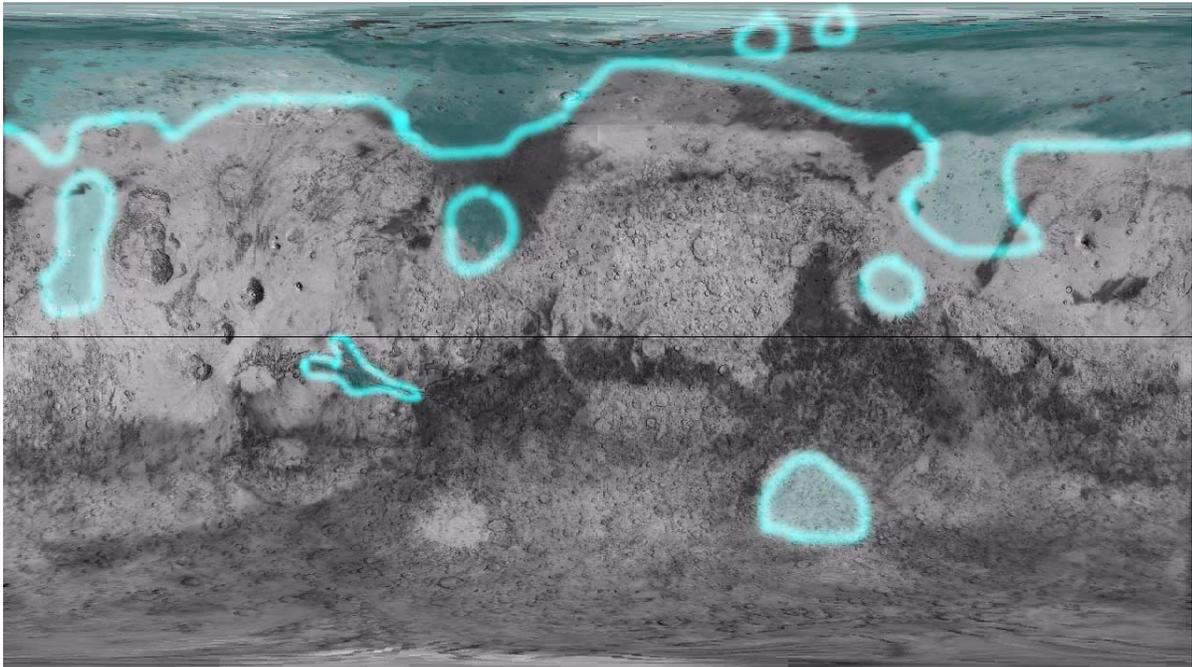


Figure 5-2. Map showing high amounts of atmospheric pressure in Hellas basin.

Regions of low thermal inertia are of interest because they provide indications of a very fine-grained top soil which could be easily mined and transported, and possibly enriched in water of hydration. This material would also be useful in construction and radiation shielding. Large regions of this material may also prove convenient for our limited-capacity, off-road vehicles. The major regions observed from the Viking orbiter include Arcadia, Tharsis, Arabia Terra, Elysium and a portion of Utopia Planitia as shown in Figure 5.3.

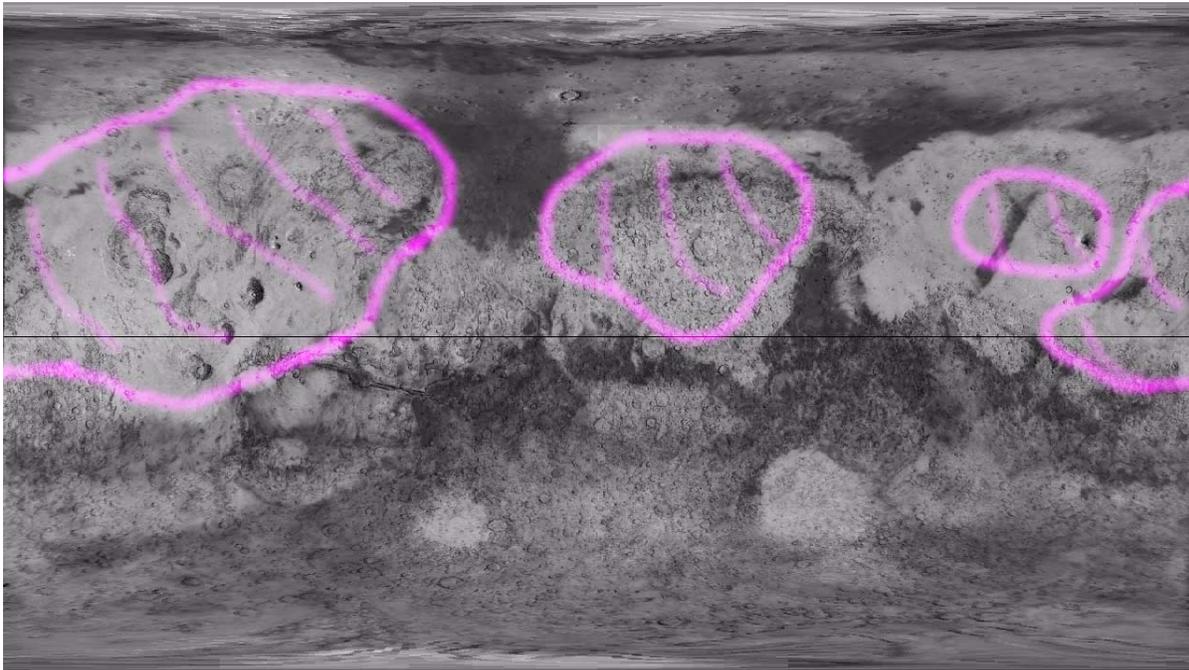


Figure 5.3. Regions of low thermal inertia, indicating fine-grained top soil.

Figure 5.4 depicts possible locations of geothermal-bearing environments which are deemed desirable locations for a permanent habitat. Current evidence suggest that the most recent formations were emplaced as recently as 250 million years ago (i.e., the Upper Amazonian units). These include the upper and lower portions of Amazonis Planitia, northern Arcadia Planitia, north eastern Acidalia Planitia, Tempe Fossae, and, of course, the Tharsis and Elysium regions of volcanic uplift.

Wind is another resource that has been considered in site selection criteria but will not be represented on the map demonstrations (though Figure 5.2 does depict the regions containing higher density air and some of the areas containing long gradual sloping terrain). There seem to be three major geophysical regions that have the long, gentle sloping terrain that is required to enhance movement of large air masses: the entire region surrounding the Tharsis Plateau including Alba Patera, both sides of Elysium Planitia and its volcanic rise, and the Hellas impact basin. Estimated near-surface wind speeds, based on Viking and Pathfinder measurements, vary between 5 and 10 meters per second. Other smaller, locally varying topographical sites that are influenced by wind include horseshoe vortices, raised crater rims, and valley terminations.

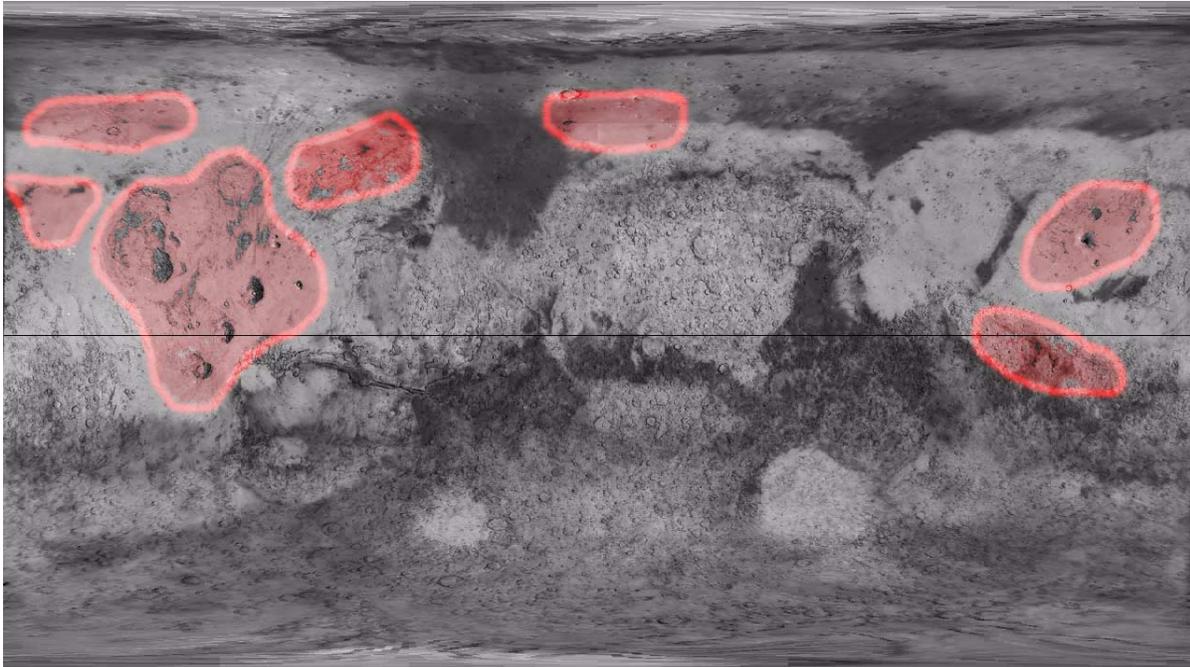


Figure 5.4. Possible locations for geothermal energy sources.

A last major resource is the sun. Research has shown that the equatorial regions between $\pm 40^\circ$ receive the most annual sunlight (not specifically shown on maps). This region is easily identified as that surface area which roughly extends, north and south, between our lines distinguishing the probable location of subsurface permafrost. This area is important specifically for solar dynamic collectors. It is photovoltaics, however, that would prove to be more useful in the northern regions during spring and summer. It has also been suggested that the southern 20° to 40° latitude bands be avoided, since they frequently contain the source regions for planetary and regional dust storms.

Two geophysical features have been considered for site selection for reasons beyond their mere scientific significance: the valley networks and outflow channels, of interest because they will provide answers concerning the volatile evolution of Mars (most importantly water). This will also help to locate current volatile reservoirs by allowing researchers to better determine the total amount of water produced by the planet. These features themselves may still retain minerals and other unexpected volatile reserves. Finally, they will also help answer one of the most asked questions about Mars: Was, or is, there life on Mars? As depicted in Figure 5.5, regions containing outflow channels are shown in green (dotted regions), while those providing signs of valley networks are shown in yellow (highlighted regions).

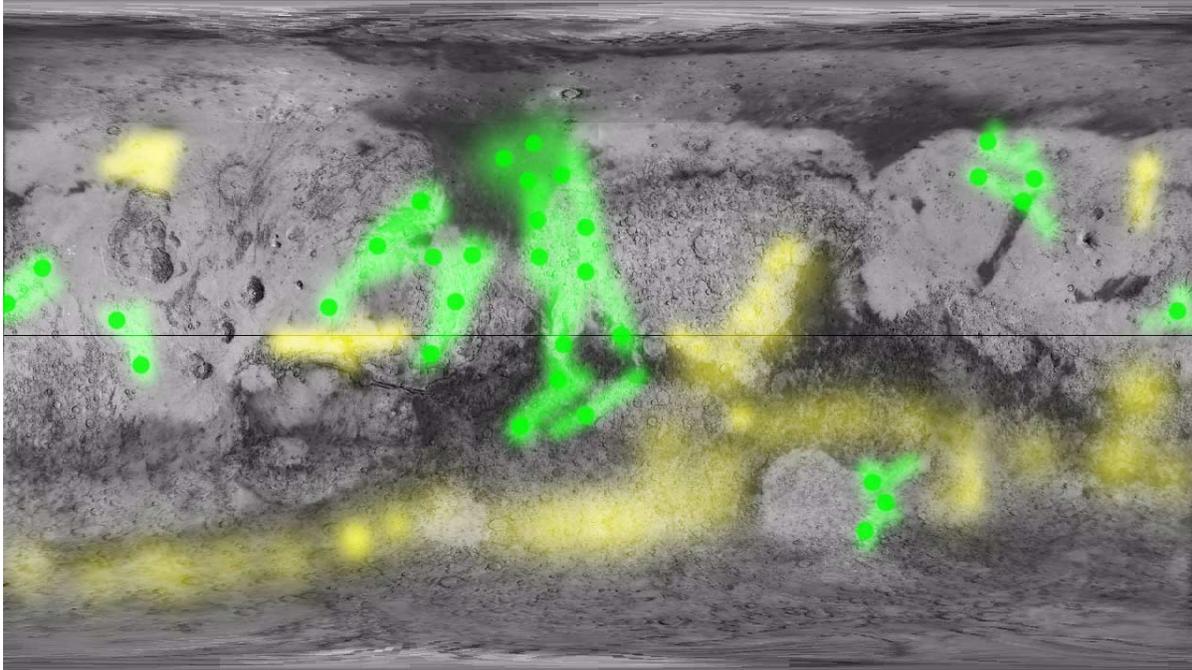


Figure 5.5. Outflow channels (in green) and valley networks (in yellow).

In light of the preceding information, three landing sites have been chosen. These sites seem to provide the broadest range of resources to ensure mission success, while maintaining the highest level of scientific interest as well (Figure 5.6). These include the border between eastern Arcadia Planitia and the Tharsis Plateau (about 120° W and 45° N); the Eastern Utopia Planitia (220° W by 45° N, near the Viking II landing site); and the eastern floor of Hellas Planitia (about 275° W by 45° S). The circles shown are approximately 1000 km in diameter and represent a suggested maximum range for ground transport. Positions of the Viking and Pathfinder landers are also shown.

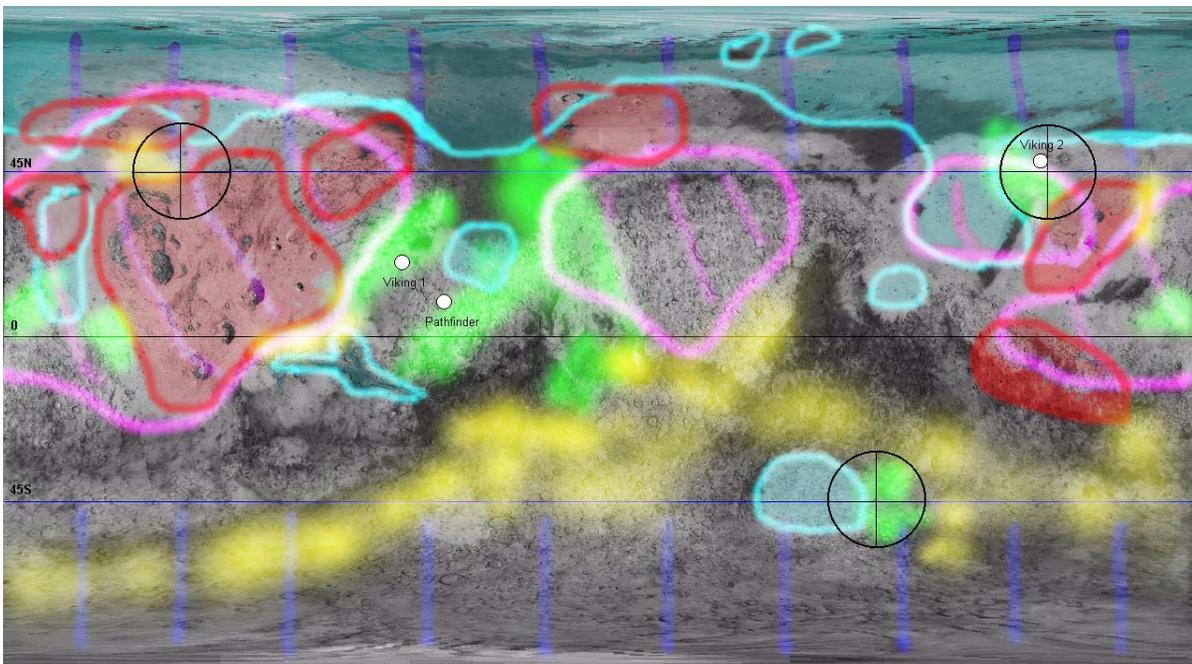


Figure 5.6. Circled areas indicate possible landing sites.

6. Conclusion

This paper has examined the feasibility of establishing an autonomous and permanent settlement on Mars beginning with the first human mission. This would be accomplished through a strategic mission plan in which scientific research is conducted and guided by the requirements for long-term survival. Through the use of established industrial and engineering principles and concepts, self-reliance by living off the land becomes a viable, economically feasible, and realistic endeavor. The identification and development of in situ resources on Mars is essential to achieving this goal. A fundamental limit on our capability to extract and use local resources is the availability of energy. The prospects for developing energy on Mars using wind, solar, geothermal, and nuclear sources have been described. Innovative and efficient additions to our fundamental technologies over the next 6 years will provide a richer and more reliable technological infrastructure from which to build this initial mission. An approach that combines multiply redundant capabilities is, as usual, the best approach for assuring that energy reserves are readily available. The ubiquitous distribution of atmospheric and surface regolith resources is fortuitous for just such a preliminary mission to Mars, since it ensures the successful development of several life support and mission-critical materials. Precursor unmanned lander and sample return missions will establish the precise properties of the atmosphere and Martian soil, and specific equipment can then be designed for initial resource extraction. Propellant, consumable gases, radiation protection, and water will be among the first resources to be developed locally. The identification of accessible and plentiful sources for other materials, especially water, will depend upon scientific investigations in the region of a landing site carefully selected for its potential resource and scientific return. Careful planning and incremental development of new resources will lead, in the near future, to a fully self-sufficient outpost on Mars.

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13. ABSTRACT (Maximum 200 words) As a planet with striking similarities to Earth, Mars is an important focus for scientific research aimed at understanding the processes of planetary evolution and the formation of our solar system. Fortunately, Mars is also a planet with abundant natural resources, including assessible materials that can be used to support human life and to sustain a self-sufficient martian outpost. Resources required include water, breathable air, food, shelter, energy, and fuel. Through a mission design based on in situ resource development, we can establish a permanent outpost on Mars beginning with the first manned mission. This paper examines the potential for supporting the first manned mission with the objective of achieving self-sufficiency through well-understood resource development and a program of rigorous scientific research aimed at extending that capability. We examine the potential for initially extracting critical resources from the martian environment, and discuss the scientific investigations required to identify additional resources in the atmosphere, on the surface, and within the subsurface. We also discuss our current state of knowledge of Mars, technical considerations of resource utilization, and using unmanned missions' data for selecting an optimal site. The primary goal of achieving self-sufficiency on Mars would accelerate the development of human colonization beyond Earth, while providing a robust and permanent martian base from which humans can explore and conduct long-term research on planetary evolution, the solar system, and life itself.				
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