



COLONIZATION

A PERMANENT HABITAT FOR THE COLONIZATION OF MARS

*A thesis submitted in fulfilment of the requirements of the degree of Master in Engineering Science (Research) in
Mechanical Engineering*

BY

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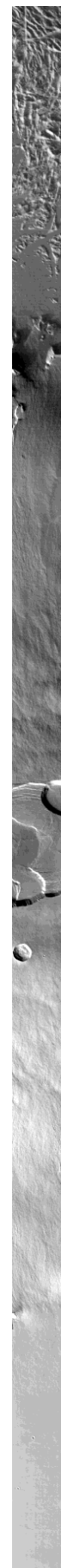
1. BACKGROUND

“Of all of the objects in the solar system, other than Earth, Mars is unique in that all the materials necessary to support life are available on the surface in some accessible form... Mars is the best candidate for the establishment of the first self-sufficient human settlement off Earth,” (Meyer and McKay, 1989).

The colonization of Mars is not a feat for the next decade, not because it cannot be done but because we are not prepared. The preparation for such a task will require input from many corners of the globe and many areas of industry, government and the public and it is a task that has been slowly gaining momentum.

Since humans first landed on the moon NASA and other space agencies, as well as individuals, have been looking to Mars as the next step. Humans could make the journey to Mars, feasibly within the next 20 years and, once it is taken, it will pave the way for, initially, short term habitation and, ultimately, permanent colonization of Mars. The early advancement to permanent habitation of Mars may be advantageous because the long duration of a manned mission to Mars will require the early development of many of the necessary enabling technologies such as resource utilisation, atmospheric recycling, power systems, habitats and other surface infrastructure, similar to those required to support a permanent colony. As many of the technologies required for the exploration of Mars will be similar to those required for colonization, and as infrastructure from manned exploration missions will accumulate, the foundations for a habitat will be laid and a colony could evolve naturally and possibly quickly.

The problems associated with living on Mars are, in many ways, simpler than those of living in space (such as on the International Space Station). Mars has 14.4×10^7 km² of surface and a gravity of 0.34 times that of Earth. Mars also has a day/night cycle very similar to that of Earth and there are local resources that can be used for industry, radiation protection, construction and consumption, none of which are naturally available in space. The colonization of Mars also has numerous benefits over the colonization of the moon, including the day/night cycle (28 days on the moon) and the variety of local resources available.





1.1. WHY INVESTIGATE COLONIZATION?

Why should we investigate the colonization of other planets? There are many reasons and different people will give you different answers. Some scientists will tell of the answers to great scientific questions that will be discovered along the way, or about what we stand to learn about Earth. Some will say that it is simply something that is there to be done, as testimony of the skill and ability of the human race, and talk of the motivation it will inspire in future generations to strive onward, to new heights. All of these appear to be valid reasons.

In the process of spreading into the solar system we will learn a great deal. We will learn more about Einstein's Theory of Relativity, about how Earth and all planets were formed, nuclear or fusion power, propulsion systems and much more. Much of what is learnt will have direct applications to many other areas of commerce and industry such as power generation, transport systems and recycling.

It has been nearly 30 years since Neil Armstrong was the first man to walk on the moon and still people talk of where they were on that day. That was certainly a testimony to the levels humans are capable of, as will be the first person on Mars, when it happens. The colonization of the solar system will be the next 'giant leap for mankind'. The inspiration provided by the race to the moon has led to probes being sent to the far reaches of our solar system as well as Mars and Venus. It has overflowed into other industries, fed the endless demand for science fiction books and movies and been the reason for countless studies and research efforts.

We should investigate the colonization of other planets now so that we are prepared and capable to commence this task when it is deemed a desirable activity by sufficient people to generate the interest and exposure to make it a reality.

1.2. WHERE TO FIRST?

There are three obvious places to start the process of colonization, the Moon, Venus and Mars. These are the three closest heavenly bodies to the Earth and they are the three that we have the most information about.

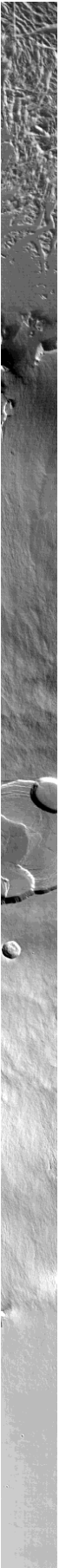
1.2.1. *The Moon*

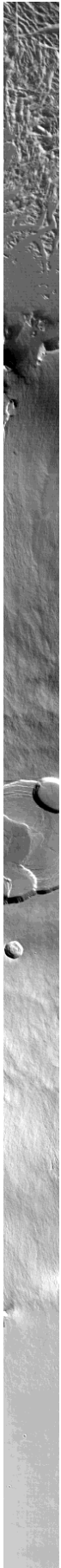
The Moon has been under observation for millennia and is the only body, other than Earth, that has had a human presence. Despite our knowledge of the Moon, anything more than say, an interplanetary launch pad, a laboratory or perhaps a small moon base appears to have many complications. Simplistically put, a habitat requires food, water, breathable air and a certain level of gravity for good health.

There are many health impacts of low and micro-gravity, including those outlined herein. Long exposure to micro-gravity, such as that found in Earth orbit and, potentially, the low gravity of the Moon (1.62 m/s^2) cause several medical problems. Muscle degradation occurs due to the lower weight of objects and reduced muscle usage. Bone decalcification also occurs in low gravity environments, causing the bones to become brittle. Rehabilitation of cosmonauts from the space station Mir appears to have been successful in treating the above problems but their reduced gravity experiences were of relatively short periods, not over periods of years to a life-time that could be experienced in a permanent habitat on the moon. It therefore seems unlikely that a child born in a lunar habitat could easily be appropriately conditioned to overcome the above obstacles to visit Earth without great discomfort or pain. In fact, being born in such low gravity would prevent the normal level of bone calcification forming.

There is practically no atmosphere on the Moon. The atmosphere that is present is known as an exosphere. There is also an exosphere in the Earth's atmosphere. It is the region of our atmosphere, above the ionosphere, where the atmosphere blends into space. The minute amount of atmosphere present on the Moon is comprised of helium, argon and oxygen. Clearly a habitat atmosphere must be manufactured, as would be the case on any known planet. The Moon's lack of significant atmosphere means the habitat atmosphere must be generated from the crushing of, and extraction of gas from, the Moon's regolith, a more complex task than simply harvesting gasses found naturally in the local atmosphere.

Amounts of water have been discovered on the Moon by the Clementine (Nozette et al., 1996) and Lunar Prospector (Feldman 1998) orbiters. This would be of great benefit to any station located there as it can be used as water for drinking, cleaning and lubrication, or broken down into hydrogen and oxygen to be included in the habitat atmosphere or used in rocket fuel.





Whilst it may be technically possible to build a base on the Moon the physical degradation of the inhabitants would make permanent residency undesirable. Having said this, there are potential benefits of a lunar outpost to the colonization of other planets. A lunar outpost could provide a training ground for colonization crews, a testing ground for new technology, or as a source of raw materials for orbital construction. The development of such a base would introduce programmatic delays to a subsequent colonization mission, however, due to limited financial and material resources, whilst at the same time adding additional risk to the total mission. There are arguments against the development of a lunar base as a test bed for the colonization of other planets, for example, solar power generation and crop production cannot be adequately tested due to the long day/night cycle and lack of environmental factors such as windblown dust. The benefits of such an outpost require further investigation but may simply add to the cost and risk of the overall mission, although it is part of NASA's current planning for ultimate Mars colonization.

As Philip Ball so eloquently states in his book *H₂O: A Biography of Water* (Ball 1999), "...if the day comes when we have made our occupation of the Earth so unsustainable that we have to look to so barren a place as the Moon to rescue us, we are in deep trouble."

1.2.2. *Venus*

The sulfuric atmosphere of Venus poses many problems to colonization. The upper layer of Venus' atmosphere is comprised of a thick layer of sulfuric acid droplets overlaying a dense carbon dioxide layer, contributing to an intense greenhouse effect. The Soviet probe, Venera 13, which landed on Venus in March of 1982, survived in these searing conditions for just 127 minutes.

Venus has an average temperature of over 450°C, with minimal temperature variation over the length of a day. The average surface pressure is in the order of 92 bars (compared to 1.014 bars on Earth) and its average surface density is approximately 65 kg/m³ (over 50 times that of Earth). Structures built in such an environment would have to be designed for considerably higher loading than for those on Earth (equivalent to that of a building situated almost one thousand metres below sea level) and would need to withstand these loads at much higher temperatures and under extremely corrosive

conditions. Furthermore, the extreme temperatures make construction extremely difficult. It is likely that automated construction processes would need to be implemented if a serious construction effort was ever attempted.

Such extreme pressures and temperatures would severely limit any outdoor excursions, even with the aid of very elaborate protection. The temperatures are high enough that, on Earth, it would turn sodium, potassium and even zinc to liquid. The temperature of Venus is sufficiently extreme to influence the strength of materials used in construction.

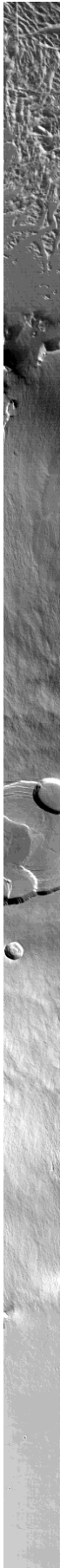
Compounding the problems with colonizing Venus, is the fact that it has a day/night cycle almost 250 Earth days, putting massive reliance on failsafe energy sources (i.e. not solar power) for the habitat and making crop growth reliant on artificial lighting.

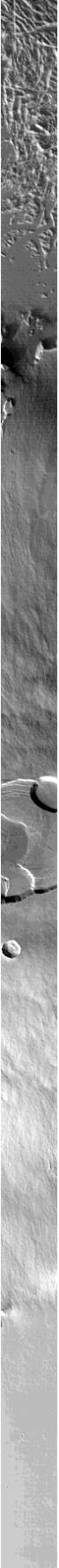
1.2.3. Mars

Mars' temperature range, averaging around -60°C , is not comfortable but it is survivable. With proper protection (i.e. insulated extra vehicular activity (EVA) suits, heated vehicles, etc.) outdoor exploration and construction is viable, unlike the searing temperature of Venus that hinders a human presence in the construction process. Indoor heating can be provided by utilizing waste heat from energy production (nuclear or fusion power plants) or industrial processes (such as ethylene production, for fuel or a feedstock for plastic manufacture).

Average atmospheric pressure is approximately six to ten millibars (0.6 to 1.0 kN/m^2), less than 1% that of Earth. Pressurizing a habitat to a suitable pressure would be a simple task; in fact the relatively high internal pressure affords some interesting ingenuity in habitat structural design. As an example, inflatable habitat extensions have been proposed for future manned Mars missions allowing for lighter, more spacious designs. These designs will be discussed in more detail on page 21 in the section on Habitat Design.

With Venus effectively ruled out on atmospheric conditions Mars possesses a gravity next closest to that of Earth and significantly higher than that of the Moon. Whilst still being less than that of the Earth this gravity level does have some benefits. Structurally, less material will be required to withstand equal mass as weights, and therefore loading, will be significantly reduced. Accordingly, this will lead to lower resource utilization.





However, there are some disadvantages. For example, particles will take longer to settle out of suspension in liquid under lower gravity conditions, having implications on several common processes, including conventional sewerage and water treatment. From a colonization perspective, however, the low Martian gravity does not pose insurmountable technical problems that could impact on habitation. It is expected that the Martian gravity of Mars will pose fewer problems than the lower gravity of our Moon, although the medical effects of Martian gravity are unknown. The effects of, and remedies for, partial gravity are discussed on page 98.

Like the Moon, Mars has been proved to have a reasonable amount of water. Photographic evidence suggests that surface channels may once have been active rivers. The example pictured in Figure 1 (taken by the Mars Global Surveyor spacecraft, 1998, courtesy of Malin Space Science Systems/JPL/NASA), below, has a distinct central channel and an oxbow. Water has been detected in the atmosphere in the past, at the very low levels of 210 PPM, and has been detected from orbit at shallow depths in the Martian regolith. As water is present, in ice form, beneath the surface, as permafrost or even in frozen aquifers, water may be easily accessible from many different regions of the surface.

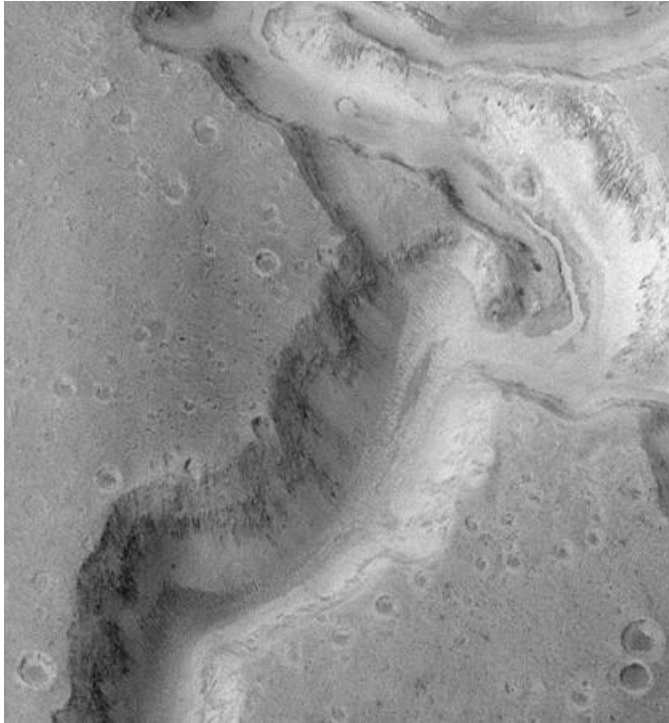


Figure 1: Nandedi Valles, part of the Xanthe Terra region.

The Martian day is almost 25 hours long. Being so similar to that of Earth, there should be no need for crew psychological or physical conditioning. In fact, research indicates that the human biological clock is set to a 25 hour cycle (Higuchi, S. 2002). Furthermore, special consideration in the mission planning process will not be required, such as artificial crop lighting. This is contrary to the very long cycles of Venus (250 days) and the Moon (27 days).

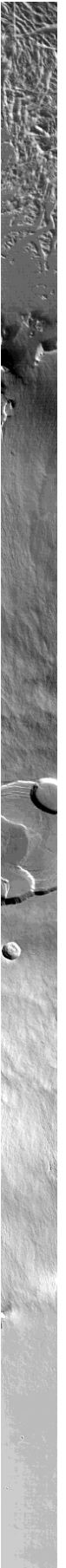
Finally, due to planetary alignment there is a launch opportunity to Mars every 26 months with current technology. This is not considered to be an unreasonably long time for a fledgling habitat to rely on consumable stores in the event of self-sustainability failure (or the decision not to rely on self-sustainability in the early stages of habitation).

Whilst, at first glance, Mars does appear quite barren, the environmental conditions and in-situ resources warrant Mars as the preferred location for colonization within our solar system, thus, Mars is the focus of investigation in this report.

1.3. WHEN SHOULD WE START ACTING?

It is considered that we should think about it now and plan to be ready to commence colonization in the near future. If the process is left for the distant future it is possible that the resources to perform such a feat will no longer exist, absorbed for the purpose of survival by a swelling population. If population levels exceed a 'critical mass' or resource use continues at unsustainable levels then there could conceivably become a time when the opportunity has passed us by. If we wish to open up this new frontier we will need to do so whilst the resources are available.

In the time before colonization we must enhance existing (and test new) technologies, prepare individuals for the journey and the roles they will play in this important journey and design and construct the machinery, equipment and space craft required for the mission. The first step will be to raise the awareness of the mission, to promote funding and support, in the lead up to the commencement of preparations. To ensure the ability to commence colonization as early as possible the mission development must be commenced during the next decade, a timeline consistent with some of NASA's plans for precursor missions.



1.4. MARS EXPLORATION BACKGROUND

For centuries people have wondered what Mars was like and if there was life there. Although the first known map of Mars was produced by Wilhem Beer and Johann H. von Mädler in 1830, Percival Lowell is typically credited for the first detailed maps of Mars, drawn from extensive viewing sessions at his observatory in the late 1800's (see an example as Figure 2 from 1895). The lines he drew resembled, to him, man-made canals and he concluded that Mars must be, or have been, inhabited.

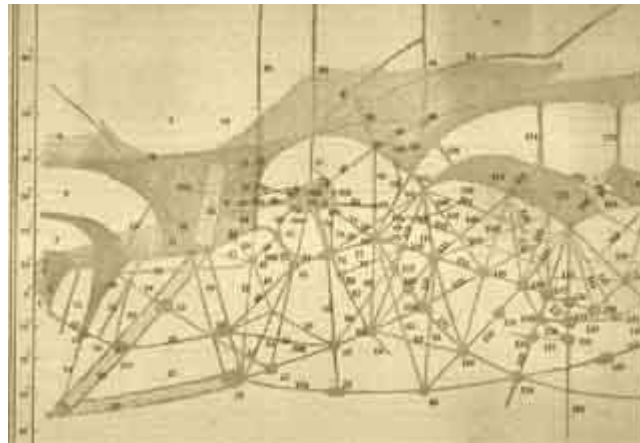


Figure 2: Percival Lowell's map of Nani Valles, part of the Xanthe Terra region.

Since then humanity has dreamed of reaching and exploring Mars. That dream began to turn into reality with the commencement of the space race between the USSR and the USA.

The USSR commenced the exploration of Mars. In 1960 the USSR launched two probes on a fly-by mission to Mars, Korbak 4 and 5. Both failed to reach Earth orbit. In 1962 the USSR tried again with Korbak 11 and 13, and Mars 1. All of the craft reached Earth orbit, but both of the Korbak missions broke apart there. Mars 1 failed when communication was lost.

The American craft Mariner 4 (Figure 3, right) was the first probe to reach Mars. In 1964, during its fly-by the craft sent the first detailed pictures of Mars back to Earth and collected the first close up data of the Martian atmosphere. Its twin craft, Mariner 3, failed during launch three weeks earlier (Mariner 1, 2 and 5 were Venus probes).

It can be seen that the images returned from Mariner 4 were of poor quality (Figure 3, left). They did, however, show a crust more similar to that of the Moon's than of Earth, and gave clues as to the age of the crust and the historical atmosphere that existed,

due to the extent of craters and their preservation. A total of 22 images were returned to Earth.

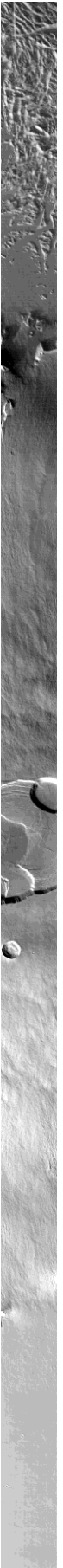
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Figure 3: an image returned from Mariner 4 showing a region known as Atlantis, between Mare Sirenum and Mare Cimmerium (Left). Mariner 4 being prepared for testing (Right) (NASA).

The USSR again attempted to send a craft to Mars in 1964, two days after the launch of Mariner 4, with Zond 2, however, communications was also lost with this craft. They launched Mars 1969A, and Mars 1969B, in 1969 but both suffered from a failure of the launch vehicle.

Mariner 6 and 7 were the next US probes to be sent to Mars. Both Mariner 6 and 7 performed their scheduled flyby of Mars (Mariner 6 only 11 days after Neil Armstrong walked on the Moon). Despite some technical difficulties onboard Mariner 7 the two probes sent back a total of 201 pictures. Mariner 7, using its infrared spectrometer, even sent back data indicating the presence of ammonia and methane. These readings were taken from areas that life was thought to be possible, reigniting questions of life on Mars.

In 1971 both the USA and the USSR were ready to launch probes to Mars. The Americans were going to send Mariner 8 and 9, both orbital craft, and the USSR was to send three orbital-landers, Kosmos 419, Mars 2 and Mars 3. Both Mariner 8 and Kosmos 419 failed to begin their trajectories to Mars, the former failing a few minutes into its flight and the latter failing after a few hours. The remaining three craft all made it to Mars, Mariner 9 shortly before Mars 2 or 3, becoming the first space craft to orbit Mars. Mars 2 and 3 had less success, Mars 2 crashed into the planet during a five week long dust storm. Mars 3 managed to land on the surface during the same storm, becoming the first man made craft to land on Mars, approximately 20 seconds after





landing however, the signal disappeared. It is possible that the lander was toppled and destroyed by the dust storms winds but there is no real evidence as to its fate. The orbital sections of Mars 2 and 3 were designed without the flexibility to change their mission after launch. This led to the craft taking photos of the dust storm until their power was drained, sending back little useful information. Mariner 9, however, was flexible and was told to shut down its cameras to conserve power. Once the storm cleared the orbiter began taking the first photos of the Martian surface from within the Martian orbit, below, covering more of the planet than any prior mission with 7,329 images returned, including the picture in Figure 4.

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Figure 4: This Mariner 9 photograph, taken on 19 January 1972, shows Vallis Nirgal, a 575 km long channel, 5 to 6 km wide (NASA).

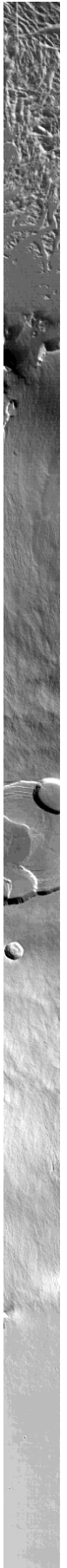
The first craft to land on Mars, *and* successfully send back useful data, was America's Viking 1, touching down on July 20, 1976 followed shortly after by Viking 2. Russia, having lost the race to the moon, were keen to win the race to examine the Martian surface and so had launched four Martian probes at the launch opportunity in 1973. The Viking missions were due to launch during the same opportunity however, the cost of the Vietnam War caused the U.S. government to postpone the missions by two years. The Russian probes, named Mars 4 to Mars 7, were not overly successful in their attempts to learn more about the red planet and completely unsuccessful at actually landing on it. Mars 4, a planetary orbiter, failed to enter Mars orbit, a faulty computer chip was to blame. Mars 5, also a planetary orbiter, managed to enter orbit and return some atmospheric data and photographs, unfortunately it only operated for a few days. Mars 6, designed to land on Mars, entered into its decent and, upon firing it's retrorockets to slow its velocity prior to landing, ceased transmission, presumably exploding or crash landing. Mars 7, another lander, missed the planet completely.

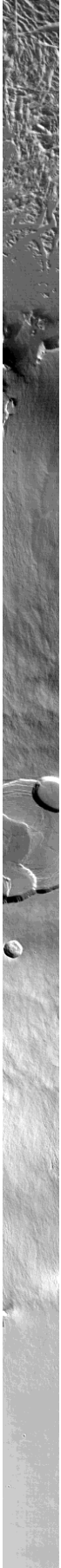
Both Viking spacecraft arrived at Mars with an orbiter and lander component to each mission. The orbiters provided many detailed pictures of the surface, some of which were used to determine the landers' final landing site. Viking 1 landed successfully on Mars in an area known as Chryse Planitia and Viking 2 landed in the region of Utopia Planitia, both in the Northern Hemisphere. Each of the Viking landers was equipped with 14 instruments. Their main goal was to determine if there was life on Mars but they were also to send back information on the composition of soil, the atmosphere and the climate and to infer something about the planet's interior. The question of life on Mars was not successfully answered. Two onboard experiments sent back data that could be interpreted as indicating life (however, it could also be reproduced by non-organic, oxidant reactions), the other experiment sent back no evidence that indicated life. There is now wide spread belief that the two positive indications were erroneous in their sensing of life and that they were actually sensing the presence of oxides in the soil created by ultra-violet radiation hitting the surface of Mars. Figure 5 shows the first image to return from the Mars surface from Viking 1.

Figure 5: An image of the Arandas crater taken from the Viking 1 Orbiter (Left). The first photograph returned from the Martian surface, a view of Viking 1's landing pad on the ground (Below) (NASA).

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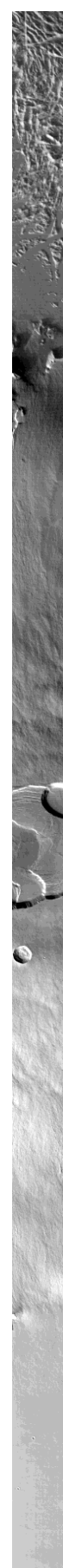
In 1988 Russia launched two missions to Phobos (one of Mars' two moons), Phobos 1 and 2. Phobos 1 was lost en-route to Mars and Phobos 2, a combination orbiter and lander, was lost near Phobos.

After a long gap since its last mission to the red planet, the United States launched Mars Observer on September 25, 1992. The spacecraft was based on a commercial Earth-orbiting communications satellite that had been converted into an orbiter for Mars. The payload of science instruments was designed to study the geology, geophysics and climate of Mars. The mission ended with disappointment on August 22, 1993, when contact was lost with the spacecraft shortly before it was to enter orbit around Mars.

The Mars Global Surveyor (MGS) was launched on 7 November 1996. After reaching Mars and a year and a half trimming its orbit from a looping ellipse to a circular track around the planet, the spacecraft began its prime mapping mission on 1 April 1999. The mission has studied the entire Martian surface, atmosphere, and interior, and has returned more data about the red planet than all other Mars missions combined. The MGS lost battery power and was lost on November 2, 2006.

Among key scientific findings were:

- MGS took pictures of gullies and debris flow features that suggest there may be current sources of liquid water, similar to an aquifer, at or near the surface of the planet;
- Magnetometer readings showed that the planet's magnetic field is not globally generated in the planet's core, but is localized in particular areas of the crust, as shown in Figure 6, below;
- Temperature data and close-up images of the Martian moon Phobos showed its surface is composed of powdery material at least 1 metre thick, caused by millions of years of meteoroid impacts; and
- Data from the spacecraft's laser altimeter gave scientists their first 3-D views of Mars' north polar ice cap.



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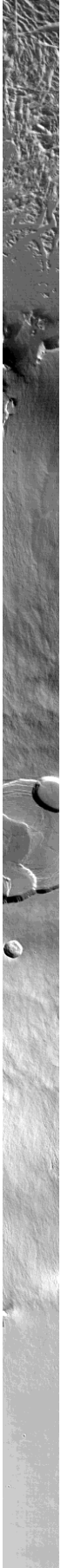
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Figure 6: Map of the magnetic field of Mars observed by the Mars Global Surveyor satellite at a nominal 400 km altitude (Connerney, J, et al., 2005).

In 1996 the USSR again attempted to reach Mars, with Mars 96. The mission ended when the launch vehicle failed.

Almost 21 years after the Viking mission landed NASA sent its next mission to the Martian surface. Pathfinder was launched on December 4, 1996 and landed, despite several technical difficulties along the way, on July 4, 1997. One goal of the Pathfinder mission was to demonstrate that the exploration of Mars could be done for an affordable cost, a goal it succeeded in achieving. The mission was undertaken for \$265 million, less than the production cost of many movies, Viking had cost over three billion 1997 US dollars. The Pathfinder lander was equipped with various instruments, including cameras, communications equipment, soil analysis equipment and weather monitoring equipment; it also carried a small rover, named Sojourner. Sojourner carried a camera, to send back close-up pictures of surface features, and an alpha-proton x-ray spectrometer, used for analysing the chemical composition of rocks.

Sojourner discovered rocks of both high and low silica contents, indicating different formation processes. These rocks also appeared to have tiny holes in their surface, characteristic of bubbles within volcanic rock. This type of rock is characteristic of the material found in the Andes Mountains of South America. Rocks, thought to be



conglomerates, made of rounded pebbles in a sand and clay matrix were also discovered. If these are, indeed, conglomerates then it is compelling evidence of previous liquid water on the surface of Mars over a long period of time as it is under the conditions of flowing water that similar examples are formed on Earth.

The Pathfinder ground crew lost contact with the lander on September 27 1997, after 84 days in operating on the surface. The mission was officially declared over on March 10, 1998.

In 1998 Japan launched its first mission to Mars; Nozomi. Nozomi experienced some problems during a trajectory adjustment, using up too much fuel and resulting in the need to extend the trajectory, incorporating an additional planetary flyby to reach Mars, however the mission failed when it became evident that achieving Mars orbit was virtually impossible. The mission controllers slightly modified the trajectory to ensure that the craft did not crash into Mars and abandoned the mission.

Mars Climate Orbiter was launched on December 11, 1998 and was designed to function as an interplanetary weather satellite and a communications relay for later Mars Polar Lander. The orbiter carried two science instruments: a copy of an atmospheric sounder on the Mars Observer spacecraft lost in 1993; and a new, lightweight colour imager combining wide- and medium-angle cameras. Communication was lost with the Mars Climate Orbiter on its arrival at Mars on September 23, 1999. Engineers concluded that the spacecraft entered the planet's atmosphere too low and probably burned up.

The Mars Polar Lander (MPL), which also carried two small probes called Deep Space 2 (DS2), was launched on January 3, 1999. The MPL was to land near the edge of the southern polar cap and dig for water ice with a robotic arm. DS2 was to be dropped from MPL during its decent and impact and penetrate the ice to measure its properties. Both missions failed on December 3, 1999.

Mars Odyssey was launched on April 7, 2001, arrived into Mars orbit on October 24, 2001 and is still operating. Mars Odyssey is an orbiting spacecraft designed to determine the composition of the planet's surface, to detect water and shallow buried ice, geology and to study the radiation environment. Mars Odyssey was the subject of the first image taken of a craft orbiting another planet, Figure 7.

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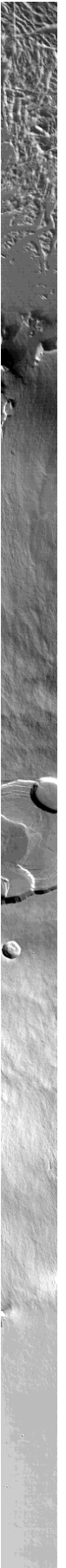
Figure 7: Image of Mars Odyssey, taken by the MGS (NASA)

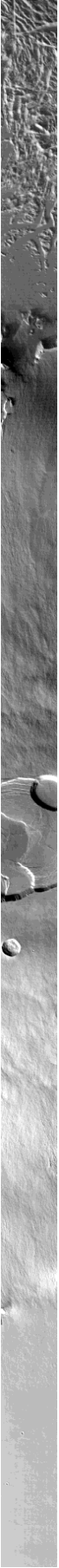
The Mars Odyssey carries three equipment packages: The Thermal Emission Imaging System (THEMIS), for capturing images of the surface in visible and infrared spectra at resolutions up to 18m/pixel in visible and 100m/pixel in infrared; GRS, a suite of three instruments - the Gamma Ray Spectrometer, the neutron spectrometer and the high-energy neutron detector; and the Mars Radiation Environment Experiment (MARIE), to measure the radiation environment in interplanetary space, in Martian orbit and at the Martian surface to help assess potential risks to any future human explorers.

Data from the Mars Odyssey mission has been compiled to form the elemental composition maps contained in Appendix B.

Planned by the European Space Agency and the Italian space agency and launched on June 2, 2003, Mars Express is exploring the atmosphere and surface of Mars from polar orbit. Its accompanying lander, Beagle 2 was released for its descent to the Martian surface on December 19, 2003, however, no communications were received and the lander was declared as lost.

The Mars Exploration Rovers, Spirit and Opportunity, were launched on June 10 and July 7, 2003, respectively. They reached the surface of Mars on January 4 and January 25, 2004, respectively. Spirit and Opportunity have identical suites of five scientific instruments: a panoramic camera; a miniature thermal emission spectrometer; a Mössbauer spectrometer; an alpha particle X-ray spectrometer; and a microscopic imager. These are augmented by a rock abrasion tool, for removing the weathered surfaces of rocks to expose fresh surfaces for examination. The payload also includes magnetic targets to catch samples of Martian dust for examination. With far greater mobility than the 1997 Mars Pathfinder rover, these robotic explorers are able to trek up





to 40 meters across the surface in a Martian day. Each rover is designed to search for evidence of liquid water that may have been present in the planet's past. The rovers are identical to each other, but landed in different regions of Mars. They were designed to last 90 days on the surface. To date they have survived over two years.

Figure 8, below, identifies the components of the lander and the position of the rover, Spirit, even identifying the track marks left in the soil. The image was taken by the Mars Global Surveyor orbiter.

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Figure 8: Spirit's landing site and tracks, taken by the MGS (NASA)

The Mars Reconnaissance Orbiter was launched on August 12, 2005 and arrived at Mars on March 10 2006. The spacecraft studies the surface, monitors the atmosphere, and probes the underground of Mars to gain better knowledge of the distribution and history of water on Mars. Carrying the most powerful telescopic camera ever flown to another planet, Mars Reconnaissance Orbiter is able to show Martian landscape features as small as a kitchen table.

In August 2007 the Phoenix Mars Mission was the first craft launched as part of NASA's 'Scout Program'. Phoenix is designed to study the history of water in the Martian arctic's ice-rich soil, the effect of polar influences on Martial the climate and whether the ice once supported life.

1.5. THE PERSPECTIVE OF THIS REPORT

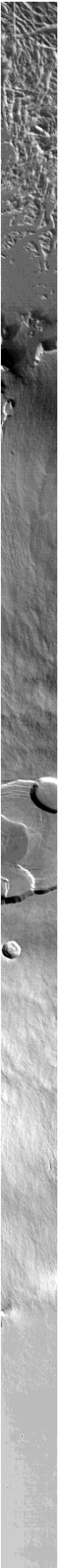
This report is designed to investigate the feasibility and processes of permanent Martian habitats to be used during the colonization of Mars. However, much of the report could reasonably be applied to a colonization mission to any suitable planet.

Generally, it is considered that the technology to undertake the habitation of Mars is present in today's society. It is not unreasonable to assume that, prior to the habitation of Mars being implemented, there will be advancements in many fields that will afford greater ease and lower cost for the establishment of a Martian habitat.

There is only a relatively small amount known regarding the detailed properties of Mars at this time. Obviously much more must be learnt. Areas for further study will also be highlighted, such as the determination of natural resource distribution. It is pointless, and dangerous, to undertake a mission of this type if it were not known if Mars had the resources necessary to support a self-sufficient habitat, although it is generally believed to.

This report will attempt to demonstrate that we have the technology to undertake such a monumental task, and that Mars has the resources to support us, thus demonstrating the feasibility of such a venture.

Regardless of the Martian resources available it will take some time for a habitat to 'get on its feet'. However, once the habitat is established and the population begins to swell, beyond the initial researchers and builders present, many things will need to be implemented for its long-term social and economic development. Such things as preservation of the natural environment, a Martian government/constitution, control of resources and the habitat's economic structure must be considered. This, however, is beyond the scope of this report.



2. FINDINGS

There are several key areas discussed by literature relating to a permanent Martian habitat. These include the habitat location, structural and architectural design, facilities, power supply, raw material source/production (including water, breathable atmosphere, food and building materials), life support systems, communications and exploration methods and cost. Some of these key themes are investigated in detail in the following sections.

2.1. Habitat Location

Proposed habitat locations fall into three main regions of Mars, within the equatorial region of 30°N to 30°S (Ishikawa, et al, 1990, Mars reference mission), on the northern polar cap (Powell, et al, 2000), and in the vicinity of the edge of the polar caps. The current NASA Mars reference mission (the base line mission design against which potential future NASA manned missions will be compared (NASA, 1989)) proposes a site in the vicinity of the Valles Marineris canyon system and the Tharsis volcanic region. This is a relatively safe and temperate equatorial region in close proximity to areas of scientific interest (Thangavelu, 1999). Appendix A contains a labelled map of Mars for reference and interest.

The global position of the habitat has several implications on the design of the facility. The further from the equatorial region the habitat is the more inclined the angle of incidence of sunlight. This will impact on the design of any photovoltaic collectors for power generation (Atkinson, et al, 1992) and the ability of plants to collect light for photosynthesis but will also reduce the amount of harmful solar radiation affecting the colonists (or reduce the thickness of solar radiation shielding required). Further to this, temperatures will generally reduce with increasing distance from the equator, increasing the energy requirements for heating but also improving the likelihood of finding sub-surface reserves of ice at easily attainable depths (e.g. for water production). The humidity of the location (largely dependent on atmospheric pressure, and therefore elevation) will also be relevant if considering the extraction of water from the atmosphere. Accessibility of habitats from space becomes more complicated further

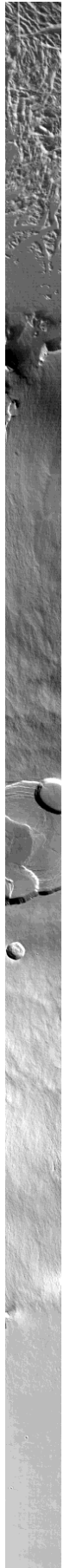
from the equator as equatorial regions offer the simplest landing, ascent and orbital support options (Ishikawa, et al. 1997).

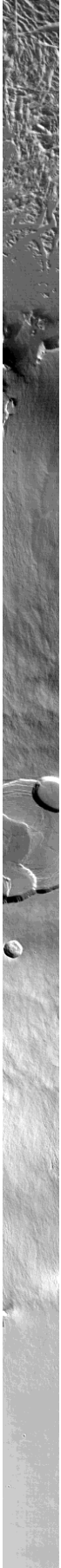
Dust storms may impact on any decision to construct facilities in particular regions. Landis and Appelbaum (1997) state that the average wind speed at the Viking Lander 2 site (on the Utopia Planitia, 48°N) was measured at 2m/s, and reaching a peak of 32m/s during a dust storm. Local dust storms can occur at any point on the surface of Mars and during any season. Local storms are most common in the Southern Hemisphere regions of Hellas, Noachis, Argyre, and the Solis, Sinai and Syria Plani, and in the Northern Hemisphere regions of Chryse-Acidalia, Isidis-Syris Major and Cerberus. Regional and global storms (which occur less frequently but can last longer and be more intense) most commonly originate in the Southern Hemisphere regions of Noachis-Hellespontus and Solis Planum-Argyre (Kahn, et al. 1992) and are likely to affect facilities located anywhere on the planet. Geels, et al. (1989) confirms the origin of large storms, generalizing the region of most storm activity as being between latitudes 20°S and 40°S.

According to Stoker, et al. (1992), three general criteria must be met by any potential base location. The site must be safe and easily accessible, have a ready supply of resources for survival (particularly water and energy), and must be in a scientifically interesting area. Stoker then goes on to list the key requirements under each of these three criteria, including mechanically stable soil, climatically mild, mid to low latitude, low altitude, and the availability of water, energy and metal ores.

Marc Cohen (1995) also describes general requirements for selecting a habitat location including, proximity to geographic, topographic and geologic features of major scientific interest and proximity to any resources of special value in the Martian regolith. Also discussed are specific requirements including, flat terrain, free of large obstacles, descent and ascent vehicle flight paths unobstructed by large features, a large, flat landing area approximately 1 to 2 kilometres away from the habitat area and soil bearing strength, and other soil properties capable of supporting a 65T lander without uneven settlement. If the habitat and landing areas are not at the same altitude, it is proposed that there be a gentle incline of no more than 1 in 50 so as not to impose excessive demands on the transport vehicles.

The possibility of a habitat located under the northern polar cap is well explored by Powell, et al. (2000). They discuss the readily available resources, such as water and





structural materials as well as providing details of a proposal to automatically construct the base without a human presence, using heated water to carve melt chambers in the polar ice deposits. Whilst Powell's habitat concept is based around the northern cap others, such as Cockell, (1995), advocate either ice cap as a potential base site. Powell's choice of the northern cap over the southern is possibly due to the superior ice cap structure, necessary to support the melt chamber proposal, however, this is not fully explained. The southern cap is believed to have a layered ice/frozen carbon dioxide structure as opposed to the solid water ice northern cap.

Cockell's concept for a base located on a polar cap is, initially, only for use as a research station, supported by a primary base located away from the harsh conditions of the poles. Whilst expressing the benefits that the poles will provide in regards to water mining he precludes the establishment of a long term base there during the initial stages of human settlement due to extreme temperature, resulting in high energy (heating) requirements and structural considerations from ice deposition on the habitat structure. Further to this, Cockell considers other regions of Mars to be of greater scientific interest due to the more clement conditions for the evolution of possible Martian micro-organisms but does not expand on this.

Ishikawa, et al. (1997), proposes that a base be constructed on the flat plain just south of Kasei Vallis (N 20°, W 70°). This location is selected as it is easily accessible from equatorial orbit, the authors expect water to be available (although do not explain why), and it is close to several significant sites of scientific interest. This site would also have the added advantage of, being slightly north of the equator, being away from the most frequent sources of local dust storms, as discussed in Kahn, et al. (1992).

Phillips (1985) highlights two areas that may be suitable for the establishment of a habitat based on the potential near surface liquid water supply in these regions, Solis Lacus (26°S, 80°W) and Noachis-Hellespontus (30°S, 315°W), the former being favourable. The reasons stated for favouring Solis Lacus include:

- Topography is relatively smooth, affording accessibility and landing safety,
- Relatively mild temperatures due to proximity to the equator, and
- Close to scientifically interesting features such as Valles Marineris.

Both regions suggested by Phillips, however, are key sources of local and global dust storms, possibly the reason for the area's relative flatness. Phillips does not consider the effect of these dust storms on the habitat.

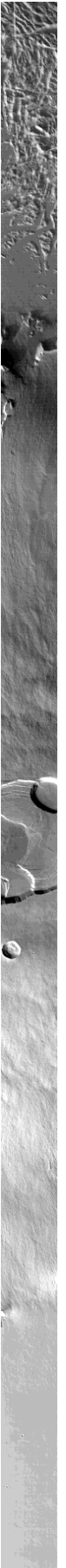
A habitat in the region of latitude 20-30°N, in a region of low altitude, appears to be an appropriate location for a habitat. Such a region will have benefits including:

- Easily accessible from orbit and typically flat terrain to facilitate safer landings;
- Denser atmosphere, due to lower altitude, than more southerly locations (benefits include more radiation protection and higher pressures and humidity);
- Reasonable compromise between high incident light levels available at the equator (photosynthesis, power generation, etc.) and likelihood of finding accessible water at reasonable depths available closer to the poles;
- Relatively mild temperatures (reducing heating requirements/energy use); and
- Avoidance of the more frequent local dust storms of the southern hemisphere (improved light source, reduced energy use, reduced maintenance requirements, etc.).

Possible regions affording the above are Chryse Planitia (40°W), Amazonis Planitia (140°W) or Elysium Planitia (170°E). Any final choice of location will need to be dependent on identifying detailed climatic conditions and local resource availabilities, including water as well as determining the importance of local scientific targets.

2.2. Habitat Design

Several attributes feature strongly in the design of Martian habitats, including habitat type, living space and safety (including radiation shielding). The key objectives of a habitat structure, at least initially, are to contain warmth, shield out hazardous radiation and contain a suitable atmosphere (Clark, 1981).





2.2.1. *Habitat Type*

There have been many different designs of Martian habitat structures proposed in the available published literature. Many early designs involved the reuse of the trans-Mars spacecraft as the surface habitat, or transporting complete rigid structures from Earth separately (as in Ishikawa, et al. 1997). These options were typically of high mass and, therefore, high launch costs and were limited in size to that which could fit within the payload area of launch vehicles such as the large, but now out of production, Saturn V rocket. Radiation shielding, critical in the Martian environment and further detailed on page 102, was often to be achieved either through the use of internal water tanks lining the habitat walls (often to be filled with locally sourced water) or by burying the capsule in the Martian regolith (Ishikawa, et al. 1997). Whilst the safety of these imported habitats could be verified on Earth the cramped living quarters and large transportation cost makes them prohibitive.

More recently the emphasis has changed from small habitats transported from Earth to transporting inflatable habitats, which have the advantage of being significantly more spacious once deployed on Mars than rigid framed capsules of an equivalent mass. Authors have proposed inflatable habitats that include designs such as cylinders (Goodyear, 1982, Siegfried, 1999), toroids, modular elements (Cadogan, et al, 1998), domes with cable restraints (Nagem, et al, 1991), spheres (Roberts, 1989) and pseudo-spheres with an upper hemispheres of one radius and a buried floor of a larger radius (Zubrin, 1997). Some inflatable structures can be utilised as either dedicated greenhouses or habitation areas utilising natural light, providing UV-resistant and/or UV-opaque materials are used in their construction, or structures may be partially buried to suit a combination of purposes (Boston, 1995). As with the early designs described above, radiation protection can be achieved by burying inflatable structures, however, this is constrained by shape and size of the unit and the practicalities of required excavation. It has been shown that a structure inflated to one atmosphere (101.4 kN/m^2) can support a depth of 17m of 1.6g/m^3 regolith (Roberts, 1989), far in excess of that required for radiation protection (refer page 102).

Inflatable structures have consistently proven to be lower in both development and manufacturing costs than rigid structures (Cadogan, 1998) and the safety of inflatable structures is higher than one might expect. Advanced materials research has produced

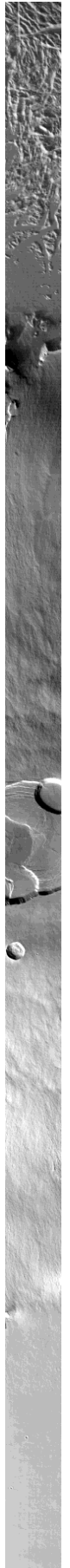
flexible fibres with yield stress in excess of twice that of steel, with rip-stop properties that would prevent a puncture becoming catastrophic (Zubrin, 1997). Further, certain designs of inflatable structures can be rigidised after inflation to prevent collapse in the event of pressure loss (Siegfried, 1999).

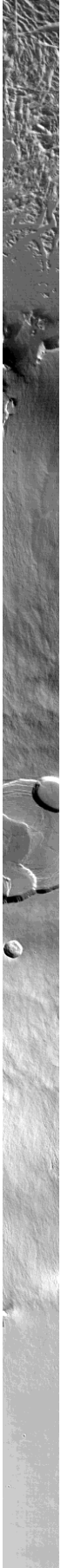
Following design studies undertaken at the University of Wisconsin, Ronald Thomson (1989) has proposed a combination of the rigid and inflatable habitat models. He proposes a design of four rigid cylindrical structures, arranged in a square with airlocks at the corners, and an inflatable membrane covering the courtyard contained within the square. Whilst this would provide a considerable margin of safety, with 5 separate pressurised areas it may prove to be cost restrictive as separate launches will be required for each of the cylinders.

Further to the transport of the habitat structure from Earth, Bruce Mackenzie (1989) proposes bringing only the bare necessities from Earth, including plastic sheeting, sealants, airlocks, etc. and constructing the structure itself from locally made bricks. This 'Roman hall' (or barrel vault) concept will take longer to construct than inflatable habitats, and require a prefabricated temporary habitat for the workers (possibly their transport module with an inflatable annex to use as a workshop) however it is readily expandable to accommodate habitat growth and requires minimal imported materials, helping to reduce costs. Due to poor tensile strength of bricks the pressurised halls must be covered in several metres of regolith to counteract the internal atmospheric pressure and keep the structure in compression, providing the added benefit of radiation shielding. Boston (1992) calculates that seven metres of regolith over a brick barrel vault structure would be sufficient to contain an internal pressure of one atmosphere.

Possibly drawing on the concept of inflatable structures, Powell, et al. (2000) proposes the melting of ice chambers within the northern polar cap and inflating 'insulating membranes' within to create habitable space. This design provides in-built radiation protection and high safety levels due to the rigid, and extensive, ice structure. Cost is kept low through the need for relatively low launch mass and construction can be relatively automated and expeditious compared to brick production and construction.

Boston (1992) suggests that caves and lava tubes could be used for habitation, providing the structural support for a relatively light weight habitat as well as providing a relatively constant thermal environment and radiation protection.





More ambitious habitat options include the covering over of entire valleys with strong, trafficable, transparent roofs (Allen, 1993). It is proposed that the internal air pressure of the habitat would support this roof with a backup support along the lines of a cable-stayed bridge. Partitions along the length of the habitat would provide modularisation for decompression protection and allow for the staged construction of the facility. Allen proposes using pressurised Martian atmosphere and biologically converting it into breathable atmosphere through a series of plant chambers within such a structure.

Drake, et al. (1992) conducted an evaluation of eight different habitat designs incorporating many different factors. The method used is an auditable method for evaluating habitat designs against one another, although involving subjective judgements. The article does attempt to evaluate the eight options discussed, however, the purpose of the article is to describe the methodology, not evaluate habitats, and the evaluation is done for lunar habitats, thus is not entirely appropriate to this research. This is a good evaluation tool, easily adaptable to a variety of requirements; however, more work is required in determining suitable factors to rate the designs against.

Many of the above habitat designs may potentially be constructed either above or below the surface. James French (1989a), in summarising the Case for Mars III Mission Strategy Workshop, proposes that a Martian habitat be constructed above the surface for several reasons. The stated advantages of above surface habitats include the simplification of expansion, the avoidance of major excavation (including potential bedrock or permafrost excavation), the ability to undertake repairs without excavation, improved possibilities for admitting natural light and the availability of horizontal entry and egress. Many of these benefits are also obtainable where the surface structure is covered in a layer of regolith for radiation protection and insulation (Clark, 1981, states that the Martian soil fines would also provide outstanding thermal insulation).

Helleckson (1997) discusses the virtues of having an interface module between the living quarters and the greenhouse facilities of a habitat. If this interface module were to contain the controls for both sections then it would serve as an ideal retreat in the case of emergency, where temporary accommodation can be established in the event of the failure of the habitat, the greenhouse or any associated systems. Supplies can be stored here and the functionality of life-critical systems can be duplicated here, perhaps with

physico-chemical systems in lieu of bio-regenerative systems, for example. With the inclusion of such a safe-haven the robustness of the habitat will be increased and the safety of the colonists will be improved. An expanding habitat may include several of these modules to provide redundancy of critical systems and allow the rerouting of air, food, water, waste, power, heat and communications in the event of failures elsewhere.

All of the technologies described herein are viable, but require varying levels of local technology/industry. For example, initially establishing habitats from the Earth-Mars transport modules, supplemented with inflatable structures and using Martian regolith as radiation protection is relatively simple and reliable, with the reliability and serviceability of the majority of components verifiable before leaving Earth, with the possibility of being established on Mars prior to a human presence. However, in the long term the construction of buried brick vaults or solid dome constructions from local resources would allow the expansion of the habitats with less input from Earth, increasing self sufficiency, safety and living space. Ultimately the enclosure of valleys or craters would create significant living space and versatility, subject to the verification of suitable ground conditions, including stability and permeability to prevent atmospheric loss or collapse.

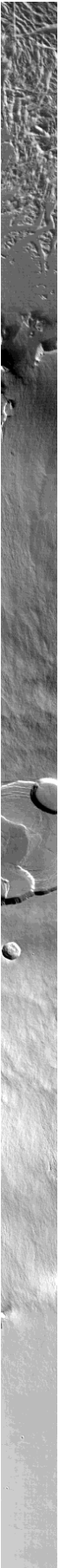
2.2.2. *Living Space*

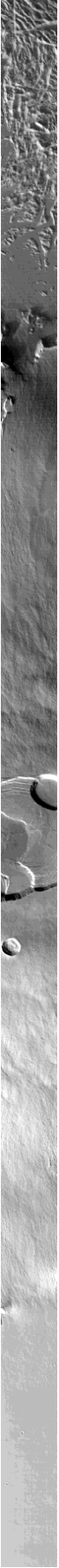
Habitable volume is an important consideration for a Martian habitat for psychological and physical reasons. Figure 9, below, plots the total pressurised volume (m^3/person) of living space for historical manned space flights/stations.

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This figure is included on page 25 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 9: Historical space habitat pressurised volume (Drake, 1998).

A NASA (1995) report indicates that the required habitable volume varies with mission duration becoming asymptotic at approximately six months. The report estimates that 19m^3 of available living space (excluding space occupied by equipment,





etc.) is optimal for crew sizes of two to twelve for a mission duration over six months in space flight. Given a 2.5 metre ceiling this equates to approximately 7.6m^2 per person and a total habitat area of up to 91.2m^2 of free space for 12 people.

Connors, et al. (1995) cite the original text of the above NASA report, originally published in 1987, where the optimal living space was considered to be 17m^3 .

Estimates that consider the additional requirements of a habitat, over that required for space travel, allow significantly more living space per person. Powell, et al. (2000) propose the provision of 40m^2 per person in their habitat below the northern ice cap. Ishikawa, et al. (1997) propose that each colonist would be allocated half of a 6m diameter and 16m long module, equating to roughly 72m^2 , or 180m^3 , for personal quarters. Ishikawa, et al. (1997) suggest a required surface area of just over 100m^2 per person for agricultural requirements, stating that 60m^2 per person is sufficient only to satisfy the dietary grain requirements. For comparison (excluding agricultural requirements) Boston (1992) describes that an apartment and a spacious house allow 36m^2 and 180m^2 of living space per person, respectively. For comparison, Biosphere 2 (described in more detail on page 90) contained approximately $1,600\text{m}^2$ per person, although it was constructed for efficiency of space per crew member.

Johnson, et al. (1975) compare the available land, per person, in several cities and towns around the world. For example, their data shows land areas per capita of Boston – 185.8m^2 , New York – 98.3m^2 , Manhattan Borough – 38.2m^2 , St. Paul, France – 27m^2 , and Rome – 40m^2 . They go on to assess the requirements for habitable area for different functions, including residential, commercial, recreational, storage and agriculture. They conclude that 94.2m^2 is required per person, excluding agriculture, however the ground area required to achieve this is only 46.6m^2 once multistorey structures are taken into consideration. Agriculture requires an additional 61m^2 of surface area per person, or a ground area of 20.4m^2 (in three levels) bringing the total ground area required per person to 67.0m^2 , and a surface area of 155.2m^2 , for a space habitat (based upon their assumption of 10,000 people). This study is one of the most comprehensive available for habitable space requirements of a habitat and, although based on an orbiting space station design, the areas assessed are equally applicable to Mars. Caudill (1984) indicates an agricultural area requirement of 58.9m^2 per person, comprised of 17.6m^2 for wheat, 13.9m^2 for rice and 27.4m^2 for fruit and vegetables,

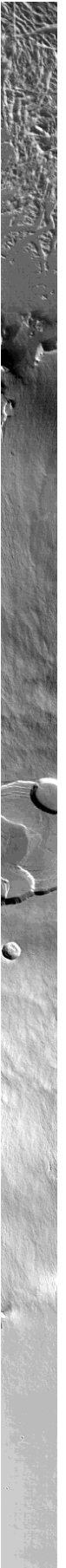
comparing favourably to Johnson's estimates but short of Ishikawa's more recent analysis.


2.2.3. *Safety*

Safety is of vital importance to the viability and sustainability of a habitat in the harsh conditions on Mars. Marc Cohen (1995) discusses the safety philosophy for the first Mars outpost in reference to Rockwell International's Space Station Crew Safety Alternatives Study (Percy et al, 1985). Cohen's selected philosophy for the first Mars outpost is to 'Cause no damage to the First Mars Outpost or injury to crew that will result in a suspension of operations'. This is also applicable to a Martian habitat and essentially states that all critical operations must continue during an incident (or a backup must take over), including habitat atmospheric containment, life support systems, etc. It allows for an injured individual, or group, to recover in an operational and safe environment. This philosophy implies the need for redundancy on all life critical systems, including redundancy in the habitat structure itself, to allow for repairs to take place. The cost of including a high level of safety into the habitat design is, as Cohen points out, not significantly more than the cost of an unsafe habitat; the expense associated with safety comes about when it is incorporated into the design during the final design stages, or during construction rather than when it is inherent in the original design.

Due to communications delay between Earth and Mars (approximately 20 minutes each way) making live conversation impossible, a habitat must have adequate medical diagnostic and treatment facilities to ensure the safety of the colonists (Billingham, 1989).

Fire prevention will be of critical importance within a Martian base as an uncontrolled fire could result in a total loss of the habitat. Smoke and thermal detection systems must be incorporated into the design of any habitat and linked to the environmental monitoring and alarm system, also, all crew should have access to a communication system to raise alarms and direct assistance. Water reserves must also be maintained for fire fighting purposes. For fire suppression in and around computer systems (which will be critical to the operation and safety of the habitat) halon extinguishers must be provided, as water, carbon dioxide and many other fire-suppressing agents can cause damage to this equipment, additional to that of the fire. Obviously the carbon dioxide in the Martian atmosphere should not be overlooked for





use in fighting many types of fires. The special case of combustible metals must also be considered on Mars, including magnesium and titanium, which are difficult to control and may not even be extinguished by flooding with the Martian atmosphere. Granular graphite, some synthetic fluids and, to a limited extent, water fog can be used to control these fires. The difficulty in extinguishing these fires must be considered prior to using the metals in areas of risk (Beattie, 1989).

2.3. Habitat Facilities

The facilities provided within a Martian habitat will significantly impact on the perceived acceptability of the habitat by the occupants. Harrison, et al. (1994), has undertaken a psychological study of mission and habitat parameters, incorporating a total of 344 college students. The study assessed 40 environmental characteristics of a 100-person mission to either the moon or Mars, each for either one month or one year. Also incorporated into the study were questions related to the acceptability of various levels of risk and the expected social recognition for mission participation. No significant differences were reported between mission destinations, however, mission duration showed significant reductions in the acceptability of limited personal control, limited emotional release, makeshift services, and high risk factors as mission duration increased. Substantial gender differences were also observed, specifically in the acceptability of limited environmental comfort and inconveniences, rated less acceptable by women, and limited emotional release, rated less acceptable by men. High risk was shown to be the least acceptable factor.

Whilst the authors of this study concede that there are limitations in their methodology, resulting from differences between students involved in role-playing and astronauts actually undertaking a mission, the results are encouraging and indicative of some important environmental factors that should be considered in designing habitat facilities.

The facilities of a Martian Habitat must accommodate office and laboratory space, living quarters, commercial precincts, industrial facilities and recreational areas. The town planning issues of combining these facilities will need to be carefully considered when planning a Martian habitat as the social stresses of the remote and isolated community could potentially result in amplified social stresses and social isolation. Joel

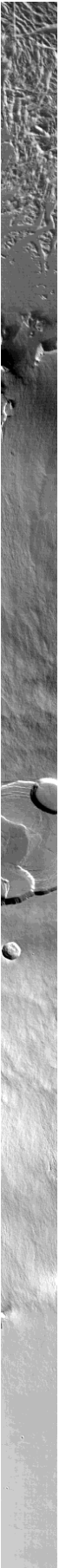
Hagen (1989) investigated these issues by looking at two examples of cities on Earth that have been built from a master plan as a green-fields development in the 1950's, those of Chandigarh (in India) and Brasilia (the Brazilian capital). Both of these cities were designed by high-profile architects who segregated the business and administrative facilities from the residential areas (which also contained shops and recreational facilities). As a result, these cities are often considered lifeless, without the social 'bustle' of the community on the streets. As an example of how these cities have failed at providing for the social aspect of the population, many new settlements have developed around the fringe of the cities with a vibrant social culture, housing the majority of the population. This has occurred despite, in the case of Chandigarh, the fact that the fringe settlements are little more than shantytowns without running water or electricity. The city centre is lifeless in comparison. In the case of Brasilia, the 'embassy sector' has many vacant lots, with most nations maintaining their 'real' embassy in Rio, the Brazilian government has now banned the construction of any new embassies in Rio in an attempt to have them established in their allocated lots in Brasilia.

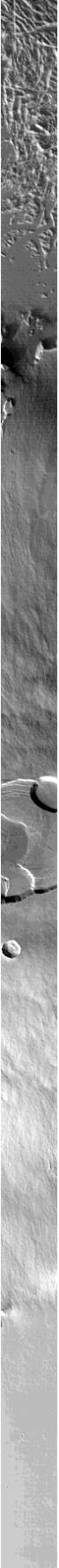
In relation to a space settlement, Hagen proposes that a city requires the flexibility to develop 'organically' in the way most cities on Earth have developed. People must be able to live, work and play in close proximity, and within a community of other people.

Greenhouses, possibly inflatable, will be an integral part of the life support system, providing colonists with fresh food as well as the transformation of carbon dioxide into oxygen through normal plant processes, they may also form recreational refuges for colonists to relax.

Beyond the living and working space a habitat must provide airlocks for access to, and egress from, the native Martian environment. Cohen (1995) describes one such airlock, designed and patented by himself, which was rated number one for minimising consumables and dust mitigation in an independent review by Boeing (Capps and Case, 1993). This study was based on lunar considerations, however, Martian conditions are similar in regards to dust mitigation and consumable usage.

Cryogenic storage facilities must be incorporated into the habitat to store consumables such as methane (fuel, stored below 112°K), hydrogen (fuel or seed gas for many industrial processes such as the Sabatier process (used industrially to produce methane), stored below 20°K) and oxygen (fuel oxidizer, life support, stored below





90°K). Louis Salerno and Peter Kittel (1999) discuss the requirements of cryogenic storage systems for use on Mars, including the passive and active cooling systems that can be employed. The thin Martian atmosphere will be of benefit to cryogenic storage, reducing the rate of temperature transfer and reducing the power demands of active cooling systems.

Unpressurised adobe storage facilities can easily be constructed with the aid of an automated brick baking oven, allowing for vehicles, infrequently needed items and spares to be stored outside the habitat, effectively increasing living area. The adobe structures would provide radiation and micrometeorite protection to the stored contents (Thangavelu, 1999). Farrier (2000) suggests that similar structures could be built with rock filled gabions for walls, with aluminium supports for the roof, possibly covered with more flat gabions, if a closed roof is required. He also suggests that the structures could be sealed (possibly with plastic liners) to allow for use as an emergency habitat, or for non-cryogenic gas or liquid storage.

The production of power, material recovery (including in-situ resource utilisation) and life support systems and their associated facilities are discussed in detail in their associated sections below.

2.4. Power Supply

2.4.1. General

There are numerous opportunities for the generation of power on Mars, however, many of the traditional methods for power production used on Earth will be unsuitable for use on Mars. Fogg (1996) compares the primary energy sources in use on Earth (in the late 1980's) to discover that, out of the four most common sources (then totalling 99.9% of all energy production), only nuclear fission is viable on Mars (then contributing 4.1% of Earth's energy). Other suitable energy sources were listed as solar thermal, photovoltaics, wind, geothermal (possibly), solar power satellite and nuclear fusion, although the last two are undeveloped. Those sources of power generation deemed unsuitable included the combustion of coal and hydrocarbons (as coal and hydrocarbons are unlikely to be present on Mars) and hydroelectric generation (due to the lack of flowing water on Mars).

Ponomarev-Stepnoi, et al. (1992) have stated that, for periods over one month and power requirements over 1kW, nuclear reactors are essentially the only power option available. This can be seen in Figure 10 by Angelo and Bunden (1985). Many possible power sources that may be useful to a Martian habitat are discussed below.

NOTE:
This figure is included on page 31
of the print copy of the thesis held in
the University of Adelaide Library.

Figure 10: Regimes of possible space power applicability (Angelo and Bunden, 1985).

2.4.2. Power Requirements

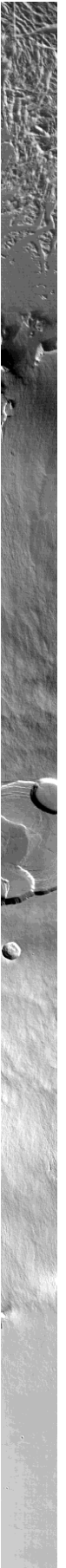
Atkinson, et al. (1992) correctly state that there is currently very little data from which to draw specific conclusions about the power requirements of a Martian base and that power requirements will vary as technology evolves. Despite the lack of direct comparisons it is still advantageous, and necessary, to estimate power requirements and several attempts have been made to quantify this.

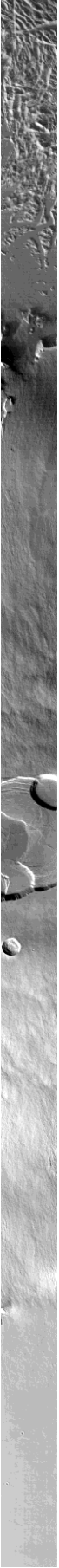
Fogg's (1996) review of available literature indicated a possible power consumption of between 1 and 100kW/per person, however, he deemed that a range of 20 to 50kW/person would be more plausible (based on Ishikawa, et al. (1990) for a habitat of 150 people).

Atkinson, et al. (1992) concludes a power requirement of 17×10^8 J/day (approximately 20kW), excluding power for construction and transportation, for a 10 person base.

Ishikawa et al. (1997) determines peak power requirements of 7MW for their 150-person habitat, or 47kW per person. This 7MW is comprised of 4MW for resource processing (mainly water electrolysis) and 3MW for general habitat power requirements.

Frank Littman (1993) estimates a power requirement for a manned base of around 200kW, excluding requirements of rovers and backup power. Although he does not specify the crew size the implied minimum is a crew of four and a possible maximum of eight to ten is assumed. This crew size results in an estimated power requirement of 20 to 50kW/person, in line with other estimates. Included in Littman's estimate is 25kW for the habitat (falling to half that at night) including laboratory and communications needs, 15kW for the greenhouse and 160kW for in-situ resource utilisation (ISRU).





Littman indicates power requirements for rovers of 10kW and 4kW for pressurised and unpressurised rovers, respectively.

Morely, et al. (1991) consider the case of a permanently manned, long-range rover. They claim a power requirement of 30kW (7.5kW per person), excluding the driving of the rover, which would add 70kW. This requirement is designed to cover the life support for a crew of 4, drilling, sample analysis, computing and thermal control. Whilst this power level may appear low it is important to remember the confined space of a rover and the reduced life support and heating requirements of this volume.

For comparison, Meyer & McKay (1995) state that the energy required to operate the Biosphere 2 experiment was approximately 100kW/person and that the average energy consumption per capita for industrialised nations is around 6kW/person.

2.4.3. Nuclear Power

Nuclear power offers several distinctive advantages over solar and chemical power systems, including compact size, low to moderate mass, long operating life, operation independent from solar and atmospheric conditions and high system reliability and autonomy. Further to this, compact nuclear power plants are capable of the supply of megawatts of energy through advanced reactor technology such as solid core, fluidized bed and gaseous core reactors (Angelo and Buden, 1985). Nuclear power production has the added advantage of generating significant quantities of heat, which can be used directly for heating the habitat, or in industrial processes.

Powell, et al (2000), Cockell (1995), and others propose the use of nuclear reactors as a lightweight power source. The SP-100, along with the Russian TOPAZ reactor, is often mentioned as useful for Mars missions due to their relatively advanced, modular design and ability to be assembled for power ranges between 10kW to 1MW (Isenberg & Heller, 1989). Jahshan and Bennett (1992) propose a modular reactor with the potential to be tens of megawatts, also incorporating interchangeable power conversion and process heat transfer modules for obtaining varying levels of power with high and low temperature heat as necessary. This design can also be launched in sub-critical parts, precluding the possibility of the reactor reaching criticality during launch accidents, and has a projected operating life of 15 years at a 70% capacity factor. The SP-100 design also incorporates a 'fail safe' mechanism where nuclear fission will not occur unless the

beryllium neutron reflectors are in position, allowing the transport of the assembled reactor ready to be activated when placed in its final position.

The use of nuclear power raises the issues of safety (radiation protection) and stability. These concerns are addressed to some extent by many authors. Solutions proposed include remote location of the nuclear plant and positioning of the plant beneath tens of metres of ice (or soil).

Bamberger, et al. (1991), propose one novel concept for remotely locating a nuclear power plant. They couple the idea of power beaming (usually associated with solar power satellites) with the use of a nuclear reactor in geosynchronous orbit. Remotely locating the reactor in orbit provides the ultimate in nuclear safety for the habitat (aside from the potential risk integral with launching nuclear fuels), however, this option introduces efficiency losses associated with the power beaming itself, resulting in a larger reactor requirement than ground based systems and introduces serious maintenance problems. Power beaming is discussed in more detail on page 42.

When looking at nuclear plant radiation shielding it is necessary to also consider the effect of neutron and gamma scattering off of the atmosphere and soil, which can increase the radiation dose (Morley, et al. 1991). A separation distance between the reactor and the habitat can be useful in reducing the required amount of shielding. However, there comes a point when the additional mass of the power transmission cable (high voltage to reduce power transmission losses) is more than the mass of shielding saved (Mason & Cataldo, 1993).

For varying power level requirements there are different nuclear technology options. Radioisotope Thermoelectric Generators (RTG) provide an effective power source for requirements less than about a kilowatt. They are currently in use on several space probes, including the Galileo probe around Jupiter. Dynamic Isotope Power Systems (DIPS) are most suited to power ranges between one kilowatt and tens of kilowatts and have an increased converter efficiency (more power output from the isotope inventory) over RTG using either Brayton or Stirling power conversion. Nuclear reactors are most suited to power levels over ten kilowatts (Mason & Cataldo, 1993), as indicated in Figure 10 above.

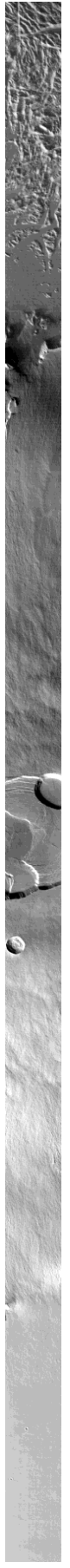


Table 1: Specific Power (W/kg) for Various Nuclear Options, Excluding Shielding

| Nuclear Option | Approximate Unit Power Output | | | | |
|----------------------------|-------------------------------|-----------------------------------|-----------------------|-------------------------------------|-----------------|
| | 200-300W | 2.0-2.5kW | 20-25kW | 100kW | 3,000kW |
| RTG (up to 1 kW) | 5.3 to 7.9 ^d | - | - | - | - |
| DIPS (up to 25 kW) | 5 to 6 ^a | 7 ^c to 10 ^a | 14 to 22 ^a | - | - |
| Reactor (up to several MW) | - | - | ~17 ^{b,d} | 30 ^e to ~37 ^b | 10 ^e |

^a Bents, et al. 1991

^b Haslach, 1989

^c Littman, 1993

^d Mason, et al. 1993

^e Reported in Boston, 1995

The information contained in Table 1 is highly dependent on system configuration, however, it does show a marked improvement in specific power for larger (megawatt) units.

Subject to ore deposits forming on Mars in the absence of plate tectonics (which is likely and discussed in detail on page 77) uranium fuel for nuclear reactors should be available on Mars. Schubert, et al. (1992) review several authors, based on SNC meteorite analysis, concluding that uranium should be present in the Martian mantle in concentrations of 16ppb, compared to a value of 25.7ppb on Earth, although significant processing and mining infrastructure would be required to rely on a local source.

Nuclear technologies are regularly used on Earth for power generation and have been designed, and commonly considered, for space applications, including for Martian habitats. Nuclear fission is therefore considered a viable technology for large scale power generation on Mars.

2.4.4. Solar Power

NASA first used photovoltaic power systems on the Vanguard satellite in 1958. More recent technologies have begun to develop very thin film cells with inherent advantages of high radiation tolerance, high specific power (W/kg) and flexibility,

increasing the potential applications for solar cells, however, thin film cells currently have lower efficiencies (Morely, et al. 1991).

Solar power is a popular choice amongst many authors including Ishikawa, et al (1997), Atkinson, et al (1992), Geels, et al (1989) and Landis, et al (1997). Several problems associated with solar energy systems include the day-night cycle (Powell, 2000) the CO₂ fog at high latitudes (Cockell, 1995 and Atkinson, et al. 1992), the obscuring of solar radiation during dust storms (Stoker, et al. 1985) and the relatively low levels of incident solar radiation (Figure 11) reaching Mars, compared to Earth, (Atkinson, et al. 1992, Drake, 1998, Fogg, 1996) all limiting the efficiency of the solar power.

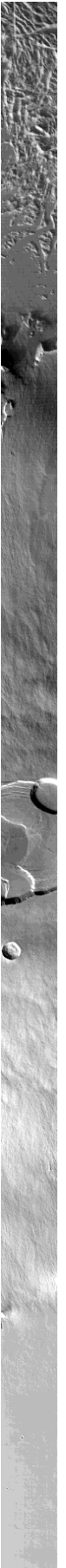
The solar irradiance on the surface of Mars, and in orbit can be seen in Figure 11, as compared to the irradiance in Earth orbit.

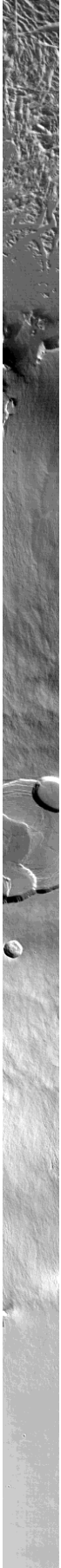
NOTE:
This figure is included on page 35 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 11: Solar irradiance, Mars versus Earth orbit (Drake, 1998).

The solar irradiance in Mars' orbit actually varies significantly during the year due to the eccentricity of Mars' orbit. Solar irradiance varies from a minimum of 493 W/m² at aphelion to 718 W/m² at perihelion (Landis and Appelbaum, 1997).

Contrary to Figure 11, Atkinson, et al. (1992) state that the total surface irradiance is only slightly attenuated by dust storms, the dust scattering the radiation but not significantly diminishing the total (this is supported by Meyer & McKay, 1995 who state that much of the light removed from the direct sunlight by dust will still reach the surface as scattered light). Under such conditions they, and others (Landis and Appelbaum, 1997), state that a horizontal panel will be most effective, as opposed to a sun tracking panel which is only most effective under clear sky conditions, as it will maintain the full 2 π steradian sky view. During dust storms, at optical depths of 5, Haberle et al. (1993)





calculate that at normal incidence almost $200\text{W}/\text{m}^2$ are available to solar panels, and with the sun at only 30° above the horizon $50\text{W}/\text{m}^2$ are available. Daily average surface solar insolation available at the equator is approximately $180\text{W}/\text{m}^2$ (with peaks of approximately $200\text{W}/\text{m}^2$ and a minimum of around $145\text{W}/\text{m}^2$) and a daily average of approximately $80\text{W}/\text{m}^2$ at the north pole (with a peak of around $300\text{W}/\text{m}^2$ but a seasonal minimum of zero due to the planet's obliquity).

Solar energy is intermittent due to the day/night cycle and is adversely affected by atmospheric dust (particularly dust settled on the panel) and so would require supplementary power sources or energy storage systems. From a design point of view dust storms can be treated as 'partially cloudy' or 'cloudy' days, and will result in additional capacity and possibly energy storage being designed into the system (Landis and Appelbaum, 1997).

Temperature also affects the performance of solar power panels. The optimum temperature for solar power production is -120°C to -70°C (Haberle, et al. 1993), which is within the surface temperature range of Mars of -130°C to $+30^\circ\text{C}$ (Kieffer, et al. 1992).

Solar panels will need to withstand the forces of the wind. Landis and Appelbaum (1997) state that the average wind speed at the Viking Lander 2 site (on the Utopia Planitia, 48°N) was measured at $2\text{m}/\text{s}$, only exceeding $5\text{m}/\text{s}$ 10% of the time, and exceeding $15\text{m}/\text{s}$ 1% of the time, reaching a peak of $32\text{m}/\text{s}$ during a dust storm. Due to lower atmospheric pressure on Mars this peak wind speed is equivalent to a gust of about $4\text{m}/\text{s}$ on Earth so wind loading is not significant, however, abrasion resistance may still be important, as sand particles will be travelling at up to the full $32\text{m}/\text{s}$. Fortunately, the problem of abrasion can be significantly reduced by lifting the solar panels above the saltation point (the height to which sand is typically lifted by wind). Due to low atmospheric pressure the saltation point on Mars is approximately 20cm above the surface. Dust (as opposed to sand) can be present in the atmosphere to significant heights and so will interact with the panel surface. Dust, however, typically consists of silicate particles of 1 to 2 microns and should not pose a significant abrasion problem (Landis and Appelbaum, 1997).

Geels, et al. (1989) address the problem of dust accumulation on solar arrays. Positioning the array as close to vertical as possible is a simple solution, however, this limits the power generating capacity of the array during high opacity dust storms.

Electrostatic adherence may be countered through the use of a tin oxide layer to provide a conductive coating, coupled with radiation induced ionization to provide for charge neutralization. A constant laminar flow of gas may also be effective at preventing a dust build-up, or turbulent bursts to dislodge accumulated dust. Mechanical brushing is also an alternative for maintaining a clean panel to maximize power generation. It is expected that the build-up of dust will be slow. The total column mass dust is $10\text{g}/\text{m}^2$ with an average particle size of around 2.5 microns, thus a very thin layer would be deposited after a dust storm (Meyer & McKay, 1989).

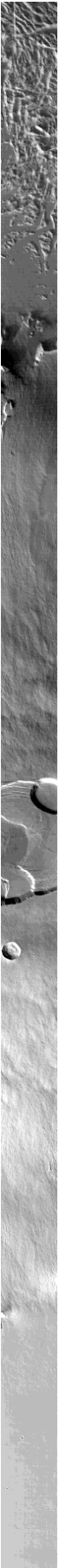
Atkinson, et al. (1992) calculate the required area of solar panel to support a 10-person base, excluding transportation and construction energy requirements, at polar, mid and equatorial latitudes using a horizontal photovoltaic collector. These calculations are based on an energy requirement of 20kWh and relatively clear sky conditions (atmospheric optical depth of 0.5). The required PV array areas are shown in Table 2, along with assumed solar irradiance. The area of the polar latitude collectors allows for the long periods of darkness by assuming a collection over a six-month period and storage for use over the remainder of the year.

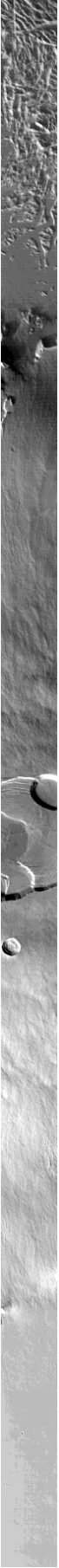
Table 2: Solar panel collector areas for a 10-person base (Atkinson, et al. 1992)

NOTE:
This figure is included on page 37 of the print copy of
the thesis held in the University of Adelaide Library.

These photovoltaic collector areas could be reduced, or power output increased, in mid to equatorial latitudes through the use of a 2-axis sun-tracking collector under clear sky conditions. This modification would come at the expense of additional complexity and maintenance.

Large scale solar power stations are currently in use on Earth and solar panels are commonly used in space and on Mars. It is therefore considered that solar technology is





viable for the habitat's use, subject to the selection of appropriate energy storage technology.

2.4.5. *Solar Power Satellite Power*

Solar power satellites, whilst being an unproven technology, are certain to be viable (Fogg, 1996). A solar power satellite, beaming power back to the base via microwave transmission, is recommended by Ishikawa, et al. (1997) as a viable method of producing 10MW of power, assuming 20% efficiency and a 13,000m² array. The satellite, orbiting in a 17,000km high geosynchronous orbit, would transmit power to the planet surface through microwave transmission, received by a rectenna on the surface (an alternative, lower mass, transmission method would be using lasers, although at one-third efficiency, Bamberger, et al. 1991).

One advantage of such a system is that the microwave transmission is not greatly affected by dust storms. Further to this the satellite will receive energy from the sun for a significantly longer period than collectors located on the surface, reducing the energy storage requirements of the base. In fact the satellite would be in darkness for a maximum of only 2 hours, 14 minutes per Martian day, or 9% of the time, around local midnight when power requirements are at their lowest (De Young, et al. 1989).

Fogg (1996) indicates one potential disadvantage of such a system. Maintenance of the satellite, will be relatively difficult due to its remoteness and as such, backup power supplies must be available in the event of the satellite failing unexpectedly (such as fuels originally synthesised with the use of beamed power (Criswell, 2000) such as a Hydrogen/Oxygen fuel for use in a fuel cell, described on page 41).

As a new, unproven technology, solar power satellites require significant development of multiple components and must address maintainability and backup systems prior to being seriously considered for this application.

More information on power beaming can be found on page 42.

2.4.6. *Wind Power*

The Viking landers measured wind speeds averaging around 5m/s, with peak speeds of over 10m/s (Meyer & McKay, 1989). Haslach (1989) suggests that a well chosen site may average wind speeds of around 14m/s. Wind speeds on Mars are considered to be

typically suitable for wind power generation above the atmospheric boundary layer (Zubrin, 1997).

McKay (1988) states that wind turbines are capable of power generation levels in the order of twenty kilowatts, despite the very low atmospheric pressure of Mars. The potential power extraction from wind is a function of velocity cubed and is only proportional to density, therefore, high wind speed will make up for low atmospheric density (Hemmat, et al. 1999). Wind power is, however, intermittent and so best used as a backup system or for uses not requiring continual power, such as the disassociation of oxygen from carbon monoxide (Haslach, 1989).

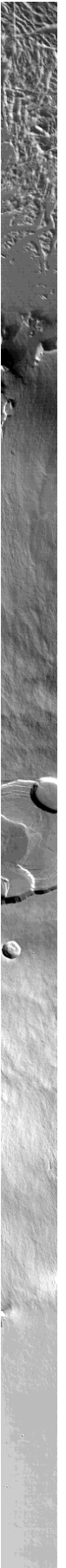
Wind turbines come in two varieties, those relying on aerodynamic drag (having a horizontal axis of rotation, such as windmills) and those relying on aerodynamic lift (having a vertical axis of rotation) (Haslach, 1989). Aerodynamic lift types far exceed the power generation capacity of aerodynamic drag types for a given swept area, they do not need to reorient themselves depending on wind direction and they have lower rotor shaft torque (Hemmat, et al. 1999). Further to this, heavy gearboxes and other equipment can be located on the ground, allowing easy maintenance access, and the blades do not suffer fatigue stresses due to gravitational loading during rotation.


Fogg (1996) indicates that to produce comparable amounts of energy a wind turbine must have blades ten times longer or operate in wind conditions 4.6 times faster than those on Earth. Ishikawa, et al. (1997) plans the use of a windmill farm as a supplementary energy source, with each 6m diameter windmill producing a maximum of 10kW.

High wind speeds are likely to be found on long slopes (such as the bases of volcanoes in the Tharsis Region) or possibly around the rim of craters with potential wind energy densities of up to 300 watts per square meter at about 33m/s wind speed (Haslach, 1989).

Further to the extraction of energy from the wind alone, Haslach (1989) proposes that a 'sandmill' could be developed to extract energy from windblown sand, via impact with the blades, close to the ground using an aerodynamic drag system.

Large scale wind farms are used on Earth and the technology is well advanced such that relatively minor development would be required for Martian applications. The turbine location is critical to its effectiveness, and it must be considered that the ideal





location for wind generation may not be ideal for a habitat location, although locations in reasonable proximity may be available. The close proximity of the habitat and power generators will reduce power transmission losses and improve the ease and safety of maintenance, and so alternative, viable technologies could be preferable.

2.4.7. *Natural Gas Power*

The combustion of methane, produced using in-situ resource utilisation methods, is a method of power generation mentioned, although not discussed, by Cockell (1995). Zubrin (1989) discusses, in detail, the method for methane production using hydrogen (readily available in the polar ice or water from other sources) and atmospheric carbon dioxide. This would make an ideal backup power source due to the easily storable nature of the methane and the portability of generators, although would require power from other sources to initially generate the methane so it is not suitable as a primary energy source.

Littman (1985) proposes the use of an oxygen/methane Stirling cycle heat engine as a 40kW backup power supply for a proposed 4-8 person, 600 day visit, and also for use on rover excursions, although the size would need to vary for larger communities. Thangavelu (1999) also proposes methane/oxygen engines to generate power on exploration vehicles, stating that a 6.8 litre engine would be capable of generating 168kW through combustion of 10% methane, 70% oxygen and 20% carbon dioxide. Methane engines are currently in use in remote environments, such as Antarctica.

Baker and Zubrin (1990) also discuss the use of methane/oxygen systems to drive rovers by generating electricity used to drive one electric motor per wheel. Two 25kW turbo-generators are proposed, for redundancy and/or extra power when required.

This technology is not suitable as a primary energy source, as the methane is not freely available and must be manufactured, although it may be suitable as a backup system or for vehicular applications. Safety concerns may include the toxicity of gas that could leak into the life support system and the combustibility and potential for significant damage to occur as a result of an explosion. Use of such technology should provide fail-safe mechanisms to ensure that safety of the stored gas.

2.4.8. *Geothermal Power*

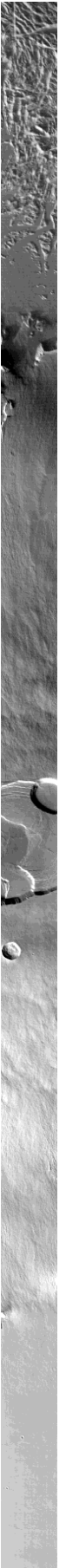
Geothermal energy has received relatively little attention despite its promise of high power outputs, high reliability, high levels of safety and low dependence on prevailing conditions due to the perception that the Martian crust is frozen to great depth (Fogg, 1996). As Fogg discusses, this is not necessarily the case for the whole of Mars and geothermal energy has been suggested by several other authors, although in far less detail, including Stoker, et al (1985). Fogg believes that there is likely to be local 'hot spots' on the surface of Mars suitable for geothermal energy production. He bases this on evidence implying there has been lava flows on the Martian surface approximately once every 10,000 years for the last few hundred million years (based on average resurfacing rates calculated from crater densities). These recent surface formations cover 4.5 million km², almost exclusively between Amazonis Planitia and Chryse Planitia, incorporating Olympus Mons, Tharsis Montes, Valles Marineris and numerous eroded channels.


One advantage with geothermal power over many of the other sources (with the exception of nuclear) is that the heat generated can either be used directly for heating and industrial uses or converted into electricity. Iceland generates the majority of its power (over 500 MWt) from geothermal energy and also uses the heat directly for the heating of buildings. Geothermal heating has proven to be one of the most reliable energy sources in use today, being on-line 97% of the time, only exceeded by hydroelectric power (Zubrin, 1996).

Geothermal power technology is well developed, however, its use on Mars is subject to extensive exploration of potential habitat locations. It is not considered to be a technology that is to be relied on for initial habitats, but should be seriously considered should local hot spots be identified following the establishment of initial habitats.

2.4.9. *Fuel Cell Power*

Hydrogen/oxygen fuel cells are very efficient ways of storing energy (Morley, et al. 1991, Landis and Appelbaum, 1997) although fuel cells do not produce energy, they merely store and recover energy produced by primary power generation technologies. Fuel must be produced with alternate energy sources such as photovoltaic cells during the day, usually through the electrolysis of water (Siegfried, 1999). Landis and





Appelbaum (1997) suggest the hydrogen/oxygen regenerative fuel cell, incorporating pressurised gas storage, as the most suitable candidate for storing energy produced by solar power for use during night-time conditions.

Carbon monoxide/oxygen fuel cells are also viable. According to Clapp & Scardera (1989), regardless of fuel, fuel cells produce approximately 1.5kW of electrical power per square metre of electrode (although efficiencies are improving) and lose about 25% of the available energy through various processes. Given that a CO/O₂ fuel cell is about 68% efficient and a typical electric motor is about 90% efficient, the effective efficiency of a fuel cell in turning electricity into mechanical work is approximately 61%, compared to 43% for a CO/O₂ diesel-cycle engine.

2.4.10. Chemical Power

Peroxides, if found to be in the Martian soil in sufficiently large concentrations, could be a major alternative energy source for the habitat (Allen, 1995).

2.4.11. Man Power

Human power can be utilised for emergency power requirements, including communications. Small bicycles attached to a dynamo have been used during polar expeditions on Earth to charge batteries for heating and a similar method could be used to electrolyse stored water for oxygen production on Mars (Cockell, 2001b).

2.4.12. More on Power Beaming

There are two main primary sources of energy proposed in available literature for power beaming, nuclear and solar. Solar power can be further divided into energy produced from solar panels and converted into laser or microwave energy (similar to nuclear power beaming), and sunlight directed directly through a lasing material (a material that can be stimulated to produce laser light) using mirrors.

The technology to generate, transmit and control the necessary microwave beams is not dissimilar to technologies used for radar and is based on a magnetron, similar to that found in any household microwave oven (Criswell, 2000). Criswell states that a solar power beaming system established on the moon could provide Earth with up to 20,000 GWe.

The safety of microwave power beaming could be considered a concern. Criswell (2000), however, states that the public is exposed to far higher levels of microwave radiation through the use of mobile phones than would be experienced from the stray levels associated with power beaming.

Located in a geosynchronous orbit, a satellite incorporating power beaming could supply energy to one or more locations within a range covering approximately 83% of the hemisphere. Power would not be generated and transmitted by a solar powered satellite during the period when it passes behind Mars and has no line of sight to the sun (De Young, et al. 1989), however, nuclear power satellites would not be affected in this way. Solar satellites can overcome this shortcoming by the introduction of a second system such that only one satellite is ever obscured from the sun at any time, this would also provide system redundancy.

Power beaming can provide power to the polar regions also (De Young, et al. 1989). Through a polar, sun-synchronous orbit numerous satellites are used to provide continuous power to any particular region, however, as Mars rotates within the polar orbit a single satellite could only transmit intermittent power to any particular location on the planet.

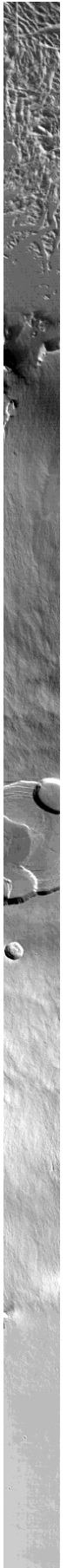
Power beaming satellites can also act as a communications satellite with the data being transferred simultaneously with the beamed power (Bamberger, et al. 1991 and De Young, et al. 1989).

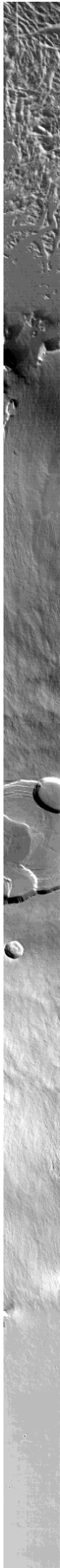
2.5. Material Sources/Production

2.5.1. Resource Availability

Maps displaying the elemental composition of the surface of Mars for water (hydrogen), iron, silicon, chlorine, thorium and potassium are included in Appendix B, displaying the global distribution and concentration (% by weight) of each element.

To the best of our current knowledge, Mars is the only planet in the solar system where self sufficient colonization is possible, due to the availability of essential resources (Friedman, 1981). The key materials required for a habitat on Mars will be those that contribute to the life support system, including water, oxygen and fuel. Further, the Martian atmosphere and soil will provide many useful elements that can be utilised in





materials production. One of the goals of the Mars Odyssey satellite mission was to map the elemental resources within the surface layer of the Martian regolith. The Mars Odyssey results, and the results of other geoscience research missions, will assist mission designers in determining the location of future stations based on resource abundance (Stoker, et al., 1992). The constituents of the Martian atmosphere (Table 3) and soil (Table 4) are listed below.

*Table 3: Atmospheric Constituents, Mars – Earth Comparison
(adapted from Owen, 1992, and Meyer & McKay, 1989)*

| Constituent | Quantity | |
|-----------------------------------|---------------------------|------------------------------|
| | Mars | Earth |
| Carbon Dioxide (CO ₂) | 95.32% | 350 ppm |
| Nitrogen (N ₂) | 2.7% | 78.08% |
| Argon (⁴⁰ Ar) | 1.6% | 0.93% |
| Oxygen (O ₂) | 0.13% | 20.95% |
| Carbon Monoxide (CO) | 0.07% | 0.12 ppm |
| Water (H ₂ O) | 0.03% ¹ | 1% ¹ |
| Argon (³⁶⁺³⁸ Ar) | 5.3 ppm | included in ⁴⁰ Ar |
| Neon (Ne) | 2.5 ppm | 18.2 ppm |
| Krypton (Kr) | 0.3 ppm | 1.1 ppm |
| Xenon (Xe) | 0.08 ppm | 0.087 ppm |
| Ozone (O ₃) | 0.04-0.2 ppm ¹ | 0.04 ppm |
| Helium (He) | 0 | 5.2 ppm |
| Methane (CH ₄) | 0.02 ppm | 1.7 ppm |
| Hydrogen (H ₂) | 0 | 0.55 ppm |

¹Highly variable with season and location

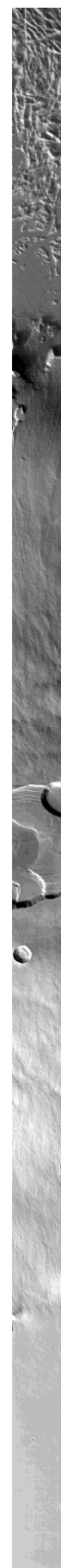
Table 4: Representative Soil Constituents (oxides are typically inferred)

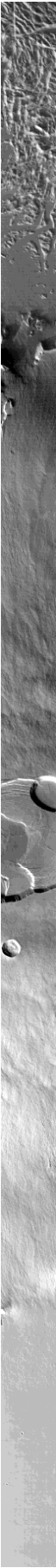
| Constituent | Quantity (% by weight) | | |
|--------------------------------|--|--|--|
| | Viking Landers representative (Banin, et al. 1992) | Mars Pathfinder 'Mermaid Dune' (Rieder, et al. 1997) | Mars Exploration Rover – Opportunity (Rieder, et a. 2004a) |
| SiO ₂ | 43% | 50.2% ± 2.5 | 45.5% ± 0.4 |
| Al ₂ O ₃ | 7.2% | 8.4% ± 0.8 | 8.8% ± 0.2 |
| FeO | 18% | 17.1% ± 1.7 | 20.1% ± 0.2 |
| MgO | 6% | 7.3% ± 1.1 | 7.2% ± 0.2 |
| CaO | 5.8% | 6.0% ± 0.9 | 7.52% ± 0.05 |
| TiO ₂ | 0.6% | 1.3% ± 0.2 | 1.09% ± 0.05 |
| SO ₃ | 7.2% | 5.2% ± 1.0 | 4.93% ± 0.05 |
| Cl | 0.6% | 0.6% ± 0.2 | 0.43% ± 0.03 |
| K ₂ O | 0.2% ¹ | 0.5% ± 0.1 | 0.48% ± 0.1 |
| P ₂ O ₅ | 0.8% ¹ | | 0.82% ± 0.04 |
| MnO | 0.5% ¹ | | 0.40% ± 0.02 |
| Na ₂ O | 1.3% ¹ | 1.3% ± 0.7 | 1.4% ± 0.3 |
| Cr ₂ O ₃ | 0.2% ¹ | | 0.52% ± 0.02 |
| CO ₃ | <2% ² | | |
| H ₂ O | 0-1% ³ | | |
| Ni | | | 640 ppm ± 40 |
| Zn | | | 280 ppm ± 40 |
| Br | | | 30 ppm ± 30 |

¹Based on Shergotty meteorite analysis

² Estimated from Labelled Release simulation

³Varies (direct Viking analysis)





For comparison with Table 3 and Table 4, above, Table 5 includes typical Earth soil composition information, for significant constituents.

Table 5: Earth Crust Constituents (NASA, 1998)

NOTE:
This table is included on page 46 of the print copy of
the thesis held in the University of Adelaide Library.

It should be noted, when incorporating the results of SNC meteorite analysis, that the University of Arizona, in analysing the results of the 2001 Mars Odyssey Gamma-ray Spectrometer equipment, determined that the SNC meteorites are not entirely representative of the surface layer of the Martian surface. They concluded this based on the differences measured in the Potassium and Thorium ratios of the spectrometer and analysis of the meteorites (University of Arizona, 2004).

Phosphorous was not originally identified in the soil analysis from Viking instruments, however, it was considered extremely likely to be present due to the ubiquitous occurrence of apatite in igneous minerals (Clark, 1981). It is expected that the phosphorous signal, in the Viking Lander experiments, was masked by the unusually strong sulphur signal, 10 to 100 times the content of terrestrial soils and rocks (Boston, 1985, Meyer & McKay, 1989). Further evidence was found in phosphorus's high abundance, relative to Earth, in SNC meteorites (thought to originate from Mars), of 0.36% to 1.31% (Banin, et al. 1992, phosphorous presence also noted by Boston, 1985).

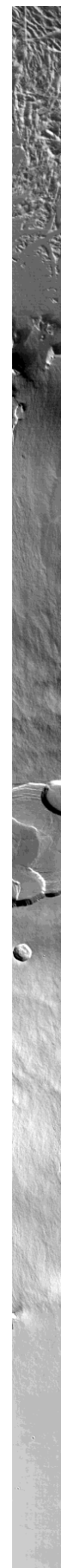
Indeed, the Mars Pathfinder mission did discover phosphorus in the Martian soil (Wänke, et al. 2000). Thus, all of the elements essential to life (C, H, N, O, P and S) are present on Mars. Most of the required trace elements (such as Fe, Mg and Al) have also been directly detected (Meyer & McKay, 1989).


The spectroscopic analysis at the site of Viking Lander 1 showed minimal difference between the composition of the soil at the surface and at a depth of 23cm (Banin, et al. 1992) indicating a homogenous surface soil layer.

NOTE:
This figure is included on page 47 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 12: Martian soil constituent summary at various locations (Rieder, et al. 2004b)

It can be seen, in the above Table 4 and in Figure 12, that the soil composition of the Viking Lander sites and the Pathfinder Lander site are similar, confirming the global homogeneity of the Martian surface layer. It is considered that minor variations are typically the result of weathering of local rocks. When the Pathfinder site soils are normalised to 44% by weight silica the soils of that location are generally lower in sulphur and higher in titanium than the soils at the Viking site (Rieder, et al. 1997). Notwithstanding this slight variance, it is generally considered that the Martian dust forms a largely ubiquitous, homogenous layer over the entire planet. The homogeneity of this layer implies that Mars' soil resources will typically be available across the majority of the surface of the planet and so available to a habitat in similar proportions and compositions almost regardless of the habitat's location.





Hydrogen is a critical element for virtually all organic compounds, for many propellants and in many manufacturing processes (Boston, 1985, Clark, 1985). Whilst it is available through the electrolysis of water, unless the habitat is located near an abundant supply of water lack of hydrogen may cause serious problems. Other than in water ice, sources of hydrogen on Mars are very minimal, including minor atmospheric constituents such as, H_2 (10 ppm), C_2H_2 (0.002 ppm), C_2H_4 (0.5 ppm), C_2H_6 (0.4 ppm), NH_3 (0.005 ppm), HCl (0.1ppm), $HCOH$ (0.6 ppm) and H_2S (0.1 ppm) (Owen, 1992 and Clark, 1985) as well as contained in some clays, salts and iron-oxyhydroxide found in the soil (Clark, 1985). As mentioned earlier, this will be a critical consideration in determining the location of a Martian habitat.

2.5.2. Resource Utilisation

Preliminary engineering studies indicate that automated processes can be developed to extract and stockpile consumables on Mars such as water, oxygen, buffer gas (nitrogen or argon) and fuel. Through the use of ISRU demanding processes such as closed loop life support, water recycling and toxicogenic filtering can be relaxed, as resources can be replenished from the surrounding environments (Meyer & McKay, 1995). The purification of gasses from the Martian atmosphere can be achieved by fractional condensation, followed by fractional distillation (Clark, 1981) to provide many of the essential elements for these consumables. Alternatively, molecular sieves can be used to separate and concentrate the atmospheric constituents. With a diurnal temperature range of approximately $70^{\circ}C$ Finn, et al. (1996) postulate that a molecular sieve may be capable of adsorption of gasses during the night and regeneration during the warmer daytime temperatures. It should be noted, however, that more efficient regeneration will require higher temperatures and more energy input than that proposed by Finn, et al. Finn, et al. also note that, in general for molecular sieves, adsorption is an exothermal process and higher temperatures reduce the capacity of the sorbent, therefore, large sieves may need to take this reduced capacity into account (or provide a cooling mechanism).

The production of primary consumables, such as fuel, oxygen, water, nitrogen and food, should logically be developed first, to provide a feedstock to mining, materials processing and recycling facilities (Meyer & McKay, 1995) and to satisfy life support needs.

The testing and evaluation of machinery for material extraction and processing, as well as for the materials themselves, will be a crucial prelude to the use of ISRU. Johnson and Leonard (1989) state key design goals of resource recovery including performance, function of complex systems, versatility/adaptability/growth, long life, reliability/safety, automation and cost. They describe a Martian Surface Wind Tunnel (MARSWTT) at the NASA Ames Research Centre that can simulate Martian surface atmospheric composition and pressure. Abrasion testing of materials can also be undertaken in the wind tunnel. Ground walnut shells are used in-lieu of silicate particles to compensate for the lower gravity. MARSWTT, or similar environment simulators, can be used to test the performance of machinery under Mars-like conditions.

The use of biological processes to transform materials found locally on Mars into useful forms should not be overlooked, particularly in view of the capabilities for creating tailored (genetically modified) organisms to accomplish certain tasks (Clark, 1981).

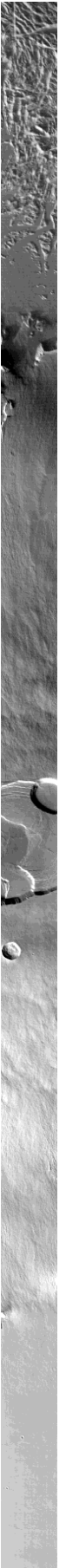
2.5.3. *Water*

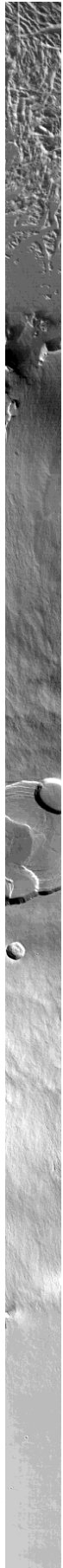
2.5.3.1. *Water Availability*

The utilization of water on Mars is critical to any habitat. It will be used for drinking and wash water and as a feedstock for propellant production, as well as having uses in countless industrial processes (Williams, et al. 1995).

Water on Mars may not be as scarce as it may appear from the apparent dryness. Estimates of the original amount of water on Mars, expressed in metres depth over the planet's surface, range from 5.9 metres to 1,200 metres (Fogg, 1995). If current rates of escape of water from the atmosphere have remained constant over the last 4.5 billion years the total amount of water lost to space would equate to a relative depth of 2.5 metres (Meyer & McKay, 1989), leaving an expected minimum relative depth of 2.9 metres of water remaining. The bulk of remaining Martian water must still be tied up in reservoirs, most likely as permafrost. There is also currently a relative depth of 0.007 of a millimetre contained in the Martian atmosphere, equating to 1.3 km³ of water (Meyer & McKay, 1995).

Figure 13, below, indicates areas of the Martian crust where ice and liquid water (below the melting isotherm) are thought to be stable. The 2km drop near the equator represents the fact that the ground surface level of the Southern Hemisphere is raised





above the northern 'lowlands' by this distance. The region marked 'dehydrated zone?' does, in fact, contain substantial amounts of water, possibly in the form of ground ice, and water bound to clay minerals, as demonstrated by Viking experiments (Meyer & McKay, 1989).

NOTE:
This figure is included on page 50 of the print copy of
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Figure 13: Cross section of the Martian mega-regolith indicating possible areas of stable ice and liquid water (Fogg, 1995).

Water may be available in many locations on Mars, primarily in the form of ice. McKay (1988) indicates that the northern polar cap is a significant, known, source of water ice (Clark, (1981) estimates at least 800 billion cubic metres). Meyer and McKay (1989) state that there is very good evidence for the existence of ground ice (or permafrost) below, or mixed in with, the Martian surface regolith, particularly poleward of 40° (including located around table mountains, rampart craters, debris flows, thermokarst pits and patterned ground, Fanale et al., 1986). Fogg (1995) indicates that the 'flowing' effect of some impact crater ejecta blankets seen on Mars is good evidence of near surface ice deposits, especially poleward of 30°. Theoretically permafrost ice should be available within one or two metres of the surface at all latitudes poleward of 40° (Cordell, 1985).

Fanale, et al. (1986) have modelled the change in ground ice over the course of Mars' history. Based on their assumptions, including that the ice layer began history at a depth of 10 metres, their model indicates that ground ice should be available at, or near, the surface poleward of 40° (or possibly 30° depending upon certain assumptions). Further to this, ground ice should not be expected for a depth of between 120 and several hundred metres on the equator side of 30°. This can be seen in Figure 14, below.

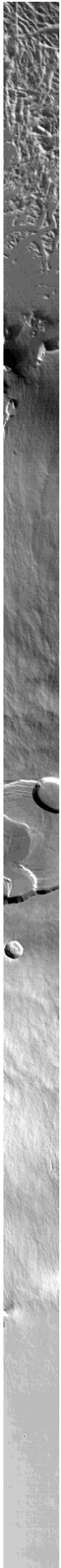
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the thesis held in the University of Adelaide Library.


Figure 14: Ground ice depth for various periods of Martian history (4.5 is the present) versus latitude for a 1 μ m pore radius (top left) and a 10 μ m pore radius (top right) with obliquity (tilt) and orbital eccentricity cycles in phase and for 1 μ m pore radius with obliquity and eccentricity cycles out of phase (bottom left) (Fanale et al. 1986).

An analysis of approximately 24,000 Viking Orbiter images shows abundant examples of lobate debris aprons, concentric crater fill and terrain softening poleward of 30°, but virtually no examples were seen equatorward of 30°, supporting the above model's prediction of surface ice locations (Fanale, et al. 1986).

Phillips (1985) states that the melting isotherm (indicated in Figure 13, above), below which water is liquid, occurs at a depth of approximately 1km at the equator and several kilometres at the poles. Fogg (1989) states that the depth of this isotherm at the equator is 1-3km and 3-8km at the poles, as marked on Figure 13. Meyer and McKay (1989 & 1995) also state that liquid water may be present at a depth of over 1km. It is important to note, however, that this does not exclude the possibility of liquid water nearer the surface, reasonably stable brine solutions are considered to be possible just below the surface (Meyer & McKay, 1995).

Large quantities of water have been proven throughout the Martian surface layer, as can be seen in Figure 15, below (NASA press release, 28 May 2002). Variances were shown between seasons, particularly evident at the poles, although this does not represent a significant seasonal change in the water abundance, but was due to the





obscuring of instrument readings by carbon dioxide solidifying on the poles during the colder winter periods.

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Figure 15: Map of Mars showing areas of high water content in the surface layer (NASA).

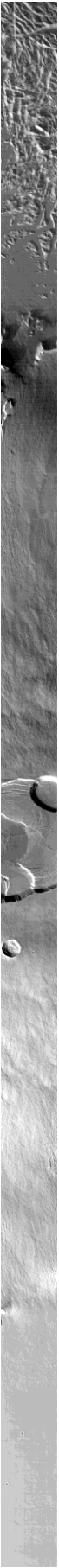
Water can be located in the soil anywhere on the Martian surface in the form of ‘water of hydration’ (Gwynne and McKay, 1997). During Viking Lander experiments, water was released from the samples of soil when heated. At temperatures of 500°C, 1%, by weight, water was released, a result that is expected to be consistent across the planet (Meyer & McKay, 1989).

The form of this water in the Viking samples could be numerous. Table 6 indicates several potential forms and concentrations in which water may be present in ‘dry’ Martian soil.

Table 6: Possible Forms and Concentrations of Water in ‘Dry’ Martian Soil (Cordell, 1985)

NOTE:

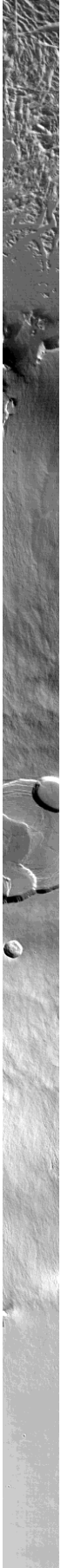
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the thesis held in the University of Adelaide Library.

2.5.3.2. Water Requirements, Production and Recycling

Boston (1992) tabulates seven different authors, which indicates an average human daily water consumption requirement of 3.129kg/person (supported by Smernoff and MacElroy, 1989) and an average daily wash water requirement of 6.5kg/person (although one author states a requirement of 18kg/person-day). Jones, et al. (1985) indicate water requirements of an 18 person Martian base. They show a water intake per person of around 2.57kg/person-day, with an additional requirement of 6.77kg/person-day for washing, laundry and toilet flushing, and so, with a minor allowance for system losses each person requires the use of 9.35kg of water per day. Whilst not directly related,



Tamponnet (1996) describes the water use requirements for a lunar mission as 3.56kg per person per day for metabolic requirements, and 25.73kg of water per person per day for wash water (including dish wash, hygiene wash and clothes wash water and toilet flushing requirements). Therefore, available literature relating to Mars habitats indicates a total water requirement, per person, including metabolic and wash water requirements, of up to 10kg/person/day, although psychological benefits may result in the availability of a larger quantity.

Many authors, including Meyer & McKay (1981), Jones, et al. (1985), Boston (1992) and others indicate that, once initial water stocks are supplied, recycling systems can minimise, or even eliminate, the levels of water needed to be input to the habitat (depending on wash water usage). The build-up of metals and other hard to remove compounds may limit the indefinite recycling potential of the water, although this may be solved using reverse osmosis, ion-exchange technology or microbial/soil bed filtration. As a minimum, leakage and habitat expansion will necessitate the need for ongoing extraction of water from the Martian environment (Boston, 1995).

Meyer and McKay (1981) state that, when greenhouse requirements are considered in addition to their above statements, 250g of water per person per day must be input into the habitat to maintain sufficient water quantities, however, this may be somewhat underestimated, as their assumptions for wash water appear to be 5 times lower than those of Jones, et al. (1985). Taking into account this extra wash water, and assuming a pessimistic 5% loss of this extra water during recycling, it can be demonstrated that the required input may need to be around 0.5kg per person per day. Jones, et al. (1985) note that water should not be used for 'space suit' cooling purposes during Martian surface excursions or water losses from the habitat will increase significantly (carbon dioxide is an abundant and suitable alternative).

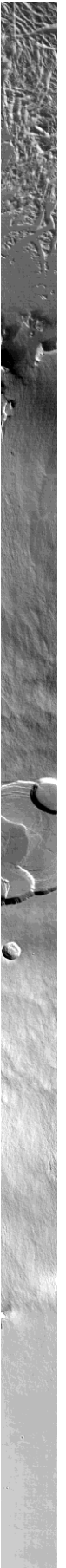
Smernoff and MacElroy (1989) discuss the fact that the number of plants required to supply a human's caloric requirements (approximately 2,800 calories per day) will purify and transpire more than enough water for human ingestion (approximately 3.1kg/day). Bio-regenerative recycling systems are supported by Biosphere 2 literature by Nelson and Dempster (1995), Cohen (1995) and Boston (1995). Others detail reverse osmosis systems combined with vapour distillation (Jones, et al. 1985 and Boston, 1995 – for the removal of metals and other contaminants). Vapour compression distillation can recover

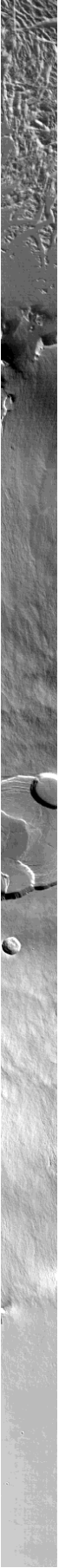
over 95% of water from the wastewater feed. Units sized for 6 people have undergone 1,000 hour tests with pre-treated urine, achieving power requirements averaging 100 to 120Wh per kilogram of recovered water. Other water reclamation methods include filtration (which includes particle/bacterial filters, activated carbon canisters and anion and cation exchange resin beds; Quattrone, 1981), thermoelectric integrated membrane evaporation systems (TIMES) and vapour phase catalytic ammonia removal system which requires no pre- or post-treatment chemicals for urine treatment.

To ease the requirements of water purifying systems several authors, including Jones, et al. (1985), propose a dual plumbing system to distribute water, one for drinking and one for 'grey' water (used for washing and irrigation). They discuss several ways in which water may be purified. Additional water obtained from the Martian environment will help to limit the restrictions on domestic water use (Smernoff & MacElroy, 1989).

It is useful to note that humans are net producers of water. The average human requires 3.129kg of water per day, from a combination of drinking water and water consumed in food. The average human metabolism outputs 3.52kg of water per day in waste product and perspiration, a net increase of 0.4kg per day. On this basis, and considering only human metabolic requirements, recycling 89% of this water into drinking water would result in a theoretical water input into the life support system of zero. Of course, there would be losses from the system that would need to be replenished by means of more efficient recycling or from external sources. It is expected that these levels of recycling can be achieved in the initial phase of human exploration of Mars (Meyer & McKay, 1995).

Water vapour is available from the Martian atmosphere, during at least some times of the year and dependant on regional factors such as temperature and altitude, although at concentrations many times less than that found on Earth. This resource can be condensed out through a process of compression and cooling of the atmosphere (McKay, 1988). The water content of the atmosphere is determined by the frost point, where the air is completely saturated with water, which occurs at night (Clapp, 1985). The 'wettest' season on Mars is the Northern Hemisphere's summer. The Hellas Basin, however, in the Southern Hemisphere has the thickest atmosphere (having the lowest elevation) and has the planet's highest local concentrations of atmospheric water (Meyer & McKay, 1989). The extraction of water from the atmosphere may be adequate for a





research station but is likely to limit significant further expansion due to the quantities of atmosphere that must be processed to obtain water (Boston, 1985).

Many authors have proposed water production/extraction systems. Clapp (1985) has designed water supply system, weighing 20kg, capable of collecting 2.79 kilograms of water in six hours using less than 70kWh. This design is scaled to supply the water required by Meyer & McKay's 1981 life-support design for 12 people (detailed in the section on Life Support from page 88, but for a crew of 8). It is based on off the shelf technology, including a single stage axial compressor and a refrigeration system, although the designed system will be noisy and require defrosting every hour or so. Clapp states that a self-defrosting unit could also be designed. Although impractical, Clapp describes that the unit would require 150m² of solar array to power the unit or, more likely, would utilise nuclear power. Every additional hour of operation would provide water for two additional people per day, according to the water requirements of the life support system described by Meyer & McKay in 1981.

Gwynne and McKay (1997) propose a system, weighing approximately 400kg, capable of producing one kilogram of water per 12 hours using solar power. As it has no moving parts it should require very little maintenance and only requires that its microwave power generator be sealed in a pressurised volume (to prevent electrical arcing), unlike conventional heating systems that require pressurised heating chambers to increase the efficiency of convection.

Williams, et al. (1995) have suggested collecting water from the atmosphere through adsorption, using molecular sieves relying on van der Waals forces. This process has less moving parts, important for reliability, and also uses less energy than the compression/cooling techniques described above. Water, being a very small molecule and highly polarised, will displace any other material adsorbed into a molecular sieve (Jones, et al. 1985). The design discussed by Williams et al., weighing only 28kg, is capable of producing 0.5kg of water per day using only 139W of power. The unit pumps filtered Martian air through a zeolite bed where moisture is adsorbed. The moisture is then heated and extracted from the zeolite using microwaves (or alternatively by lowering the surrounding air pressure) then collected and condensed for storage. The particular design exposes approximately 25cm³ of zeolite to an airflow of 8m/s. The unit could be scaled up to produce more water if additional power is available.

Jones, et al. (1985) state that half a cubic metre of molecular sieve can adsorb about 58kg of water at saturation, 98% of which can be reclaimed with a simple regenerator. As atmospheric water content rises during the day, molecular sieves will collect more water during the day than the night (Finn, et al. 1996). Gas from airlock purging or certain industrial processes can be vented through molecular sieves to minimise water losses from these processes. Note that successive molecular sieves can adsorb other molecules from the Martian atmosphere in the preference of water, carbon monoxide, carbon dioxide, nitrogen and finally argon and oxygen (Jones, et al. 1985) so molecular sieve technology may have a wide range of applications on Mars. Molecular sieves can also be used to create rough vacuums (much like a sponge can be used to empty a bucket of water) and also to pressurise gasses (Finn, et al. 1996).

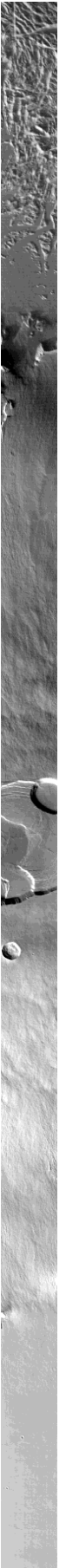
Helen Hart (1985) studied the possibility of a windtrap designed to passively constrict wind flow, thus increasing the velocity of, and cooling, the atmosphere, designed to precipitate water ice. She concludes that, whilst a pressure drop could be achieved, the resultant temperature drop was too small to be useful in extracting water.

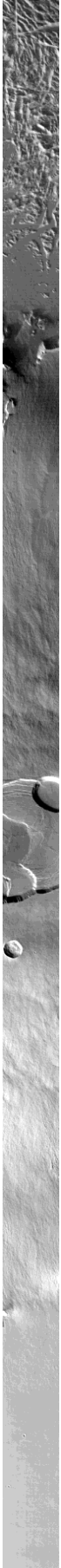
The power requirements for water extraction from various sources are summarised in Table 7.

Table 7: Power requirements of water extraction (adapted from Clapp, 1985, Clark, 1985, Haslach, 1989 and Williams, et al. 1995)

| Water Source | kWh/kg water |
|--|--------------|
| Atmosphere (compression/cooling technique) | 70-103 |
| Atmosphere (molecular sieve) | ~6.8 |
| Soil (0.3% water-containing soil, heated to 500°C) | 47 |
| Soil (2.0% water-containing soil, heated to 500°C) | 9.0 |
| Soil (2.0% ice, heated to 0°C) | 1.5 |
| Permafrost or Polar Ice | <1.0 |

It can be seen that, depending on soil conditions, the extraction of water from the soil is the most efficient method of obtaining water that can be implemented regardless of the extraction plant's location on the Martian surface (note that high altitudes have





minimal quantities of atmospheric water, limiting molecular sieves). This is best achieved using microwaves to heat the water through dipole rotation. As this method concentrates the heating on dipolar molecules of a certain size, depending on frequency, energy is not wasted heating the bulk mass of the soil itself, as would be the case with convection heating (Gwynne and McKay, 1997). The use of molecular sieves is the most efficient method of obtaining water at sufficiently low altitude and, clearly, melting ice is the most economical method in areas where ice is present.

Clark (1981) states that between 10 and 100 tonnes of water could be extracted from the Martian soil per month using a 50kW thermal source.

The task of extracting water from the atmosphere requires a very large throughput of atmosphere. To obtain one litre of water from the atmosphere Meyer & McKay (1989) state that one million cubic metres of atmosphere must be processed at 100% efficiency, although this would depend on the local atmospheric water content, and therefore frost point. According to Clapp (1985), to produce 2.79kg of water (using his design described above) would require the processing of 12,500kg (625,000m³) of Martian air, assuming a frost point of -60°C, a typical frost point near the equator. Despite the large volumes required, due to the low power requirements, and the fact that the movement of soil would be unnecessary, the collection of water using large molecular sieves may be preferable to other methods. The atmosphere is essentially a non-exhaustible source of water as it is readily replaced with moisture from the ground and/or the poles.

Permafrost, where present, could be extracted from the Martian soil by heating a drilled hole to melt the permafrost and bring it to the surface as vapour, where it could be condensed (Meyer & McKay, 1995).

Phillips (1985) suggests a modified 'horizontal gallery' (a large diameter perforated pipe) be installed to intercept groundwater. This method has been successful in obtaining groundwater from permafrost on Earth, examples in Alaska are cited in the reference. The concept involves burying a perforated pipe, perhaps 1m in diameter, in the permafrost with heating elements and filled with a gravel medium. The heating elements would thaw the permafrost and the water would drain to a sump for pumping to the habitat in a thermally insulated pipe. The pipe would drain back to the sump when not in use to prevent freezing inside the pipeline.

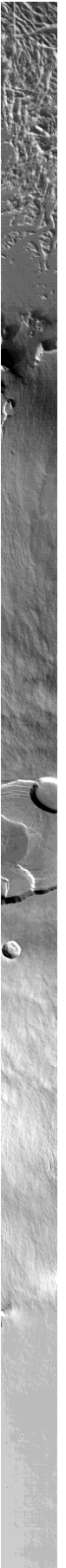
Obviously, having access to the polar ice caps would guarantee an abundant source of water which could be economically obtained and purified through vacuum distillation (Cordell, 1985). Alternatively, water can be purified using a thermoelectric integrated membrane evaporation device, relying on reverse osmosis followed by vapour distillation, capable of producing 3.1kg/hr of water with a 600We and 600Wt load using a 350kg unit (Jones, et al. 1985).

2.5.4. *Atmosphere*

Oxygen is critical to human life support systems. Fortunately it is relatively abundant on Mars. Oxygen is the major constituent of carbon dioxide (which comprises 95.32% of the atmosphere – refer Table 3). The atmosphere of Mars also contains small amounts of oxygen that can be separated from the atmosphere. It is assumed that the minerals in the Martian soil (such as aluminium, iron, silicon and magnesium) are in an oxidised form, thus the oxygen component of the soil may be over 40% by weight (Clark, 1981). It is believed that there may be as much as 4,000kg/m² of absorbed CO₂ in the Martian regolith, which is equivalent to over 10 kN/m² of atmospheric pressure (Meyer & McKay, 1995), which can be extracted and converted into oxygen. The reduction of metal oxides to produce metal ingots will also provide a source of oxygen (Rosenberg, 1992). Further to this, McKay (1988) states that oxygen will also be found locked up in carbonate rocks within the Martian crust (lunar carbonate rocks are considered the major oxygen source for lunar bases).

The average human requirement for oxygen is approximately 0.83kg/person-day (Boston, 1995, Meyer and McKay, 1995). Once produced (as a breathable mixture) the bulk of it will be continuously recycled within the life support system (either biologically or chemically), newly produced gasses will be required to make up for leakage (Boston, 1995).

A prototype system at the University of Arizona has produced oxygen from the thermal decomposition of carbon dioxide. The carbon dioxide is heated to 1,200°C where it thermally decomposes into carbon monoxide and oxygen, the oxygen is then preferentially transported across a zirconia membrane (this method is also discussed by McKay, 1988 and Ash, et al., 1989). The production of oxygen from CO₂ in this manner requires large amounts of energy to initiate the thermal decomposition. The prototype uses 288We and 2,000Wt (27kWh/kg) to produce 2kg of oxygen per day. It is expected





that in a well insulated, mature system this requirement could reduce to around 12kWh/kg (Meyer & McKay, 1995). One advantage of using this process is that the residual carbon monoxide can then be utilised as a reducing agent in iron production, and other industrial processes (Spiero & Dunand, 1997), or as a fuel (see page 74). Heat can be provided to this process using radioactive decay (Ash, et al. 1989) or by passing the gas through heat exchangers, removing waste heat from other equipment or industrial processes. Solar assisted cyclic processes making use of cadmium, zinc, iron, antimony or nickel catalysts also exist to decompose carbon dioxide (Clark, 1981).

Oxygen can also be produced from existing Martian resources through the electrolysis of water created during the Sabatier reaction or the Bosch reaction or from water sourced from wastewater systems and atmospheric vapour (Quattrone, 1981, Meyer & McKay, 1981 and Clark, 1981). The Sabatier reaction is used industrially for the production of methane fuel, converting hydrogen and carbon dioxide to methane and water with up to 99% single pass efficiency. The Bosch reaction converts CO₂ and hydrogen into solid carbon, water and heat with a relatively low single pass efficiency of around 19%. Further, oxygen can be obtained from the carbothermal reduction of silicon dioxide, or any other oxide that is more easily reduced than silicon dioxide, such as iron oxide, (Rosenberg, 1992).

Breedlove, et al. (2001) discuss a photo-electrochemical approach for a backup, low capacity carbon dioxide separation and conversion device, creating carbon monoxide and oxygen. They state that the available solar power of 250W/m² on the Martian surface will be more than adequate to power the direct photochemical, or photo-electrochemical, deoxygenation of carbon dioxide.

Oxygen can also be sourced naturally from carbon dioxide using plants, with 0.727g of oxygen produced for every gram of carbon dioxide assimilated into a plant, concurrently producing 1 gram of plant matter for every 1.383g of carbon dioxide assimilated (Bula, et al. 1997). Boston (1995), however, provides a slightly higher estimate, stating that for every 1kg of cellulose a plant produces it will release 1.2kg of oxygen. The use of plants in the recycling of oxygen within a habitat is discussed in more detail in the section on life support, from page 88.

Oxygen requires a buffer gas if it is to be used in a breathable atmosphere. The buffer gas is required to reduce the concentration enough to prevent it being flammable

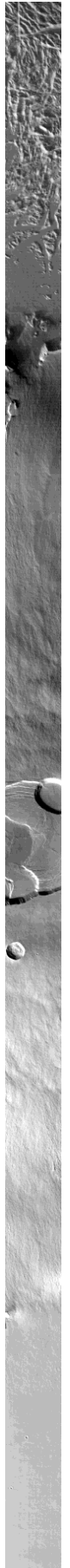
and to prevent high oxygen concentrations causing a form of narcosis and being toxic. Carbon dioxide is unsuitable as a buffer gas as it becomes toxic at levels around 1 kN/m² (Meyer & McKay, 1995). Nitrogen and argon, both available in the Martian atmosphere, make suitable buffer gasses, as they are both non-toxic, although analysis of the long-term effect of argon exposure is limited (Meyer & McKay, 1981, Boston, 1995). McKay (1988) calculates the energy cost of extracting buffer gasses from the Martian atmosphere to be about 10kWh/kg of buffer gas produced. One kilogram of buffer gas can be extracted from 31kg of Martian atmosphere through a process of cooling and pressurising to remove carbon dioxide (both in liquid and solid forms) to leave a nitrogen/argon mix containing only 2% residual carbon dioxide (Meyer & McKay, 1981).


Should it be necessary or desirable to separate the nitrogen and argon into separate components (for health reasons or to extract the argon for use as an electric propulsion fuel for ion engines or for other applications), this can be done using similar techniques to that used on Earth to produce liquid oxygen. Oxygen and argon have liquefaction temperatures differing by only 2.9°C and argon liquefies at a temperature 9.9°C warmer than nitrogen (87.2°K versus 77.3°K). The separation should be achieved for 1.96kWh/kg of argon and can be produced through an automated process (Meyer & McKay, 1981).

An oxygen/argon mix can be obtained through the use of a molecular sieve. As argon is inert (and so has no van der Waals forces to bind with the zeolite) and oxygen is large and non-polarised, neither molecule is significantly adsorbed by the molecular sieve's zeolite bed, whilst the remaining Martian atmosphere constituents will be trapped in the bed (Jones, et al. 1985). The gas captured in these sieves during the process can then be sent to another molecular sieve system to extract the water and other elements, as described above.

Once produced in sufficient quantities the atmospheric buffer gas is not consumed and so only needs minimal ongoing production to replace leakage and losses from the system.

Whether oxygen is produced through carbon dioxide decomposition, or obtained through the molecular sieve removal of other atmospheric constituents, or some other method, the Martian atmosphere must first be concentrated and filtered to remove fine dust particles to prevent fouling and damage to systems (Ash, et al., 1989).





A schematic of one possible integrated process for processing Martian atmosphere, as described in Meyer & McKay (1995), is included below in Figure 16. In this process the main energy requirement is for the compression of the atmosphere to above the triple point of carbon dioxide, over 5.1 atmospheres (approximately 520 kN/m²). Most of the carbon dioxide condenses out at this pressure and can be removed, the remaining CO₂ is cooled to solid form via expansion from 5 atmospheres to a working pressure of 2 atmospheres and is also removed. Buffer gas remains and has been produced with an energy input of approximately 9.4kWh/kg (Meyer & McKay, 1995). This buffer gas is combined with oxygen produced by the electrolysis of water.

The system will also extract water from the atmosphere, or it can be used specifically to extract water without the need for such high levels of pressurization (Meyer & McKay, 1995).

NOTE:
This figure is included on page 62 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 16: Martian atmosphere processing schematic diagram (Meyer & McKay, 1995).

There are many alternatives when designing the mix of the habitat's atmosphere, and pressure can also be varied significantly. Alternatives range from low pressure, high CO₂ greenhouses to Earth-like conditions. Biosphere 2 adopted an atmospheric pressure of approximately 88.5 kN/m² (normal atmospheric pressure at the facility's altitude) with a mix of 76.5% nitrogen, 20.5% oxygen, 2% water vapour, 0.9% Argon and .03% carbon dioxide, very similar to the composition of Earth's atmosphere (MacCallum, et al., 1997). Caudill (1984) suggests a partial pressure of oxygen of 22.7 kN/m², nitrogen of 26.6 kN/m², carbon dioxide of less than 0.4 kN/m² and water vapour of 1.0 kN/m², however, partial pressures and total pressures more closely resembling those of Earth could also be adopted. The partial pressure of oxygen that humans can tolerate for

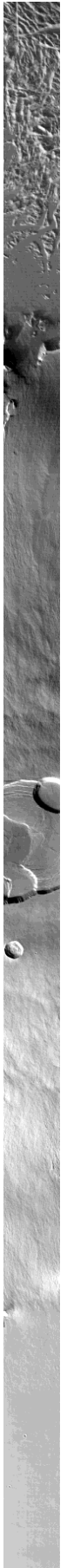
extended durations is a minimum of 19 kN/m² and a maximum of 32.4 kN/m² (although lung irritation can occur at this level). Greenhouse atmospheres can vary from that in the habitat and may have carbon dioxide levels of around 10%, to improve the rate of growth (Wittwer, 1992), and pressures as low as a few tens of kN/m² (Mayer & McKay, 1995).

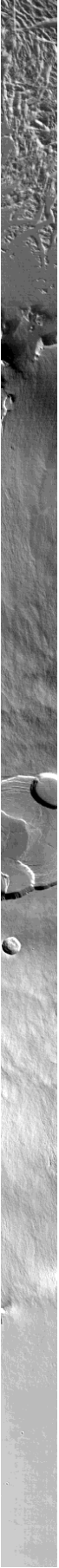
2.5.5. *Hydrogen Peroxide*

Hydrogen Peroxide (H₂O₂) may be one of the most important manufacturable products on Mars (Clark, 1981). It can be decomposed under controlled conditions into both water and oxygen (via a metal or enzyme catalyst) producing mechanical energy for power or propulsion and also producing heat. It can also be used as an explosive, bipropellant or monopropellant fuel, (Clark and Pettit, 1989), bleach, disinfectant and antifreeze. Hydrogen peroxide can also take part in chemical reactions, sometimes as reductant and sometimes as oxidant, depending upon the specific reaction (Clark, 1989).

One cubic meter of hydrogen peroxide (stored at 0°C and weighing 1.47 tonnes) can produce 692kg of oxygen, enough breathing oxygen to sustain one person for 917 days, 778kg of water, enough drinking water for one person for 517 days, and 1,175kW-hr of energy. Alternatively, if combined with carbon dioxide and sunlight, the water produced could, theoretically, produce up to 648kg of edible dry food (enough for one person for 432 days) and another 1,383kg of oxygen (Clark & Pettit, 1989). Note that the periods determined by Clark & Pettit above are not consistent with the requirements for human consumption described by Meyer and McKay (1995) in Table 12, below. The above stated periods of sustenance may vary by up to 25%, depending upon the human consumption requirements adopted.

Hydrogen peroxide may be available in the atmosphere or soil in minor quantities. Alternatively it may be produced from water at a cost of 8 to 80kW-hr/kg (Clark and Pettit, 1989) or through the electrolysis of aqueous sulphuric acid (Clark, 1981). H₂O₂ can be produced during periods of low power requirements, such as at night or mid-day (when photovoltaic systems may overproduce power), and stored for use during periods of high power need, during emergencies or on rover missions.





2.5.6. Food

The nature of the Martian environment dictates that food production occurs indoors. Whilst a completely closed ecosystem is not necessary due to the possibility of the resupply of elements from local resources, an essentially closed agricultural system is possible and has been developed for use in arid regions on Earth (Boston, 1985).

Ideally, greenhouses would be stocked with plants comparatively well suited to the harsh conditions of Mars (Boston, 1988) this would include UV tolerance to maximise the amount of natural light that may be used and, thus, minimise power consumption. Alternatively, due to the radiation environment on the Martian surface, the development of radiation resistant strains of crop may be desirable (or the use of UV filters (Cockell, 2001a) or artificial lighting). Plants used for breeding must be protected from the effects of harmful radiation to ensure the genetic integrity and future viability of the crop, however, this degree of protection is not necessary for crops being planted for consumption (Boston, 1985). The risk of crop failure due to radiation from solar flares and such (expected to occur once every solar cycle of 11 years) may be acceptable (Meyer & McKay, 1995), provided there are sufficient reserves kept (food caches), and replacement breeding stock is secure. For information on the Martian radiation environment see the section on radiation from page 100.

Greenhouses are capable of supplying food to the colonists. Within closed greenhouses, as a by-product of photosynthetic reactions, the plants will provide a bio-regenerative supply of oxygen to, and remove carbon dioxide from, the life support system. Further to this, other by-products include polymers (cellulose, glues, rubber, etc.), fibrous materials (for paper, fabric, etc.), chemicals (medicine, dyes, oils, etc.) and structural materials (wood, bamboo, etc.) (Mackenzie & Dunand, 1997).

Transparent greenhouses may be very energy efficient, as the sun provides lighting and some heat. Meyer and McKay (1995) have stated that the light levels incident on the surface of Mars, even during dust storms, is greatly in excess of the minimum levels required for photosynthesis. This is supported by Boston (1988) who states that most plants on Earth are over saturated with light, although some crops, such as corn, do not 'light-saturate' and may benefit from additional lighting. Measurements taken during the Biosphere 2 experiment shows that the intensive agricultural area of 2,232m² received 2,403kW of solar energy. This equates to approximately 1.1kW/m² (Nelson and

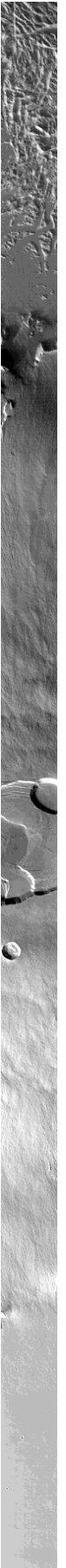
Dempster, 1992). This is well above the average levels incident on the Martian surface, at the equator, of $180\text{W}/\text{m}^2$, so the crop areas and efficiencies achieved in the Biosphere 2 are not directly transferable to the situation of a Mars habitat.

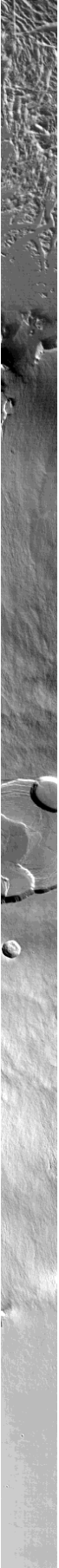
Inflatable greenhouses have been proposed by Boston (1981), Cadogan, et al. (1999), Roberts (1989), Ishikawa, et al. (1997) and others, however, the UV resistance of the plastics may be a potential cause for failure over time. Inflatable greenhouses are light and compact and so could be transported from Earth relatively easily in the early stages of habitation, however, it may be advantageous to construct further greenhouses out of glass, concrete and metal once appropriate industry is established. In both cases the UV effect of the materials on plant growth and material stability must be considered.

Greenhouses could be buried to provide radiation protection for the plants at the expense of higher energy levels for artificial lighting, although the additional lighting energy consumption would likely be offset by reduced heating requirements, unless the heat is available 'free' as a by-product of power generation or industrial processes. To reduce the structural requirements of these structures the internal atmospheric pressure can be designed to support the overlying mass of soil. Buried greenhouses would also be protected from minor meteor impacts and the strong winds and abrasion of dust storms. A possible compromise between buried greenhouses, with higher energy requirements, and surface greenhouses, with higher radiation exposure, would be to have some greenhouses buried and some on the surface (Boston, 1981) or partially buried greenhouses. Greenhouses that use artificial lighting can draw benefit from the higher use of power by optimising the wavelength of the light to suit the requirements of photosynthesis of specific crops and also act as a heat source.

Heating of the greenhouses may use a significant amount of power. The heating requirements of the greenhouses can be reduced through the inclusion of reflective shutters, drawn at night, and the inclusion of bulky rocks, sand and water to store heat during the day for release at night (Mackenzie & Dunand, 1997, Meyer & McKay, 1995).

Greenhouses can either be human-rated (suitable for human activities in a shirtsleeve environment) or plant-rated (unsuitable for humans without breathing apparatus and, perhaps, pressure suits) (Mackenzie & Dunand, 1997). Greenhouse atmospheres could be provided by compressing the raw Mars atmosphere to a few tens of kN/m^2 and supplementing with oxygen and nitrogen, also extracted from the atmosphere (Meyer &





McKay, 1995). Laboratory experiments using sealed bell jars have demonstrated the feasibility of growing plants under Mars-like, low atmospheric pressure conditions (Clark, 1981).

A low pressure, plant-rated, atmospherically controlled greenhouse will benefit the plants as well as reducing the requirements for construction materials (due to lower structural requirements). However, if such an atmosphere was used, to avoid the need for bulky protective clothing for humans tending the crops within the greenhouse, the addition of a remotely controlled plant transport system and air lock could be of benefit (Mackenzie & Dunand, 1997). Boston (1985) reports that, further to tailored atmospheres, greenhouse efficiency can be further increased through the use of antitranspirants, used to minimise the water loss of plants without harming them.

Several greenhouse atmospheric environments were proposed during the Case for Mars I workshop, summarised by Boston (1981) and detailed in Table 8. The highest-pressure atmosphere is designed to be human-rated to allow attendance to the crops without breathing apparatus or pressure suits. The other atmospheres are provided as examples of plant-rated atmospheres that could be designed to optimise the productivity of the edible portions of the crops.

Table 8: Possible Atmospheric Environments for Martian Greenhouses (Boston, 1981)

NOTE:
This table is included on page 66 of the print copy of
the thesis held in the University of Adelaide Library.

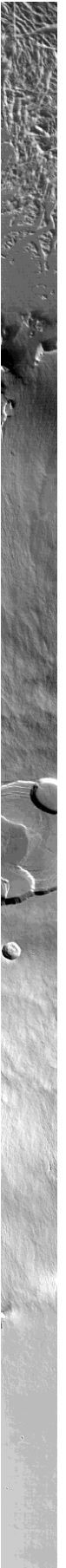
Bula, et al. (1997) have developed a simulation model for determining the effect of different variables on plant growth, showing very accurate results for potatoes when compared to experimental results. Variables incorporated into the model include photosynthetic material mass of the crop, irradiation, temperature, atmospheric carbon dioxide concentration, water, nutrients, plant age and photoperiod. Models such as this will be useful in predicting the appropriate atmospheric composition for greenhouses.

Dietary requirements vary from individual to individual. Further, the specific knowledge of any potential alteration to these dietary requirements, when on another planetary body, is lacking (Meyer & McKay, 1995 and Boston, 1995). However, energy requirements can be estimated based on terrestrial and astronomical figures. Boston (1988) anticipates human consumable requirements (including food water and oxygen) to be essentially the same as the requirements on Earth. Typical energy requirements for sedentary men (70 kg) are estimated to be around 2,000 calories, increasing to 4,500 calories for very active men, such as miners. Typical energy intake for Apollo mission astronauts was shown to be 2,793 calories, below the recommended 3,000 calorie intake (Boston, 1995). The Biosphere 2 experiment crew each consumed an average of 2,216 calories per day, although the crew lost an average of 8.8kg each over the 24-month experiment (Nelson and Dempster, 1995).

Saha and Trumbo (1996) have investigated the nutritional adequacy of limited vegan diets (diets which are likely to be similar to that consumed by early colonists) in rat populations, tracking growth and nutritional status. The vegan diets were known as vegan-5 (wheat, rice, soybean, white potato and cowpea) and vegan-10 (wheat, rice, soybean, white potato, cowpea, sweet potato, peanut, cowpea leaves, lettuce and canola oil). The vegan-10 diet was superior to the vegan-5 diet, being significantly higher in calcium content and resulting in an almost 100% increase in weight gain versus the vegan-5 diet. Although, the vegan-10 diet still only resulted in 50% of the weight gain of the control group. When supplemented with additional vitamins and minerals the vegan-10 diet resulted in adequate growth and nutritional status, comparable, in many respects, to the control group, although with only around 80% of the weight gain (possibly partly due to a reduced protein digestibility).

Hender (2007) assessed several variables associated with greenhouse crop growth and productivity on Mars including high carbon dioxide concentrations; low light, water, and nutrient levels; and the effect of low pressure and magnetic fields. He concluded that crop growth under conditions that would be expected in Martian greenhouses was feasible and that stress factors should be able to be compensated for by elevating carbon dioxide levels within the greenhouses. These findings are supported by other studies.

Crop yields can be improved through the use of carbon dioxide enriched atmospheres (Wittwer, 1992 and Smernoff & MacElroy, 1989) and are not significantly





affected by reduced pressures (Walkinshaw, 1986, Boston, 1981). In fact, many plants on Earth, particularly C-3 plants, are restricted in growth due to a lack of carbon dioxide (Meyer & McKay, 1995). The carbon dioxide can be sourced directly from the Martian atmosphere (Meyer & McKay, 1995). Smernoff and MacElroy (1989) state that the availability of carbon dioxide for plant growth should allow for the production of more food than immediately required, also providing extra oxygen which can be stored or used for propellant combustion.

Most plants, particularly C3 plants (comprising 17 of the 21 most important food crops; Wittwer, 1992), do require certain amounts of oxygen for aerobic mitochondrial respiration. All plants require nitrogen and introduced soil bacteria can fix nitrogen at partial pressures below 1 kN/m² (Klingler, et al. 1989). A variety of other authors have experimented with varying the levels of carbon dioxide, humidity (useful for seed germination), and atmospheric pressure to maximise the ratio of edible plant mass to waste (Boston, 1988). Other factors that can influence yield include light intensity, light duration and nutrient levels. It may be beneficial to grow different types of plants in separate greenhouses, each under optimised conditions (Boston, 1988).

The labs of Frank Salisbury (an experienced scientist with experience in intensive wheat horticulture in closed environments) are breeding ultra-dwarf strains of wheat (less than 40cm tall) and very high yield varieties that would be well suited to growth in a closed ecosystem. They have experimentally varied environmental factors including light intensity and duration, temperature, plant density and nutrients and managed to achieve yields of 60g/m²/day, compared to field grown records of 12-14g/m²/day (Boston, 1995).

Other crops have been studied in confined environment monocultures including potatoes, soy beans, lettuce and oil-producing crops (in NASA studies) and wheat, chufa, potatoes, carrots, radishes, tomatoes, cucumbers, kohlrabi, dill and peas (in Soviet studies). Boston (1995) further reports studies concluding that a minimal complete diet requires 10 main crops, soybean, peanut, wheat, rice, potato, carrot, chard, cabbage, lettuce and tomato. Caudill (1984) also recommends that additional classes of food be consumed, including the following varieties: sugar beets, broccoli, berries, onions and corn. For comparison, the biosphere 2 experiment included over 50 crops, including

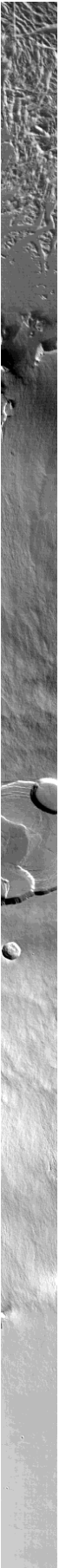
most of the above, as well as goat's milk and meat, pork, fish, chicken and eggs (Nelson and Dempster, 1995).

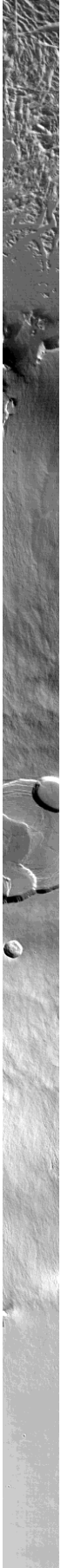
Additional food sources can be introduced through the use of aquaculture to grow fish and crustaceans (Boston, 1985). Aquaculture, utilising human waste as fertiliser, operates commercially on Earth producing shrimp and fish. Fish varieties, such as Tilapia, can grow rapidly in dense concentrations and various crustaceans have been suggested for aquaculture systems (Boston, 1995). Bluem and Paris (2001) also support the use of Tilapia (*t. rendalli*) and discuss that edible plants can also be produced in aquaculture, including Ceratophyllaceae (hornweed) and Lemnaceae (duckweed). These plants produce oxygen and food for the aquatic animals (and/or humans) which in turn supply carbon dioxide and ammonia and/or ammonia ions (which may require conversion to nitrate ions by ammonia-oxidizing bacteria) to the plants. Small closed equilibrated biological aquatic systems (CEBAS) have been flown on the space shuttle demonstrating this aquatic system for fish and plant production (Bluem & Paris, 2001).

Subject to suitable water reserves, Boston (1988) suggests the use of the Tilapia fish used in Biosphere 2 for aquaculture on Mars. Aquatic animals have a high conversion efficiency ratio (i.e. they are an efficient food 'crop') and Tilapia, in particular, can survive on very little oxygen, and in high concentrations, in a confined environment.

Microbial food production is a rapid method for producing high protein (7 to 12% dry-weight) biomass. Biomass doubling rates are approximately 0.5-2 hours for bacteria, 1-3 hours for yeast, 2-6 hours for algae and 4-12 hours for filamentous fungi. Microbes can also be selected to provide nutritional supplements to diets lacking in certain vitamins and amino acids (Boston, 1985).

Microbes can also play a role in waste disposal as they can be fed on substrates such as cellulose, human waste and food processing waste, some bacteria require only carbon dioxide as a carbon source. Back-up cultures can be kept freeze dried for long periods as a contingency in case of a complete harvest loss or contamination. For species of algae, bacteria and yeast that are not very digestible, protein extracts can be produced, or they can be used as a feedstock for other organisms. Boston (1995) reports that the upper limit of human consumption of unprocessed algae or yeast appears to be in the range of 100 to 200g/day, however, processing is possible. Processing of most microbial materials will be necessary in order to make them edible and appealing (Boston, 1985).





On Earth, some algae are actually used to produce products for use in manufacturing and industry. Algal processing technologies may allow for a significant portion of human protein requirements to be met by algae. Whilst algal systems are highly productive in relation to power and space requirements it is likely that higher plants will still provide a significant portion of the dietary requirements due to their psychological and nutritional advantages (Smernoff & MacElroy, 1989).

Biosphere 2 initially considered the use of hydroponic and aeroponic growing techniques but ultimately decided to adopt a soil-based system. Although these systems efficiently use available space (Boston, 1988), the decision to use soil-based systems in Biosphere 2 was made for a variety of reasons that may also be applicable on Mars. Soil can play a significant role in air purification (discussed below on page 90). Soil also simplifies the creation of low energy waste recycling and composting systems. Finally, hydroponic and aeroponic systems rely on the production of nutrient solutions that may be difficult to produce in Biosphere 2 (as may be the case on Mars).

Biosphere 2, importantly, achieved a sustainable and productive food production system incorporating over 150 crop varieties, including herbs and spices to maintain a nutritional and tasty food supply. In addition to growing crops, Biosphere 2 also kept animals for food and milk, including Vietnamese potbellied pigs, African pigmy goats, chickens and Tilapia Mozambique fish, with little additional load on the agricultural system, as they ate mainly plant residues inedible to humans (Nelson & Dempster, 1995). As no one technique or system will optimally satisfy the requirements of a food supply a variety of foodstuffs should be produced (Boston, 1988) as was the case in Biosphere 2.

Plants will require carbon dioxide, nutrient fertiliser and water (Meyer & McKay, 1995) as well as a growing medium. The suitability of Martian soil for supporting food production is currently untested, however Meyer & McKay (1995), and Banin (1989) have stated that it could be conditioned (possibly including the need to leach away salts, oxides and toxins) to serve as a plant growth medium, with fertiliser produced from atmospheric constituents. Without this measure the soil may be unsuitable due to high chlorine levels and possibly aluminium levels. Although found at lower than terrestrial levels, the presence of aluminium in the soil could potentially cause toxicity under acidic conditions believed to exist in the in-situ Martian soil. High chlorine levels may also constrain the plant's water uptake (Banin, 1989). Boston's workshop summary (1981)

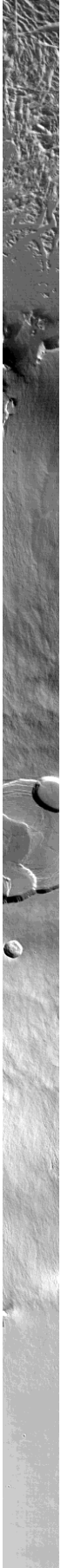
agrees that processing of the soil to some extent will be required prior to using in a greenhouse and notes that adding wastes, stored on the flight to Mars, would provide an early boost to the system.

Stoker, et al. (1993) have stated that all of the inorganic nutrients necessary for plant growth should be available from the Martian soil, while organic nutrients can be provided from waste from the human habitat. Some supplemental nutrients may be required. Masarik (1997) states that the abundance of nitrogen in the Martian soil is not currently known, and Banin (1989) stated that potassium may be at sub-optimal levels. Smernoff & MacElroy (1989) point out that several essential micronutrients have not been directly measured on the Martian surface including boron and molybdenum. Future surface missions can be tasked with the search for these elements. Banin (1989) also points out that the mineralogical form of the nutrients is currently unknown, so the solubility of the nutrients, and availability to plants is impossible to assess without further study. Some algal species are capable of reducing nitrogen (N_2) into biologically assimilated (fixed) nitrogen such as NH_4^+ or NO_3^- , which will assist in the conditioning of native Martian soil, soil inoculation with cyanobacteria should suit plant requirements (Smernoff & MacElroy, 1989). It is also interesting to note that cyanobacteria are one of the best protected organisms against UV radiation (Cockell & Andradý, 1999) and so may be able to pre-treat soil in more exposed UV environments prior to its use as a crop growth medium. Nelson & Dempster (1995) agree that the inoculation of the Martian soil with microbes will be necessary to improve the suitability of the soil for crop growth. Boston (1995) reports that the presence of the clay in the soil will provide habitats for these microbes, which will be critical in mobilising essential elements for plant nutrition, and for retaining plant nutrients.

Physically and chemically, the Martian soil should be suitable for supporting rooted plants (Banin, 1989). The soil forms a loosely packed, porous medium. The high concentration of smectites (and its excessive swelling characteristics) and the fine porosity may cause non-optimal water/air ratios in the rhizosphere, although the high iron content may counteract the swelling and the porosity can be improved through blending with other materials.

If it is revealed, however, that the soil is an unsuitable, or undesirable, medium then a hydroponics system could be adopted. Such a system is utilised commercially in a





controlled light and atmosphere greenhouse by Phytofarm producing year round produce in a compact manner, with a 50,000 seed per day sowing rate. In this venture, lights are positioned closer to the plants than would otherwise be possible by immersing the lights in water. This patented technique allows heat from the lighting system to be transported to other areas for use. The nutrient application, recycling and replenishment is automated with multiple redundancies. Phytofarm have reduced seed germination times significantly within the system, for example spinach is germinated in one day instead of the usual eight. The major manual work involved in this particular system is the selection and transplanting of the best plants into the growing troughs, and the harvesting of the grown plants (Boston, 1985).

Boston (1985) describes another private venture, United Energy Corporation, incorporating a mix of species including shrimp, fish, microbes, plants and animals, using human waste as fertiliser and balancing gas exchanges. She also refers to systems capable of consistently producing over 400,000 kilograms of fish, shrimp, vegetables and algae per acre per year.

Whilst the density efficiency of wheat, shown in the experiments of Frank Salisbury above, cannot be achieved with many other crops, Salisbury has estimated that approximately $50\text{m}^2/\text{person}$ is a reasonable crop area for 'space farms' (Boston, 1995). Although not optimised for space, the Biosphere 2 experiment utilised a plant growth area of $2,232\text{m}^2$ for eight people, or $279\text{m}^2/\text{person}$ (Nelson and Dempster, 1995), including fruit trees, vegetables, legumes, grains and herbs, and is likely to provide marginal or insufficient calories to Mars habitat inhabitants (Boston, 1995). Another six studies, summarised by Boston (1995), suggested plant growth areas of between $13\text{m}^2/\text{person}$ and $56.9\text{m}^2/\text{person}$ would be required, although one other study proposed an area of $820\text{m}^2/\text{person}$ (based on conservative field yields), which appears unreasonably high. Ishikawa, et al. (1997) estimates a greenhouse area of approximately 100m^2 per person.

Due to the relatively small volume of water, soil and air in a closed ecosystem, pesticides and herbicides can cause serious health hazards if introduced. Biosphere 2 implemented techniques including the selection of resistant crops, utilisation of small plots (to reduce the spread of disease), crop rotation, introducing beneficial insects to control pest insects (ladybugs, praying mantis, parasitic wasps, etc.), and manual controls

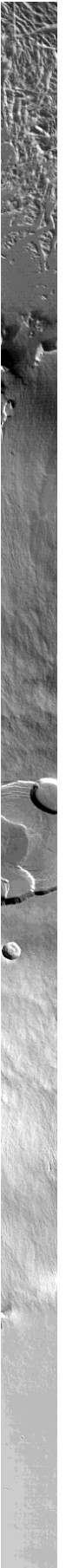
to alleviate the need for chemicals. Suitable quarantine measures should be reasonably effective at keeping out pests and diseases. Certain safe sprays can also be utilised such as soap and light oil (Nelson & Dempster, 1995).


The inedible waste from crop growth typically consists of 10-30% lignin, 25-50% hemicelluloses and 25-40% cellulose. Cellulose can be used for a variety of applications including furniture production, interior wall coverings, clothing and textile fibre, paper, cellophane and other cellulose-ester plastics or it can be fed to animals or used as a growth stock for mushrooms (Boston, 1995). Further, cellulose can be used as a building material reinforcement, similar to straw used in adobe construction (Boston, 1988). Smernoff and MacElroy (1989) describe that the inedible waste from plant growth can be processed into edible material by converting the cellulose and hemicellulose into simple sugars and feeding the sugars to micro-organisms, such as yeast, to provide high quality protein.

Crops, and many plants in general, require the involvement of insects or wind to pollinate them for reproduction. Where pollination is required in these, or a similar manner, the effect can be achieved manually, through the use of statically charged brushes, or fans, as appropriate, or pollinating insects, such as bees, can be introduced, which will provided the added advantage of producing honey. It is necessary to note that insects may have special requirements for their wellbeing. Bees, for example, require UV-A for navigational purposes. The Biosphere 2 structure blocked UV-A radiation, resulting in the failure, and death, of the bee populations. In the case of UV-A being blocked by the greenhouse materials, the use of artificial UV-A radiation will be a suitable remedy. Some spider species use the UV-A reflectance from their web to lure prey and is also implicated in the vision of some fish and lizards (Cockell and Andraday, 1999). There is a reduced incidence of UV-A on the Martian surface, as discussed in the section on radiation, from page 100.

2.5.7. *Fuel*

It is considered unlikely that hydrocarbons will be found on Mars. Therefore, fuels will need to be manufactured from basic resources such as those found in the atmosphere and water. Another source of fuel may be to produce hydrocarbon substitutes from algae (Boston, 1985) or genetically modified bacteria (De Young, et al.





1989) or to synthesize hydrocarbon fuels from carbon dioxide and hydrogen using Fischer-Tropsch chemistry (Meyer & McKay, 1995).

The production of an oxidant is required for the burning of most, but not all, fuels in the natural Martian environment. Oxygen is produced as a by-product of the manufacture of many fuels, although not always in stoichiometrically suitable quantities (Meyer & McKay, 1995). If required, additional oxygen for oxidation can be obtained through the electrolysis of water, should a sufficient water supply be available, or through the thermal decomposition of carbon dioxide, or via several other methods previously discussed.

The production, storage and use of various types of fuel are discussed below. Methane is considered a convenient fuel for use on Mars and is considered as a base case.

Carbon dioxide, comprising 95.3% of the atmosphere, with the addition of hydrogen can be converted to methane and water through the Sabatier process. Water can then be electrolysed to return half of the original hydrogen to the reactor process and to provide oxygen for life support or as an oxidizer for the methane fuel produced during the process (Zubrin, 1997). As sufficient oxygen for full methane combustion is not created during the Sabatier process it will be necessary to obtain additional oxygen. This can be done by either electrolysing additional water or by pyrolysis of the methane, creating solid carbon and hydrogen, and then running the Sabatier process again, producing yet another batch of oxygen and recovering the original amount of methane (Meyer & McKay, 1995). Methane is a popular fuel, considered by many authors (including Zubrin, French, Meyer and McKay) and is also otherwise useful as the base material for the production of many chemicals and plastics (Spiero & Dunand, 1997).

Giudici (1989) has compiled a design for a Mars processing plant from published designs for atmospheric and fuel processors. The design unit, weighing 2.5 tonne, and requiring 24.4kW of power, uses water and Martian atmosphere as inputs to produce methane (for fuel), liquid oxygen (for an oxidizer and/or the atmosphere), argon (for the atmosphere) and nitrogen (for the atmosphere and/or fertiliser). The unit's electrolyser can also be used to produce hydrogen and oxygen to run fuel cells. The methane can be used directly as a fuel or used as a feedstock to produce other fuels, as described below.

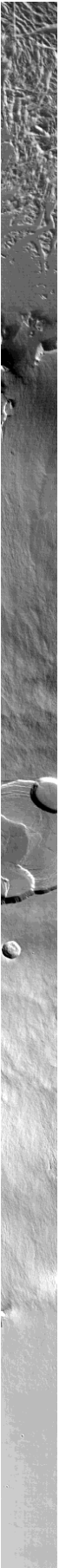
Carbon monoxide (and oxygen) can be produced through the electrolysis, or thermal decomposition, of carbon dioxide. Carbon monoxide will react explosively with oxygen

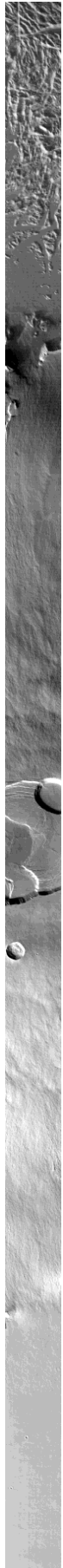
at high pressure and temperatures over 654°C (Clapp & Scardera, 1989). It is a less potent propellant than methane, however it does not require a source of hydrogen and so may be advantageous if water is scarce, costly to extract or otherwise valuable. Due to the relatively low Martian gravity, and therefore low thrust requirements, it is possible to design a two stage, chemically propelled spacecraft capable of returning to Earth directly from the Martian surface using carbon monoxide as a fuel. Carbon monoxide is also a suitable fuel for use by rovers and can be transported as compressed gas (Meyer & McKay, 1995). Whilst carbon monoxide is suitable for using in internal combustion engines (with oxygen) to produce mechanical energy it can also be the fuel for fuel cells (again with oxygen), producing electrical energy and expelling carbon dioxide. Carbon monoxide, however, must be handled with caution due to its toxicity. As little as 200ppm of carbon monoxide in breathable atmosphere will give humans headaches and at levels of 5,000-10,000ppm can be fatal in two to 15 minutes (Clapp & Scardera, 1989).

Methanol may be a more convenient rover fuel than methane or carbon monoxide as it can be stored as a liquid under most ambient Martian conditions and so does not require bulky cryogenic equipment to cool and maintain the fuel in liquid form. Methanol can also be used as a heating fuel in emergency situations due to its ease of storage and can also be used with current combustion engine technology or fuel cells. Methanol also has other industrial and agricultural uses (Meyer & McKay, 1995).

A hydrogen/oxygen fuel mix provides a 25% greater specific impulse than methane/oxygen fuel (Thangavelu, 1999) so would be a highly desirable fuel. This fuel could be produced in the presence of a sufficient hydrogen feedstock (i.e. water), however hydrogen is significantly more difficult to store, as it requires cryogenic cooling, and so is less appealing (French, 1989b) unless necessary. For example, hydrogen requires a storage temperature of 20°K, compared to 112°K for methane, requiring far more power to maintain.

Meyer and McKay (1995) discuss another fuel with a better specific impulse, better storage properties and that makes better use of potentially limited hydrogen reserves than methane (CH₄), that being acetylene (C₂H₂). Acetylene requires 25% more oxygen during combustion than methane, however, the production of oxygen, as described in the section on producing atmosphere, from page 59, is a relatively simple process. Acetylene is produced through the pyrolysis of methane and is commercially manufactured using





the Sachsse process, producing the by-products of carbon monoxide (which can also be used as a fuel) and hydrogen (which can be reused).

Acetylene is liquid below 193°K, making it relatively easy to store compared to hydrogen and methane, discussed above. Unfortunately, when stored as a high-pressure gas at high temperature acetylene may disassociate into ethylene. Depending on storage conditions this may need to be inhibited, possibly through an admixture of carbon monoxide. Further, acetylene has a very high flame temperature, which may require further combustion engine development, although, again, adding carbon monoxide will reduce this temperature with a reduction in thrust of around 10% (Landis, 1997).

Hydrogen peroxide (H_2O_2) easily produced through several processes including the electrolysis of sulphuric acid, has been used as a rocket fuel and makes a good energy source (Allen, 1993). H_2O_2 can be used to store oxidant for fuel reactions as it easily produces oxygen through catalytic decomposition and does not require the cryogenic storage of oxygen. It can be stored as a liquid if maintained at a temperature below $-2^\circ C$ (Meyer & McKay, 1995).

As previously mentioned, not all fuels require an oxidant to burn. Calcium cyanamide ($CaCN_2$) and carbon disulfide (CS_2) are two examples of fuels that will 'burn' atmospheric carbon dioxide and may be useful in powering rovers, although carbon disulfide, and its combustion by-product carbonylsulfide (COS), are both highly toxic to humans (Clark, 1981 and 1989). Calcium cyanamide is also valuable as a fertiliser and weed killer (Britannica, 2001).

Specific impulse (I_{sp}) is the number of seconds a pound of rocket propellant can be made to produce a pound of thrust and is a recognised measure of fuel performance. The higher a fuel's specific impulse the less fuel needs to be used for any particular task, and thus the less fuel mass that must be carried. Table 9 contains the specific impulse of various fuels that can be produced on Mars by means of chemical engines.

Table 9: Approximate Isp of fuels derived from Martian resources when used in chemical engines (Meyer & McKay, 1995)

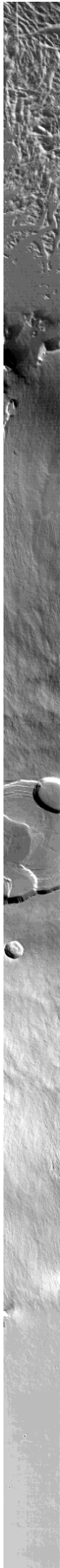
NOTE:
This table is included on page 77 of the print copy of
the thesis held in the University of Adelaide Library.

Alternatively, through the use of nuclear propulsion technologies it would not be necessary to 'burn' fuel, rather any gas could be heated and expelled to create thrust or mechanical energy. Carbon dioxide, compressed and stored as a liquid (at an energy cost of 84kWh/tonne), can generate an I_{sp} of 280 seconds with the proper reactor size and configuration, sufficient to launch into a Hoffman transfer directly from the surface of Mars to Earth (Zubrin, 1989). Nitrogen or argon could also serve as a suitable propellant. These gasses will not react with reactor components. Hydrogen, when used with nuclear propulsion (as opposed to a chemical engine described in Table 9) with its I_{sp} of 950 seconds could be used for interplanetary flight (Zubrin, 1989).

2.5.8. Minerals and Salts

Over the geological life of Mars, concentrated mineral deposits are likely to have formed through numerous mechanisms. Key processes for accumulating concentrated mineral deposits on Earth include plate tectonic activity, volcanic activity, magmatic activity, hydrological activity and metamorphic and chemical sedimentary activity. Of these, only plate tectonics is absent on Mars (although the early presence of plate tectonics on Mars is currently a subject of discussion).





Despite the overall low mean density of Mars ($3,933.5\text{kg/m}^3$ versus $5,514.8\text{kg/m}^3$ for Earth; Esposito, et al., 1992) the mantle of Mars appears to exceed the density of Earth's mantle, which is consistent with significant heavy element abundances. However, whilst chemical models of the Martian mantle suggest that it is rich in heavy elements there is no data to currently predict mineral *concentrations* (Cordell, 1985).

Cordell (1985) discusses various methods of mineral concentration that may have been, or are still, in effect in the Martian mantle. Regional or contact metamorphism could be capable of concentrating metals through hydrothermal fluids and also through exclusion from the first minerals to solidify. Sedimentary processes may have formed evaporite and mineral concentrates, either in salt pans or interstitially in pore spaces. The possible lack of plate tectonics on Mars may have resulted in an increased concentration of mineral deposits due to hotspot melting.

Meteor impacts could initiate magmatic differentiation of minerals and, if ground ice or water is present, may also subject minerals to hydrothermal alteration (Clark, 1989).

Potential mineral deposits (based on Earth analogs) that may be found on Mars due to certain geological processes include those listed in Table 10, which is partial and speculative.

Table 10: Potential Mineral Deposits on Mars

| Process/Feature | Possible Mineral Deposits | Source (includes) |
|-------------------------|--|-------------------|
| Sedimentary | Soluble Salts | Cordell, 1985 |
| Volcanic | Copper, Zinc, Lead, Silver, Gold | Clark, 1989 |
| Magmatic (hot spots) | Tin, Uranium, Apatite (Phosphate), Magnetite (Iron), Gemstones. | Cordell, 1985 |
| Rift Systems | Apatite, Vermiculite (used in plaster and insulation), Chromium, Nickel, Copper, Silver, Uranium, Evaporites, Salt | Cordell, 1985 |

| Process/Feature | Possible Mineral Deposits | Source (includes) |
|-----------------|--|-------------------|
| Hydrothermal | Iron-rich Smectites, Carbonates, Iron Oxides, Sulfates | Cordell, 1985 |

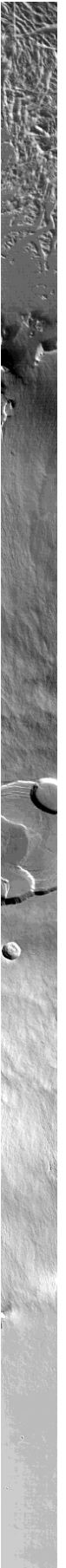
Clark (1989) describes the potential constituents and concentrations of salts on Mars. Salts comprise up to 15% of the Martian fines and are thought to be composed of sulphates (magnesium and sodium), lesser amounts of sodium chloride and possibly magnesium and/or calcium carbonates. Trace elements may be present in the salts, including copper, zinc, arsenic, selenium, bromine, rubidium, cadmium, indium, tin, antimony, mercury, titanium and lead, and could be purified and used in alloys or coatings, or used in isolation. Salts can be extracted from the soil using water and separated using differential crystallisation under controlled conditions and refined using various processes including distillation, electrolysis and reverse osmosis (Clark, 1981). Plaster can be produced from calcium sulphate (Meyer & McKay, 1989).

Metals can be produced through the melting and subsequent electrolysis of raw materials. For example, it is possible that Martian soil can be melted and electrolysed to release oxygen and produce alloy ingots, which can be subsequently purified into separate metals. This process will also produce a slag that could be used to manufacture bricks.

2.5.9. *Metals*

Metal ores of particular significance for construction and materials manufacturing include potassium, carbon, calcium, nitrogen, sodium, phosphorous, silicon, aluminium, iron, magnesium and titanium (Stoker, et al, 1985). Further to these Clark (1981) includes the additional metals of lead, zinc, antimony, tin and copper stating that, whilst their typical abundances could be only a few hundred parts per million, they would be easily concentrated if found in the form of soluble salts.

In addition to those metals previously identified in Table 4, several metal concentrations have been inferred through measurement from SNC (Martian) meteorites, as included in Table 11 indicating their presence and order of magnitude only. It should be noted that local concentrations measured in-situ (where measured and included in Table 4) have varied from meteorite analysis.



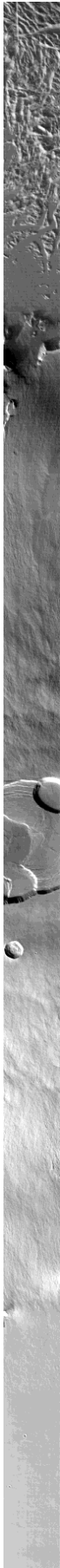


Table 11: Inferred (mantle) metal concentrations on Mars

| Metal | Meteorite (Mantle) Measurement |
|------------|-----------------------------------|
| Cobalt | 68 ppm |
| Nickel | 400 ppm |
| Copper | 5.5 ppm |
| Zinc | 62 ppm |
| Molybdenum | 118 ppb |
| Tungsten | 105 ppb |

Steel could be manufactured from the Martian soil. It should be possible to use hydro-metallurgical treatments similar to those used on Earth for processing iron ore (Meyer & McKay, 1995). Iron oxide could be extracted from Martian soils magnetically. For soils lacking a separate or crystalline iron oxide phase then iron oxide could be concentrated through aqueous acid leaching of iron bearing soils, followed by neutralisation to iron hydroxides and roasting to iron oxide (Meyer & McKay, 1995 and Clark, 1981).

According to Allen (1993) and Spiero & Dunand (1997), iron oxide (hematite) in the Martian soil can be reduced by carbon monoxide (produced from the carbon dioxide in the atmosphere, possibly through thermal decomposition) in an electric furnace into iron and carbon dioxide (the Wiberg process). Iron can be transformed into steel through the addition of carbon to the iron. Iron production will result in 'waste' materials from the chemical reactions, including oxygen, steam and heat, all of which can be harvested for use elsewhere. Another method for producing iron is through reacting hematite with hydrogen (Zubrin, 1997 and Spiero & Dunand, 1997), producing iron and water (the water can then be electrolysed to recycle the hydrogen). Carbon (coal) is commonly used to reduce iron oxide on Earth, producing iron and carbon monoxide. This may also be possible on Mars (Meyer & McKay, 1995), assuming the carbon is purposefully produced or made as a by-product of other processes. Also, as discussed for producing oxygen,

iron oxide (or any other oxide equally or more easily reduced than silicon dioxide) can be reduced with methane to produce iron (Rosenberg, 1992).

Carbon, added to iron to produce steel, can be produced through the Bosch process, creating carbon and oxygen from carbon dioxide and hydrogen, through the electrolysis of water (Boyd, et al, 1989). Alternatively, it is possible to pyrolyze methane into carbon (graphite) and hydrogen (Meyer & McKay, 1995, Zubrin, 1997), a process that is the most common method of industrially producing pyrolytic graphite on Earth.

In addition to being used to refine iron, carbon monoxide can also be used to refine nickel through the carbonyl Mond process (Spiero & Dunand, 1997).

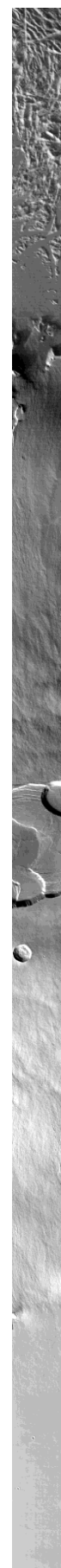
Aluminium and magnesium are commonly produced through a process of molten salt electrolysis. Using electricity and sufficient chlorine, this should also be achievable on Mars (Stoker, et al. 1993 and Clark, 1981). The metal containing chlorides may be present in the Martian regolith, and so easily concentrated (Spiero & Dunand, 1997). Leaching of these salts is likely to be necessary prior to using the regolith in greenhouses.

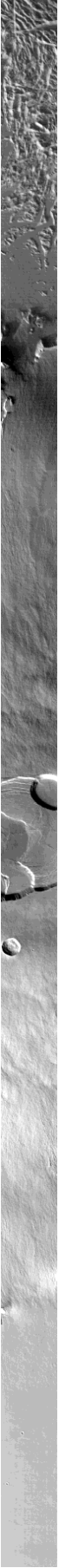
Magnesium (through the Dow process) can be hand ladled from the surface during the molten salt electrolysis process and poured directly into moulds (Clark, 1981). Magnesium blocks can be oxidised and fired at 1,500°C to produce sintered refractory bricks, or fused at 2,800°C to produce super-refractory bricks (Clark, 1981) and used to build high temperature ovens, or otherwise used to manufacture structural elements such as beams and columns (Clark, 1989).

The electrolysis of magnesium and aluminium is simpler than the pyrometallurgical reduction of iron due to the relatively low temperature requirements and no reducing agent is needed, such as carbon monoxide or hydrogen (Spiero & Dunand, 1997). This may make the use of these metals preferable to iron for structural purposes.

Other metals can be electrolysed from salts also. For example, the Kroll process is used industrially to produce titanium through the reduction of titanium chloride by magnesium (Spiero & Dunand, 1997).

Copper can be easily reduced from copper oxide, however, it is rare and may not be globally distributed in the surface dust layer in the same way as iron. However, copper may be found to occur in soils formed by the weathering of sulphide concentrations at the base of lava flows (Meyer & McKay, 1995). Copper's abundance is thought to be





5.5ppm in the Martian mantle, compared to 28ppm in Earth's crust (Longhi, et al. 1992), as measured from Martian meteorites.

Spiero & Dunand (1997) have identified several characteristics of metal casting that should be investigated under Martian gravity conditions before use. Under one-third gravity castings may have higher porosity (due to bubbles rising more slowly), higher shrinkage porosity (due to poorer liquid feeding within the mould) and altered grain size and shape (due to different heat transfer regimes due to reduced convection). These may create problems with the final product that must be investigated.

2.5.10. Non-Metals

Sulphur, comprising 7.2% of the soil in the form of SO_3 (Banin, et al. 1992), is one of the most chemically versatile elements of the periodic table (Clark, 1981). Sulphur can make several strong acids, reducing agents (sodium dithionite is powerful enough to reduce iron oxides) and oxidizing agents. Sulphur bearing compounds are used in the manufacture of such things as fertilizers, dyes, catalytic agents, ion exchange resins, detergents, emulsifying agents, explosives, sweeteners, fungicides, insecticides, elastomers and more (Clark, 1981).

Silicon can be produced by the reduction of silicon dioxide by methane (Rosenberg, 1992). The process can be integrated through further reactions to return the methane for further silicon dioxide reduction and to produce oxygen, requiring the input of only the raw material and energy.

2.5.11. Fertilizers

Ammonia can be synthesised from reacting atmospheric nitrogen with hydrogen (Meyer & McKay, 1989). Another source of nitrogen is in the form of nitrate evaporite minerals. These minerals rarely form in large quantities on Earth as they are easily soluble, however they may be found on Mars, particularly in areas of low elevation where the last remaining liquid water could have existed. Estimates of the possible amount of nitrogen originally on Mars range from 2 to 30 kN/m^2 (Fogg, 1995). If current rates of escape of nitrogen from the atmosphere have remained constant over the last 4.5 billion years the total amount of nitrogen lost to space would be 0.14 kN/m^2 (Meyer & McKay, 1989), leaving at least 0.06 kN/m^2 to approximately 30 kN/m^2 remaining.

Ammonia can then be used to produce numerous fertilizers. The Oswald process can combine ammonia and oxygen into nitric acid. Nitric acid, combined with ammonia, sodium carbonate or calcium carbonate, can produce ammonium, sodium and calcium nitrates. Urea can be produced from ammonia and carbon monoxide. The methods for this can be adapted from common processes used on Earth (Meyer & McKay, 1995).

Organic fertilizer can come from the habitat waste. Introducing suitable bacteria into the soil, in conjunction with suitable crops such as legumes, can allow for the fixing of atmospheric nitrogen into nitrites and nitrates (Meyer & McKay, 1995).

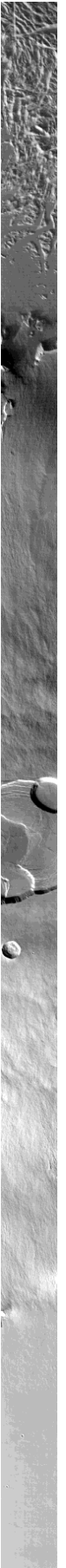
2.5.12. Glass and Ceramics

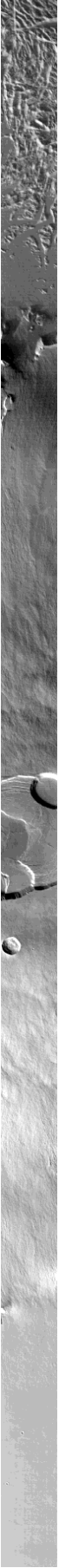
The silicate content of the Martian sand can be used to make glass through thermal fusion, however, the high iron oxide content, if not removed (possibly through reduction with carbon monoxide followed by magnetic separation, as is undertaken on Earth) may result in black glass (Clark, 1989). The stabilizer (calcium oxide) and fluxes (sodium oxide and potassium oxide) used to produce high quality glass are also constituents of the Martian regolith (Cockell, 2001a). Opaque glass can be used as a construction material, even if not usable as a transparent medium (Stoker, et al. 1993). Due to the lower gravity, glass will need to be kept molten for a longer duration to allow the bubbles to escape before solidification (Spiero & Dunand, 1997).

Apart from window or structural glass, glass fibres can be made for use in composites (Spiero & Dunand, 1997), as is common for improving the tensile strength of concrete on Earth.

Unlike plastic (described in the following section), glass absorbs ultraviolet radiation without degradation of the material. It typically absorbs wavelengths below 360nm and so will be unsuitable where the transmission of UV-A or UV-B is desirable. Glass is typically also very brittle without the addition of laminates and has the potential to fail catastrophically where used to maintain pressure differentials (Cockell, 2001a).

Ceramics can be produced from local materials (Meyer & McKay, 1989) through the baking of hydrous materials or by partial fusion of anhydrous materials. Many of the abundant clays thought to exist on Mars are not suitable for ceramic production, such as smectites, due to their expansive properties (Stoker, et al. 1993).





2.5.13. Rubbers and Plastics

Plastics can be made from local materials for the production of building materials (such as beams, columns, sheeting, pipes and electrical conduits), household items (such as crockery, furniture and utensils), and industrial uses (such as pump impellers, machinery housing/guards and mixing/storage tanks) as well as countless other versatile applications.

Plastics have several advantages over glass. Plastic is light-weight (typically with specific weights of 1-1.3, compared to 2-4 for glass) it can be easily moulded into complex shapes and is easily machined to detailed dimensions, it is typically less brittle, and thus safer than glass for structures and it is more versatile for the artificial manipulation of the ultraviolet environment. Polyacrylic plastics generally block UV radiation below 290nm and, through the addition of UV absorbing additives such as benzotriole derivatives, can absorb wavelengths from 290nm anywhere up to around 400nm. Most UV absorbing additives, unfortunately, are highly complex and may not be able to be manufactured on Mars initially but rather transported from Earth (Cockell, 2001a).

Organic material (including plastics) to be used externally on Mars must be stabilised to resist the deleterious effects of ultraviolet radiation. Clark (1981) suggests that fluorocarbons would be suitable candidates, however, he states that fluorine may be very rare on Mars. Banin, et al. (1992), however, detail the chemical composition of the SNC meteorites which reveals an abundance of fluorine of approximately 35ppm and Longhi, et al. (1992) lists 32ppm, compared to an abundance of 16.3ppm in the Earth's mantle. Clark (1981) further suggests that polymerised chloroprenes, polysulfides, polyvinyl chlorides and polysulfones may be useful polymers, and that chloro-sulfonated polyethylenes have excellent resistance to sunlight, heat and abrasion.

UV absorbing plastics will degrade rapidly in extreme UV environments and so characteristics for blocking UV radiation may be traded off for a longer lasting material (Cockell, 2001a). Any plastic to be used in ultraviolet environments should be tested for longevity prior to use. Solutions to the problem of rapid UV degradation do exist. Cockell (2001a) describes a situation where two sheets of UV-transparent plastic can sandwich a layer of UV absorbing aqueous solution, which absorbs UV and dissipates it through heat radiation or fluorescence. One possibility for use in the aqueous solution is

rutin, produced in large quantities on Earth, where 15g/m² of sandwich sheeting would be required. Alternatively, films could be manufactured to absorb ultraviolet light, which could be replaceable or itself resist UV-degradation, thus protecting the plastic from degradation.

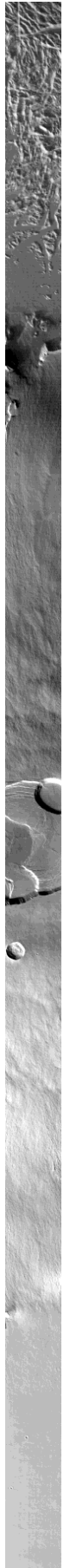
De Young, et al. (1989) briefly discuss the formation of polymers using carbon dioxide and water as raw materials, including through the use of genetically engineered bacteria that produce hydrocarbon products. Clark (2001a) describes how ethylene can easily be produced by reacting carbon monoxide (from the decomposition of carbon dioxide) with hydrogen, which can then be polymerized into polyethylene and used to produce bottles and bags. The ethylene can also be converted into propylene through a process of dimerization and metathesis that can, in turn, be polymerised into polypropylene. Methane can also be used as a base material of the production of many plastics (Spiero & Dunand, 1997).

Using only carbon dioxide and water sourced locally on Mars, Cockell (2001a) also describes the production of plexiglass sheets, useful for building transparent structures when combined with UV absorbers. This process also produces the ethylene used in processes described above and formaldehyde which, upon polymerization, can produce a diversity of resins.

Boston (1995) suggests that guayule could be grown for its rubber. Guayule contains latex rubber in its bark, roots, leaves and stems, however, in its wild state takes four to five years before it can be harvested (Britannica, 2001). Another high yield, low cost source of latex rubber is found in the Russian dandelion, located mainly in the plant's roots and can be harvested annually (Britannica, 2001). These natural rubber sources may satisfy demands for rubbers prior to facilities being developed for synthetic rubber production.

Polysulfide rubber has good low temperature flexibility, flex-crack resistance and resistance to oxygen and ozone (Clark, 1981).

Algae production can produce many useful products in this area. Algenic acid is used in the rubber industry on Earth and plastics can be produced from algae (Boston, 1985).





2.5.14. Miscellaneous Materials

Other materials that can be produced from local resources include sulphur paint, ammonium nitrate explosives, ion-exchange media, sulphur-based hyperacids, reductants and oxidants and solvents (Clark, 1989).

2.5.15. Construction Materials

Materials will need to be carefully selected for strength and durability in the very cold environment of Mars and also need to be resistant to corrosion by the Martian soil. One present-day example of a suitable plastic is polytetrafluoroethylene (PTFE) which is suitable for use at temperatures down to -200°C and is UV resistant. As stated above, the diurnal temperature range on Mars can be more than 50°C , therefore thermal expansion must also be considered.

Abrasion resistance will be an important factor of any construction materials exposed to the Martian environment (including the materials used for EVA suits and rovers) or be wrapped in an abrasion proof coating. Due to lower atmospheric densities (0.02 kg/m^3 at 6mb and 0°C on Mars compared to 1.17 kg/m^3 at 1atm and 25°C on Earth) a wind speed on Mars of 50m/s (180 km/h) would be equivalent to a 3 km/h wind on Earth, in regards to the resultant force. However, sand and ice crystals would still be travelling at 50m/s under these conditions and cause significant abrasive forces (Cockell, 2001b).

Portland cement (commonly used throughout the world in construction) is generally made by the partial fusion of calcareous material with aluminosilicate material (Clark, 1981). Typical principal components of Portland cement are tricalcium silicate, $3\text{CaO}\cdot\text{SiO}_2$ (conventionally referred to as C_3S), dicalcium silicate, $2\text{CaO}\cdot\text{SiO}_2$ (C_2S), tricalcium aluminate, $3\text{CaO}\cdot\text{Al}_2\text{O}_3$ (C_3A) and tetracalcium aluminoferrite, $4\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Fe}_2\text{O}_3$ (C_4AF). Typically 'normal blend' Portland cement is comprised of these constituents in the following ratios, 48-65% C_3S , 10-30% C_2S , 2-11% C_3A and 7-17% C_4AF (Ryan & Samarin, 1992).

Clark (1981) discusses three alternative cement types, Erz, Sorel and sulphur cement. Erz cement, widely used in Germany, is manufactured by substituting iron rich material for the aluminous component. Sorel cement, manufactured from magnesia and magnesium chloride, is a very hard and strong product. Sorel cement, however, is attacked by water, limiting its use on Earth and also in Martian habitats, however, it may

have some niche uses on Mars outside of the habitats where liquid water cannot exist. Sulphur cement can be used for rapidly building block wall constructions, as it achieves most of its final strength in just 5 minutes. It is made of 97% pure sulphur, the balance comprises a plasticiser and chopped glass fibres.

The presence of magnesium and sodium sulphates in the soil, in the presence of water, can cause serious damage to standard concrete structures constructed on Mars. Whilst liquid water is not present in the soils in their current state the presence of a heated habitat may provide sufficient warmth to melt ground ice in the vicinity of the structure. Under such conditions the sulphates will react with the hydrated calcium aluminate of Portland cement, causing swelling and cracking of the cement matrix. 'Sulphur resistant' Portland cement may be a viable countermeasure, having a C_3A content limited to less than 5% and typically 50-60% C_3S , 15-25% C_2S , 2-5% C_3A and 10-15% C_4AF . Well-compacted, high strength concrete will also assist in resisting sulphate attack (Ryan & Samarin, 1992).

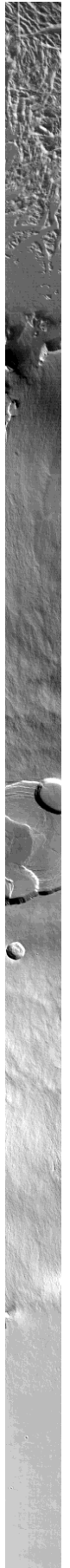
The sulphate salts themselves can act as cements when mixed with adequate water. Bricks could be manufactured from Martian soils using this characteristic, baking them in ovens to recover the water (Clark, 1989), however, contact with liquid water will be detrimental to the bricks unless coated with a suitable sealant.


Using clays and salts believed to exist on the Martian surface (based on Viking Lander scientific results), Robert Boyd and others (1989) have conducted experiments to produce artificial duricretes for use as a construction material. They propose the use of 1% Kevlar reinforcing to strengthen the clay disks they produced, with tensile strengths approaching that of cement concrete and brick.

The clays present in the Martian regolith could be extracted and formed into bricks in a fairly conventional manner (Clark, 1981).

Plaster can be produced locally using vermiculite (deposits of which are associated with rift systems, described in Table 10) or lime (CaO), sand and water.

Plaster-of-Paris can be manufactured from calcium sulphate and used to manufacture small objects, such as tiles, or as a sealant, or moulds for low melting point metals (Clark, 1981).





Carbonates are expected to be present in significant quantities on the Martian surface including calcite (CaCO_3), magnetite (MgCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$). There may also be large nitrate deposits associated with the above mentioned carbonates (Meyer & McKay, 1989).

Steel or aluminium can be fashioned in to wire baskets, or gabions, and, when rock filled, can be used to quickly build vertical walls or to retain embankments. In the low pressure Martian atmosphere (with low water and oxygen content) these metals should not corrode significantly (Farrier, 2000).

2.6. Life Support

2.6.1. General Life Support

Meyer & McKay (1995) report average requirements for human life support, as detailed in Table 12. Other authors' estimates compare favourably with those in Table 12, for example Jones et al. (1985) indicate a water requirement of 2.6kg/person-day and Boston (1995) tabulates seven different authors, which indicates an average water consumption requirements of 3.129kg/person-day and an average oxygen requirement of 0.848kg/person-day.

Table 12: Average Requirements for Human Life Support (Meyer & McKay, 1995)

NOTE:

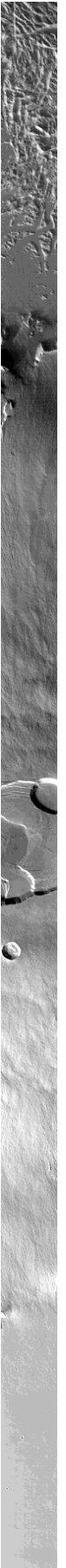
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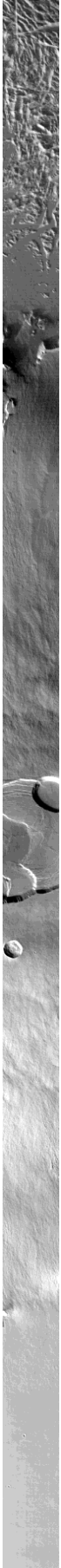
Significant environmental factors relevant to a Martian habitat are air quality and quantity (fresh/stale exchange rates, toxicity), light (intensity, quality, duration), confinement (restricted volume, privacy), restricted access to communications, diversity of aesthetic and recreational activities and stress (Grymes, et al. 1995) and food production and water recycling. All of these factors must be accommodated in a Martian life support system. The major functions of a Martian life support system are to produce breathable atmosphere (oxygen and buffer gas), remove carbon dioxide and toxic substances, control humidity, produce or recycle water, grow food and recycle waste. Recycling will significantly reduce ongoing input requirements of the system (Meyer & McKay, 1981). Temperature, wind speed, noise and vibration must also be controlled (Billingham, 1989).

Typical wastes that will require recycling in a closed bio-regenerative system include human solid and liquid waste (0.10 and 3.52kg/person/day, respectively; Meyer & McKay, 1995), grey (kitchen, hygienic wash and clothes wash) water (5.46, 7.77 and 12.50kg/person/day, respectively; Tamponnet, 1996) and a variety of potentially volatile technogenic gasses emanating from materials within the habitat (MacCallum, et al. 1997), including sealants, paints, industrial chemicals and fertilisers.

Many systems exist to recycle the habitat's atmosphere, many of which also incorporate the growth of food and the recycling of water. Early bio-regenerative life support experiments in Russia and the USA began by utilising the fast growing green algae *Chlorella Vulgaris* to recycle air and water for humans. The Institute of Biomedical Problems, in Moscow, conducted trials of this system with humans in small chambers for periods of 15 and 30 days. Boston (1992) reports that dome Soviet experiments have provided sufficient oxygen for one person in just 8m² using *Chlorella*.

The next major step was to incorporate higher plants into the system for food production. The Institute of Biophysics, in Krasnoyarsk, Siberia, first achieved this with their Bios-3 experiments, where crews of two to three lived for up to six months, with nearly completely regenerated air, water purified by plant evapo-transpiration and 11 crops supplying about half of their nutritional requirements. Whilst the majority of human wastes were not reused in the system the crew did harvest crops and process and cook food within the system and even burned straw from the wheat to raise carbon dioxide levels to around 1,400ppm to increase plant photosynthesis. The totally closed





habitation complex of Bios-3 was 315m^3 in area, including 63m^2 dedicated to providing food (hydroponically). 75-80% of the food consumed during the experiment was grown within the closed system, the remaining food was taken from an initial store within the chamber (Boston 1995). Scientists involved in the experiment estimate that this food growth area is sufficient to feed two humans but could provide the oxygen requirements of four to five humans (Boston, 1985), other sources indicate that a food growth area of 25m^2 is sufficient to revitalise air for one moderately active person (University of Texas, 2001).

Since 1978 NASA's efforts have concentrated on controlled ecological life support systems (CELSS), largely focussing on high yield systems for biomass and food production (Nelson & Dempster, 1995). Whilst initial research was focused on higher plants, the incorporation of algae, bacteria, fungi and animals, including aquatic animals, is not excluded (Smernoff & MacElroy, 1989), although the exclusion of animals would simplify the mass-balance of the system. The purpose of a CELSS is to create a life support system which is largely independent of resupply (Caudill, 1984).

In 1991 Biosphere 2, in Arizona, the largest closed bio-regenerative test bed in the world (and first biospheric system), began a very successful two-year closure incorporating complete recycling and was only energetically open (Nelson & Dempster, 1995).

Biosphere 2 was an essentially closed bio-regenerative ecological system (outward atmospheric leakage was less than 10% per year) energetically open to electricity, temperature and sunlight (admitting 65% of the sun's photosynthetically active radiation) used to test theories and technology for possible space applications. Covering a footprint of $12,766\text{m}^2$ and enclosing a volume of $204,045\text{m}^3$ it remains the largest such life support experiment ever attempted. The structure included a human habitat ($1,077\text{m}^2$ including living and working quarters), an agricultural zone ($2,232\text{m}^2$) incorporating waste recycling, areas including rainforest, savannah, desert, marsh and ocean ($5,815\text{m}^2$) and two variable volume chambers, known as lungs, to allow for atmospheric pressure variations without leakage ($3,644\text{m}^2$). It included sustainable food production, air purification (through soil bed reactors), wastewater treatment and water recycling (Nelson & Dempster, 1995) for a crew of up to eight people.

During the Biosphere 2 closure a single resupply of oxygen was required. This was required as the concrete structure sequestered large amounts of CO₂, and reduced light levels within the dome (65% of incident light penetrated the dome structure) reduced the rate of photosynthesis, slowing oxygen production (Nelson and Dempster, 1995).

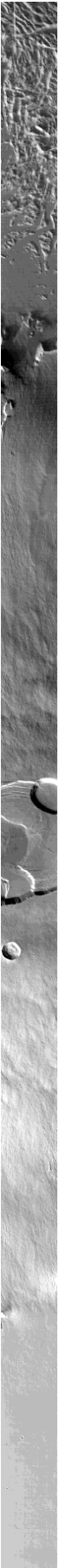
MacCallum, et al. (1997) state that many CELSS concepts have relied on waste degradation methods requiring high amounts of energy, such as wet oxidation and super critical wet oxidation, which also results in the loss of the energy chemically bound into the wastes. Bio-regenerative systems are capable of breaking down wastes into low complexity materials that can be used as food-stocks for bacteria, algae and higher plants. In Biosphere 2 sewerage, kitchen and wash water was purified through the actions of microbes and aquatic plants and then used as irrigation water. Potable water was distilled from the atmosphere using two humidifiers and treated with a UV sterilizing system. The use of aquatic plants, such as water hyacinth and canna was a useful source of purified water, due to their high rate of transpiration, followed by distillation. No odour problems were reported from the marsh system that was used for this process in the test module (Biosphere 2's small-scale predecessor).

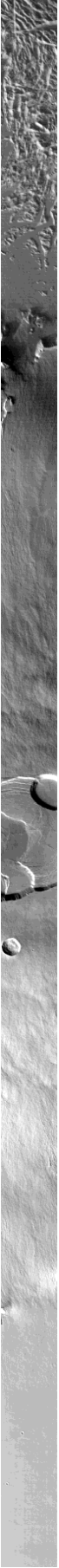
Whilst physico-chemical systems are likely to dominate initial habitats, such as many of the systems described herein, bio-regenerative systems, such as Bios-3 and Biosphere 2, are likely to replace these systems for a permanent habitat (Nelson & Dempster, 1995). The key to a bio-regenerative system is that plants will provide food as well as converting carbon dioxide to oxygen and purifying water (Smernoff & MacElroy, 1989).

The system should be automated, where practical, to minimise the time taken tending to the system, particularly food production. The crew of Biosphere 2 worked an average of 66 hours per week including 46% on food production, 20% on communications and 10% on repairs and maintenance (Nelson & Dempster, 1995).

Compartmentalisation and redundancy of various life support functions is essential. This allows sections to be disconnected or isolated in the event of failure, disease or contamination to protect the rest of the system. This approach will also allow for the gradual expansion of the habitat by adding additional modules (Boston, 1981 and Smernoff & MacElroy, 1989).

Many authors, such as Boston (1992), have described recycling processes using plants and physical/chemical systems to recycle air, control temperature, humidity and oxygen





and carbon dioxide partial pressures within a greenhouse and a crew habitat. Boston's system senses rising concentrations of carbon dioxide and, using CO₂ scrubbers, transfers this from the crew habitat to the greenhouse where plants use the carbon dioxide for growth and provide oxygen for the crew. Other options are described below.

Meyer and McKay (1981) describe a Martian habitat life support system for eight people, based on space station (existing) technology, incorporating the key systems relating to atmospheric and water purification. The required inputs for this design are 4.5kg of buffer gas (nitrogen/argon mix from the Martian atmosphere), 1.1kg of carbon dioxide (from the Martian atmosphere) and approximately 235kWh of consistent energy per eight crewmembers per day. A schematic detailing the material flow and subsystems associated with this design is presented in Figure 17 below. The leakage rate indicated in this diagram could possibly be reduced, however, this increases the problem of toxicogenic control (Meyer & McKay 1981).

NOTE:

This figure is included on page 92 of the print copy of the thesis held in the University of Adelaide Library.

Figure 17: Eight person life support system incorporating recycling technologies. Figures are in pounds per day per eight persons (Meyer & McKay, 1981)

Meyer and McKay also considered the requirements of food production for incorporation into the above life support system design. The greenhouse is sized to provide enough food for the crew and also supplies more than enough oxygen. Excess water from the crew habitat is sent to the greenhouse and supplemented by an additional 4.1 pounds (1.87kg) of water per day. In addition the greenhouse requires the input of

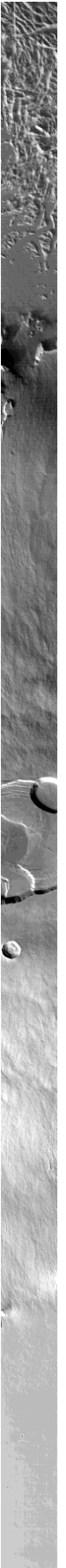
22.3 pounds (10.1kg) of carbon dioxide from the Martian atmosphere per day. The interrelationship can be seen in Figure 18, below.

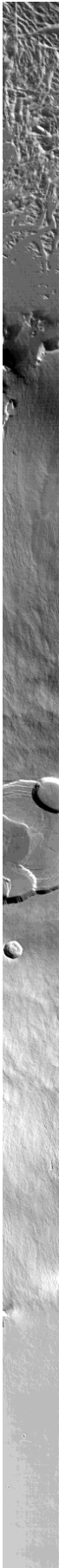
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the thesis held in the University of Adelaide Library.

Figure 18: Incorporation of a greenhouse to the above life support system design. Figures are in pounds per day per eight persons (Meyer & McKay, 1981)

Due to vast differences in the required flow rate of Martian atmosphere to be processed for each process, and the various methods employed to extract the input requirements of the system, separate subsystems are suggested for each process. Various methods of extracting the required inputs have been previously discussed. It should be noted that centrifugal compressors would be the preferred choice for pumping Martian atmosphere within these systems, as they are less affected by the pitting caused by airborne dust and sand (Meyer & McKay, 1981).

Finn, et al. (1996) propose the use of molecular sieves (adsorption separators), in combination with industrial and biological processes, to generate a breathable atmosphere, water and fuel. Figure 19 is a schematic representation of their proposal.





NOTE:
This figure is included on page 94 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 19: In-situ resource utilisation of Mars atmosphere constituents for life support and fuel production (Finn, et al. 1996)

Nitta, Otsubo and Ashida (2000) of the Institute for Environmental Sciences in Japan describes a closed ecological experiment facility (CEEF) undergoing pre-habitation testing (Nitta, 2005), in Rokkasho village in northern Japan, with temperature and humidity control. The facility consists of a closed plantation experimentation facility, a closed animal breeding and habitation experiment facility and a closed geo-hydrosphere experiment facility. The facility is studying the life-support mechanisms in a completely closed space. The plant module includes 90m² of artificially lit cultivation area (lit by more than 100kW of sodium lamps) and 60m² of cultivation area utilising solar lighting. Whilst mass balances have not been included, the facility's system diagram is shown in Figure 20, with interfaces between the modules.

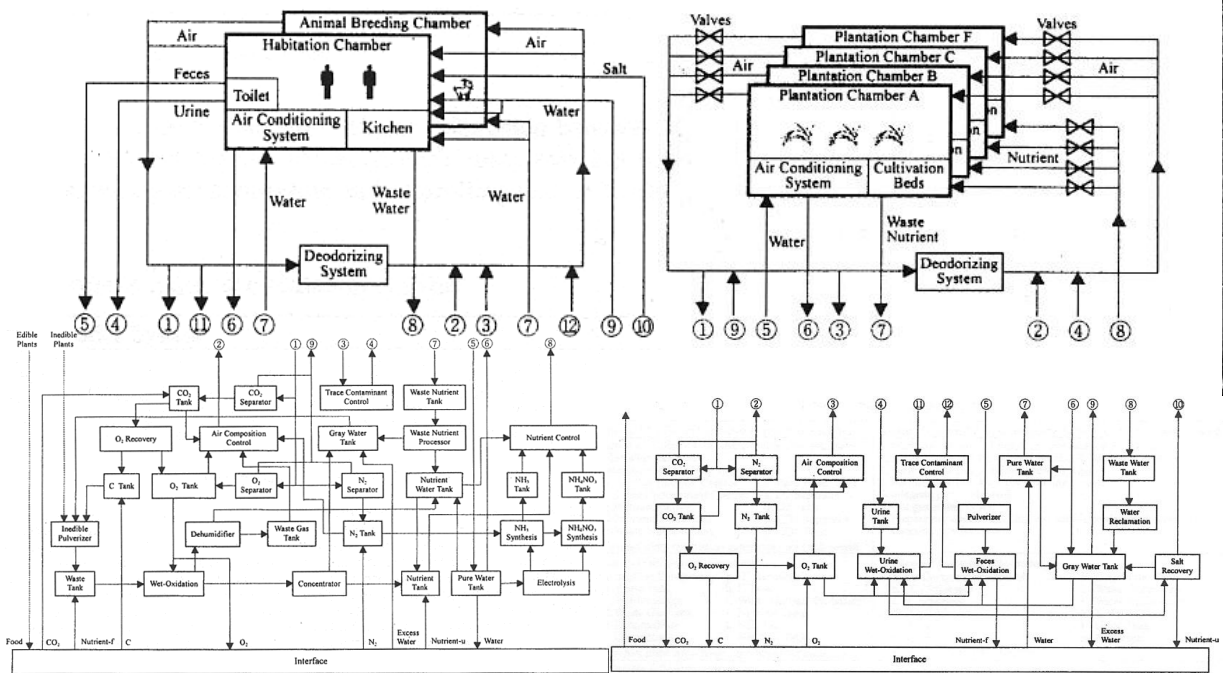
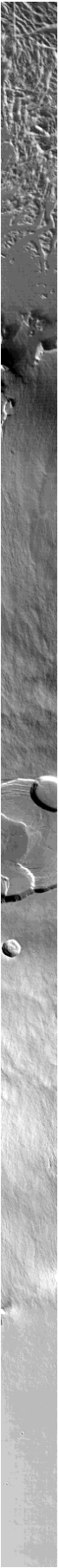


Figure 20: CEEF closed animal breeding & habitation module (left) and closed plantation module (right) system diagrams with interfaces (Nitta, Otsubo and Ashida, 2000)

Few life support systems reviewed incorporate a method for the safe and efficient removal of toxic substances from the habitat's atmosphere. Activated carbon filters or catalytic oxidation are some options reliant on high energy requirements or consumable parts. Biosphere 2 utilised the microbial content of the soil used for food growth to metabolize the toxic chemicals that were outgassed from materials and equipment, including solvents and acids. Called a soil bed reactor, blowers force air upward through the soil, exposing it to the metabolic action of the microbes. The diversity of microbes are capable of metabolizing a wide range of gasses that could otherwise cause toxic build-ups. The entire Biosphere 2 atmosphere could be passed through the soil bed reactors each day and was very effective, also ensuring good aeration of the crop growth medium (Nelson & Dempster, 1995). The existing Martian soil will require the addition of organic matter and microbes for both crop growth and the possible operation of a soil bed reactor (MacCallum, et al., 1997).

Biosphere 2 utilised a constructed marsh, including aquatic plants and their associated microbes, to recycle human and animal waste as well as domestic wash water whilst also producing an abundance of animal fodder and requiring very little energy or maintenance. The aquatic plants also concentrated and removed heavy metals from the water. Treated water was then pumped to the irrigation supply, providing any remaining nutrients to the crops (Nelson & Dempster, 1995).



Contamination control is an important part of any closed system as trace gasses can quickly build up to toxic levels (Boston, 1988). Highly autonomous and reliable analytical sampling systems will be required in a Martian habitat to provide data that may indicate potentially dangerous trends in the constituents of the atmosphere and water. The production of any commonly used consumables of this system must be achievable on Mars, however, some minor and high quality consumables could possibly be imported if in-situ manufacture is impossible and no alternative exists (Nelson & Dempster, 1995). Analytical systems developed for Biosphere 2 included atmospheric modelling and real-time monitoring (analysing for CO, CO₂, O₂, O₃, NH₃, N₂O, NO, NO_x, H₂S, CH₄ and total non-methane hydrocarbons), thermodynamic monitoring and real-time control and water nutrient analysis. Systems conducted preliminary data analysis and raised alarms where trends became dangerous. Such systems play a part in a closed system for safety as well as research (MacCallum, et al., 1997). Carbon dioxide will be one of the most commonly produced toxic gasses.

The fluctuations in carbon dioxide in a closed system need to be carefully controlled as significant changes can occur in a short period of time. Nelson and Dempster (1995) note that the ratio of atmospheric carbon to carbon contained in the vegetable matter on Earth is in the ratio 1:1, whilst the Biosphere 2 ratio was around 1:100. This means that a relatively small change in the biomass of the system can have a significant effect on atmospheric CO₂ levels. For example, as plant and soil respiration is dormant at night Biosphere 2 scientists observed fluctuations of 500-600ppm CO₂ between night and sunny days, equating to 20-50% of the total atmospheric content of CO₂. Significant seasonal variations of CO₂ were also observed, varying from 1,050ppm in June 1992 (summer) to 2,450ppm in December 1991 (winter). To assist in the management of atmospheric carbon dioxide levels in Biosphere 2 the crew used a physico-chemical precipitator capable of lowering CO₂ levels by 100ppm/day, a process that was reversible by heating the CaCO₃ that the system produced. The crew also pruned and dry-stored rapid growing plants to lockup additional amounts of carbon (composting the vegetation would have released the carbon back to the atmosphere).

Apart from using molecular sieves to remove carbon dioxide from the habitat's atmosphere (described above) solid amines can be used with a similar method. When molecular sieves were used on Skylab the atmosphere was pre-filtered with a silica gel absorber bed to remove water vapour from the air flow so that the carbon dioxide

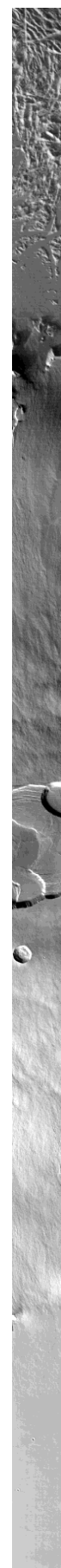
collected in the molecular sieve was not displaced by the smaller water vapour molecules. With any such system the rate of carbon dioxide removal decreases as the molecular sieve/amine starts to become saturated. An alternative method, with a constant carbon dioxide removal rate, is to use an electrochemical depolarized concentrator. This concentrator produces electricity and electrochemically removes carbon dioxide from the atmosphere which can then be vented or sent to a greenhouse or Sabatier (or other) CO₂ reduction system for conversion to oxygen. Single person water-cooled concentrators have been demonstrated with constant carbon dioxide removal efficiency of 91% (Quattrone, 1981).

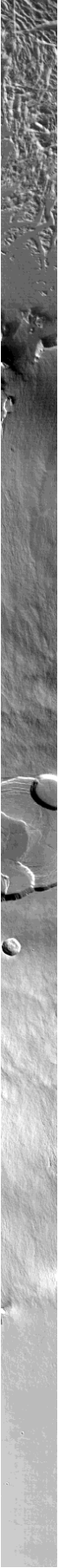
The physical process of removing trace contamination through 'artificial' means will require the use of several subsystems including catalytic oxidation, charcoal adsorbers and chemical adsorbers. Some trace gasses can be readily catalytically oxidised to carbon dioxide and water, however, some gasses may 'poison' oxidation catalysts and must be removed by pre-treatment. Further to this, some gasses become highly toxic when oxidised and so must be removed by post-treatment and some organic materials cannot be oxidised and so must be adsorbed (Quattrone, 1981). Figure 21, below, outlines Quattrone's (1981) concept of air revitalisation.

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This figure is included on page 97 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 21: Air revitalisation system (Quattrone, 1981)

Allen (1995) proposes the use of a CELSS tank growing spirulina, illuminated by electric lights for photosynthesis, for the supply of food in his Earth-Mars transport model. Spirulina is a nutritious family of algae with a history of human consumption in Africa (*spirulina platensis*) and South America (*spirulina geitleri*) and is low in toxicity





(Boston, 1985). This concept can be adapted to supply part of the food requirements of a Martian habitat.

Cockell (1995) states that the growth of plants and the development of a closed ecological system would be difficult if the habitat experienced polar conditions. Further, the fog generated by the vaporization of previously deposited carbon dioxide from the polar caps (during summer periods) would cut down incident light, adding to the difficulties. Powell (2000) also discusses poor lighting conditions, although the cause is the long day-night cycle at polar latitudes, creating difficulties for the use of solar power. Powell proposes alternative power sources to overcome this problem, however, Cockell does not discuss the possibility of artificial lighting to overcome the lighting issues he has raised. This warrants further investigation, not only to allow the possibility of polar habitats, where desirable, but also to allow indoor crop growth and to supplement natural lighting, if desirable.

Heating and thermal insulation will be an important aspect of any habitat on Mars. Temperatures measured at the Viking Lander 2 site (48°N) ranged from a maximum of around -30°C in the summer day to a minimum of -120°C in the winter night and had a maximum diurnal variation of more than 50°C. Whilst the thin Martian atmosphere will reduce the rate of convective heat loss from a habitat, heat sources will be an important part of any life support system. Heat sources could come from the waste heat of many of the power generation options (such as nuclear and geothermal), or from industrial processes. Alternatively methane or electrical heaters could be utilised. Sulphur foam, with excellent thermal insulation properties, can be produced from local resources and applied to the outside of structures as a form of insulation (Clark, 1981).

Other biological challenges of the Martian environment include lower gravity and high surface radiation levels compared to Earth norms. Life support systems must also adequately address any deleterious effects of these, which are discussed in the following sections.

2.6.2. Partial Gravity

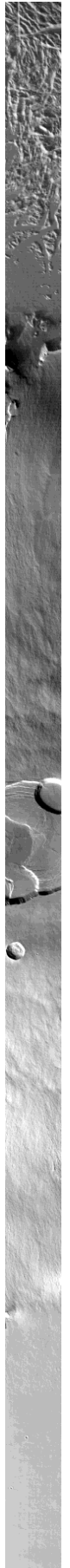
To date humans have only experienced full gravity (on Earth) and micro-gravity (in orbit) for any appreciable period of time. Very little is known about the effects of partial gravity yet gravity's role in human development is vital and the effects of partial gravity must be understood. Gravity is the single greatest influence on the size, shape and

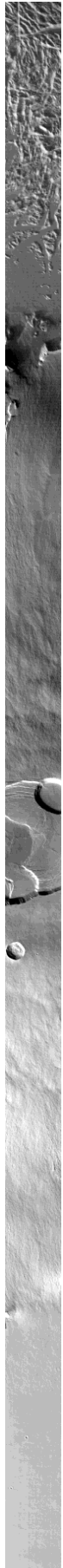
strength of bones. The reduced gravity environment of Mars will result in reduced muscle use and less strain put on the bones. In micro-gravity this results in bone demineralisation (Grymes, et al. 1995) and a similar effect could be expected in partial gravity, resulting in more fragile bones and probably longer healing times. Keller and Strauss (1993) assessed the effect of various exercise types and bed rest (which results in similar changes to bone as space flight) and their effect on bone mineral content. The results of their study indicate that weight training or artificial gravity environments, which impose high loads on the skeleton, may be some of the better options for safely maintaining the musculo-skeletal system. Further, they suggest that a gravity field of $\frac{3}{8}$ Earth's gravity (as on Mars) will maintain skeletal strength above the fracture limit associated with an Earth gravitational environment.

Micro-gravity also results in other medical problems such as blood volume loss (red blood cell mass reduction; Taylor, 1993) and muscle disuse atrophy (a reduction of size, weight and strength).

Micro-gravity also causes both acute and chronic effects on the nervous system, primarily due to changes in proprioception and sense of body orientation (Grymes, et al. 1995). Whilst this may temporarily effect people travelling through micro-gravity it is considered unlikely to cause any effects in partial gravity due to the continual sensory feedback that will be present.

Immune cell responses have been experimentally shown to reduce by approximately 35% following exposure to zero gravity and is accompanied by a reduction in white blood cells and atrophy of lymph organs as well as decreases in other areas of the immune system. The body's natural healing processes also appear to be altered by the effects of micro-gravity. Currently it is uncertain if these observed effects are a result of micro-gravity (although circumstantial evidence exists suggesting that it is so), or a result of the experience of returning to Earth's gravity. Similarly, it has not been possible to determine whether these effects are the result of some other 'space-flight' related effect, such as radiation exposure, or are truly associated with micro-gravity (Grymes, et al. 1995). As there is no long-term data relating to partial gravity environments, it is not obvious if this immune suppression is specific to the effects of micro-gravity or if similar effects would be observed in partial gravity.





Other predicted effects of reduced gravity (depending on the degree of reduction) include fatigue, urinary retention, muscle unco-ordination, renal calculi, cardiac arrhythmia, reduced plasma volume, dehydration and weight loss (Taylor, 1993).

Importantly, it is not yet known if there is a critical threshold value of gravity below which humans cannot survive (Taylor, 1993). Whilst it is probable that the deleterious effects of partial gravity will stabilise at some level there are still far too many unknowns to quantify this. It may be that the effects of partial gravity will have only a minor impact on residents of Mars as, after adjusting to the partial gravity, a trip to the higher gravity of, say, Earth will be uncommon or even rare.

Of particular importance to a Martian habitat is the effect of partial gravity on human foetal development, a field in which no research has been undertaken.

Countermeasures to physiological alterations due to micro-gravity are in use in today's space programs and are likely to be effective in partial gravity environments where necessary. These countermeasures include exercise (varied), mechanical (lower body negative pressure, gravity suit), dietary (mineral supplements, fluid loading), pharmacological (space sickness medication), psychological (biofeedback) and artificial gravity (Grymes, et al. 1995).

It is unknown if there is a linear relationship, for the above medical issues, between micro-gravity and Earth's gravity, or if there is some threshold amount where these effects become significantly reduced. Whatever the case, long duration space missions have indicated highly variable results between individuals and a great deal of very long duration research is still required (Boston, 1985).

2.6.3. Radiation

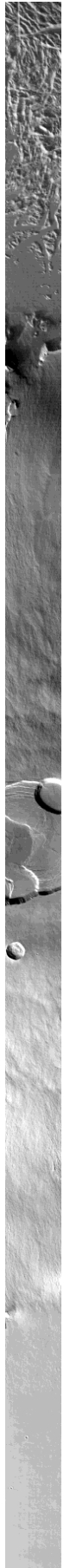
UV radiation has been shown to inhibit photosynthesis in plants and micro-organisms, damage growth hormones in plants, increase rates of DNA damage and mutation and a wide range of other effects (Cockell & Andrady, 1999). Radiation levels on the Martian surface, compared to the surface of the Earth, are shown in Table 13. To put these figures in perspective, and appreciate the beneficial effect of the Earth's atmosphere it should be noted that radiation levels at the top of the Martian atmosphere are 57% less than the level at the top of Earth's atmosphere. Actual values will depend on factors such as cloud cover, atmospheric dust levels, season and latitude.

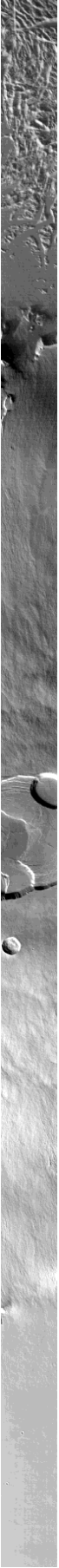
Table 13: Surface UV Radiation Levels, at a zenith angle of 0° (Cockell & Andradý, 1999)

| UV Radiation | Earth Surface (W/m ²) | Martian Surface (W/m ²) | | |
|-----------------|--------------------------------------|-------------------------------------|---------------|----------|
| | | Perihelion | Mean Distance | Aphelion |
| UVC (200–280nm) | Negligible | 4.1 | 3.4 | 2.8 |
| UVB (280–315nm) | 2.0 | 9.6 | 7.9 | 6.6 |
| UVA (315–400nm) | 56.8 | 37.9 | 31.1 | 26.6 |

The high carbon dioxide concentration of the Martian atmosphere effectively absorbs UV radiation below approximately 190nm. Ozone does build up during the winter period at high latitudes, absorbing some radiation around the 250nm range, however, the levels of ozone are two orders of magnitude less than those on Earth and is not effective at all in summer. UVA is less on Mars than Earth due to Mars' extra orbital radius and the fact that Earth's atmosphere does not significantly attenuate UVA (Cockell & Andradý, 1999).

UV and ionising radiation exposure must be minimised and not permitted to significantly exceed Earth's exposure levels inside habitats, including greenhouses. The carbon dioxide content of the thin Martian atmosphere effectively blocks short wavelength UV radiation but does little to prevent the passage of longer wavelength UV and ionising radiation. Permanently occupied habitats on Mars would need to provide radiation protection similar to that of the Earth's atmosphere in order to prevent potentially life-shortening and reproduction-threatening problems in humans, plants and animals. The primary source of radiation (99% of the total) will originate from solar flares and galactic cosmic radiation (GCR), primarily in the form of ionising radiation. Flares can be monitored and solar storm shelters utilised to provide increased radiation protection during these events (Boston, 1985). It should also be noted that Mars does not have a magnetic field to trap charged particles from these events (Grymes, 1995). It is evident that ionising radiation poses a more significant threat on Mars than ultraviolet radiation. A more detailed coverage of radiation protection can be found above.





2.6.4. Radiation Shielding

On Earth, the worldwide average radiation dose received by a person is 0.27 rem per year, almost half of which is from atmospheric radon (Goldman, 1996, Gaines, 2000). It is interesting to note that there is no increase in cancer mortality in populations living in low-background radiation environments when compared to populations living in higher natural background radiation environments (Goldman, 1996). Studies of individuals exposed to the Hiroshima and Nagasaki A-bombs, comparing those exposed to a yearly dose of between zero and 10 rem with a sample of people from other regions, shows no apparent difference between the two groups. This challenges the notion that cancer risk is always proportional to dose, in fact, Goldman goes on to state that most studies indicate that the higher natural background radiation environments often have a lower cancer mortality rate.

The Health and Safety Executive, in Britain, has attempted to quantify the “acceptable” risk arising from radiation exposure. Their recommendation, adopted by many countries around the world, is that the level of radiation received by workers (in industries involving radiation exposure) is no more than 2 rem per year, and the level of exposure to the public is limited to 0.1 rem per year (Gaines, 2000). The National Council of Radiation Protection and Measurements (NCRP) in America has recommended, and NASA has accepted, annual limits of radiation exposure for astronauts in low-earth orbit of 50 rem per year, and a career limit of between 100 and 400 rem, depending on age and sex of the astronaut (Stanford & Jones, 1999). The NCRP are currently (2006) reviewing their draft report containing radiation protection recommendations for travel beyond low-earth orbit.

The radiation environment on Mars is considerably harsher than on Earth necessitating the need for effective radiation shielding and use of radiation resistant materials. Mars does not have a magnetic field to trap charged particles as occurs on the Earth (Grymes, et al. 1995). It also lacks a substantial, permanent ozone layer and has a very thin atmosphere incapable of blocking significant amounts of radiation over 190nm.

Despite the increased distance Mars lies from the sun its surface is dosed with a UV-B flux of approximately 4 times greater than the Earth’s surface. Further to this, as there is no effective ozone layer on Mars, the surface also receives UV-C radiation (Cockell, 2001b). UV radiation of less than 190 μ m is filtered out by the carbon dioxide in the

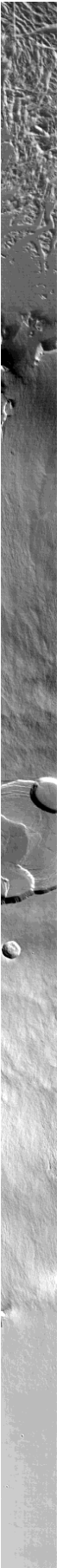
atmosphere (Meyer & McKay, 1995, Boston, 1995). 99.9% of the increase in biologically effective UV dose, compared to that received on Earth, is attributable to the UV-B and UV-C levels on Mars (Cockell and Andradý, 1999). Cockell (2001a) indicates that theoretical calculations indicate that unprotected free DNA is susceptible to approximately 950 times more damage on Mars than on Earth.

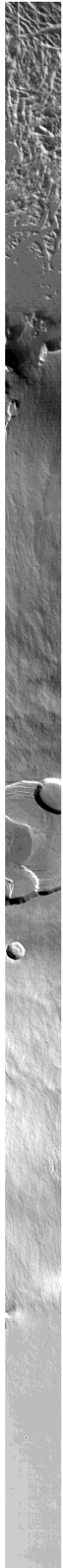
Galactic cosmic radiation (GCR), composed of very high energy particles, is also present at the Martian surface, consisting of around 87% protons, 12% alpha particles and 1% heavy particles ranging from lithium to tin, as is high energy solar flare radiation (Boston, 1995). GCR will be a health risk on Mars due to the low atmospheric density, as it is in interplanetary travel. In space, a depth of approximately 1.2m of regolith should cut a GCR dose from 24 rem/year to around 10 rem/year, at a depth of approximately 0.2m the GCR dose should be cut to around 12 rem/year (Tillotson, 1997). He goes on to note that secondary radiation effects may actually cause slightly higher GCR doses at depths between 0.9m and 0.2m. On the surface of Mars these doses would be cut by 50% or more simply by the presence of the planet itself and the surrounding terrain.

The Mars Odyssey spacecraft measured the unshielded radiation skin dose equivalent for people on the surface of Mars (during solar minimum), indicated in Figure 22.

NOTE:
This figure is included on page 103 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 22: Radiation skin dose equivalent for astronauts on the surface of Mars near solar minimum; from the MARIE experiment (Saganti, et al. 2004)





There are few methods currently available on Mars for radiation protection as the cost and practicalities of transporting shielding from Earth, for anything larger than a tiny habitat, is cost prohibitive. The effectiveness of a radiation shield of a given thickness comes from the density of the material used. The only readily available in-situ materials on Mars for practical use as radiation protection are water and soil. Whilst protection from ultra-violet radiation can be provided using very thin, even transparent, materials, protection from ionising radiation (GCR) is considerably more complex (Boston, 1995). Depending on habitat location and design, protection from radiation may require the construction of heavily shielded 'safe havens' to protect against infrequent, but large, solar flares (Clearwater and Harrison, 1990).

The Martian atmosphere has a total column mass of about $20\text{g}/\text{cm}^2$, equivalent to a layer of water approximately 15cm thick (Meyer & McKay, 1989, 1995). This compares to a column mass on Earth of approximately $1\text{kg}/\text{cm}^2$, equivalent to a layer of water approximately 10m thick, thus the protection afforded by the Martian atmosphere is trivial. Essentially, $1\text{kg}/\text{cm}^2$ of an insulating material will need to be added to a habitat to provide equivalent radiation protection to that of the Earth's atmosphere. This could be achieved with a 10-metre layer of water or a 6.25-metre layer of soil (Meyer & McKay, 1995), assuming average density of $1,600\text{kg}/\text{m}^3$ (based on Viking lander results, Christensen & Moore, 1992). This is rather simplistic and does not consider the reduced level of radiation reaching Mars, due to its distance from the sun, nor does it address Mars' lack of a magnetic field, which would protect it from ionising radiation from solar flares and GCRs.

In relation to supporting a regolith layer on a habitat to protect against radiation, Roberts (1989) calculates that an inflatable structure pressurised to one atmosphere can support a 17 metre deep layer of soil. Boston (1992) states that this is well in excess of the depth required for radiation protection. A soil layer would also block out all UV-radiation and does not necessarily have to be equivalent in density to the Earth's atmosphere to be effective. The thin Martian atmosphere itself does provide radiation protection equivalent to $27\text{g}/\text{cm}^2$ of aluminium (Kuznetz & Gwynne, 1992). Stanford and Jones (1999) indicate that estimates of radiation shielding to protect astronauts in space from a large coronal mass ejection (CME) vary from 5 to $20\text{g}/\text{cm}^2$ of aluminium, or equivalent. The equivalence of the radiation protectiveness of a number of materials

is shown in Figure 23, below. The horizontal line is the annual exposure limit for astronauts.

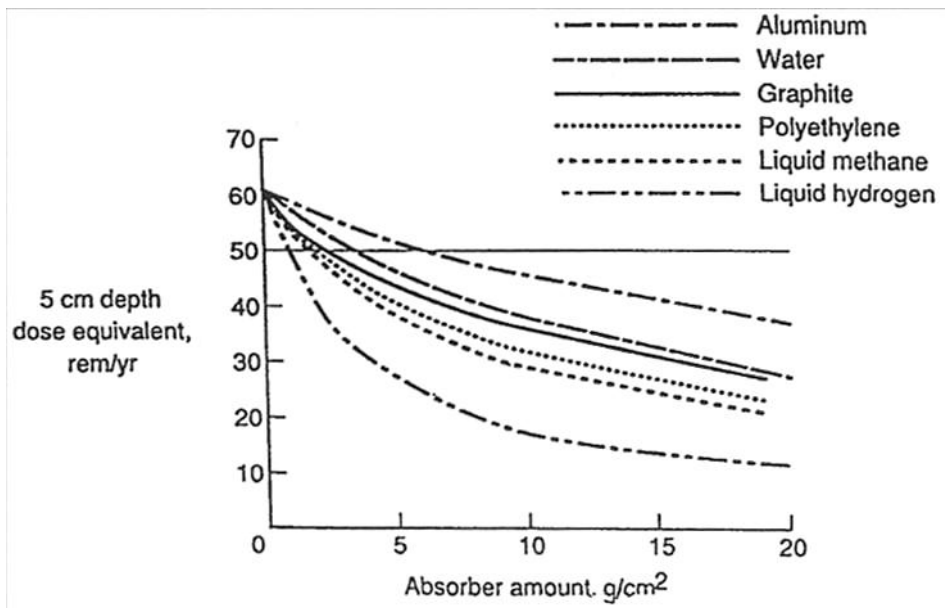
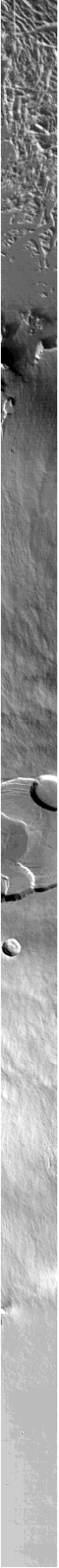


Figure 23: Material effectiveness of galactic cosmic ray radiation reduction, at solar minimum (Stanford & Jones, 1999).

Of the available radiation shielding options various authors have considered constructability of shields. Martian soil can be collected and deposited over a structure through the use of a simple bucket and dragline (McKay, 1988), or excavation machinery and conveyor belts (Brierley et al, 1997). Water can be extracted from the atmosphere, the ground, ice deposits or manufactured through chemical reactions and pumped into water tanks covering the roof of the habitat (Cohen, M. M. 1995). Rooftop water tanks can be designed to allow natural light to filter through, reducing energy consumption and providing natural light to greenhouses for plant growth below (French, 1989a). Alternatively, in a polar location water could be sprayed over the habitat to create a frozen shielding layer. A 30cm thick layer of ice will reduce exposure to a 20-rem solar flare by an order of magnitude (Cockell, 2001b). Baker and Zubrin (1990) suggest that a 10cm layer of water would be suitable for blocking most of the protons during solar proton events but the article is silent on detailed values.

The most conservative recommendation reported by Boston (1992) to protect against very high energy particles is 30-40g/cm², equating to 20-25cm of soil cover, however, Boston reports suggestions that 20g/cm² is adequate for long term human exposure. If



there is a need to reduce the amount of radiation protection it is possible to create shelters to protect from the severe radiation of large solar flares (Grymes, et al. 1995).

If habitats are entirely covered to protect from radiation then the requirements of power demand will significantly increase due to the need for artificial lighting (Cockell, 2001a), although it is possible to utilise mirrors (and other means) to some extent to permit the use of some natural light.

Blocking all UV radiation may not be the best alternative, however. UV-A, for example, is required for the navigational purposes of bees, is beneficial to the vision of some fish and lizards and may be used by some spider species to attract prey. Further to this, UV-A activates photolyase (required for thymine dimer repair; the cleaving of thymine cross-linked dimers in DNA is the most common type of DNA damage); it may also be associated with other repair processes, including some found in plants, and it induces pigment synthesis (Cockell and Andradý, 1999). Cockell (2001a) also indicates that the flavonoid content of leaves is partly determined by UV-B exposure. This is important as the behaviour of some herbivorous insects can be altered by flavonoid concentrations, as can the sex ratios of some butterflies. Further, the removal of UV-B and UV-C also prevents photosynthetic inhibition in plants. Cockell (2001a) highlights the concern that UV-A and blue light levels (at 47-67% of terrestrial levels, see Table 13) may be insufficient to induce the above-mentioned photolyase response to repair DNA damage caused by UV-B.

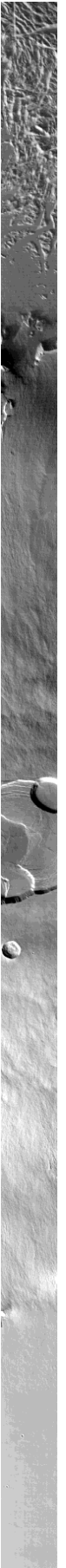
Of the 950 times more damage estimated to free DNA on Mars than on Earth, approximately 78% is caused by UV-C, approximately 22% from UV-B and 0.01% from UV-A. Cockell and Andradý (1999) recommend the complete elimination of the UV-C spectra, the reduction of UV-B radiation to at least terrestrial levels (80% or more removal) and state that UV-A can remain unattenuated (or artificially increased if desirable) due to lower than terrestrial incident levels (however, natural polarization should be maintained). Certain plastics, or coated glass, can be designed to produce a desirable UV radiation spectrum (Cockell, 2001a), but is not likely to be effective in reducing incident GCR on its own.

2.7. Communications

Communications with Earth and other surface areas of Mars will need to be maintained at all times. Below is a brief description of simple communication methods that will achieve this.

The time lag for communications between Earth and Mars (up to 20 minutes each way) must be considered and cannot be reduced, as it is constrained by the speed of light. This delay varies depending on the distance between Earth and Mars. Further, communication between Earth and Mars becomes impossible, without the use of inter-planetary relay satellites, when the Sun-Earth-Mars angle becomes sufficiently small (i.e. the planets are in, or near, opposition) when the sun blocks or interferes with straight line communication (Thangavelu, 1999). Inter-planetary relay satellites would be expensive and difficult to maintain, as they must be located a substantial distance from Earth (possibly somewhere along Earth's orbit) to allow communications to be beamed around the sun and brief, infrequent communication blackouts may be preferable.

Communication can be maintained between Earth and Mars with high rate (20 Mbps), though energy intensive, Ka-band (18 to 40 GHz) frequencies (although only for half the day when a line of sight can be maintained). Communications can otherwise be maintained via Mars-orbit satellite relays at a moderate rate (100 kbps) using X-band (7 to 12.5 GHz) frequencies during times when the Ka-band is ineffective. The X-band satellite system can also be used for communication with remote explorers or other colonies (Thangavelu, 1999).



3. PROPOSED HABITAT DESIGN

The design of a habitat for Martian colonization will be extremely specific to the proposed location and the objectives of the habitat's population. Even generalised designs must be specific to a region (such as polar, equatorial, southern/northern hemisphere, etc.) due to significant environmental variances affecting major design decisions (including, but not limited to, method of power generation, utilisation of natural light, source of water and extraction method, thermal insulation, and the life support system). Notwithstanding this, conceptual details of one possible design are described herein.

This concept design is provided to form the basis of further study and refinement as additional information becomes available (such as confirmation of assumptions, new discoveries and the completion of further research and system design). It assumes that the conceptual habitat (referred to simply as 'habitat' for the purposes of this section) will accommodate a population of 10,000 people.

The habitat is to be located within the Amazonis Planitia (35°N, 135°W) or Chryse Planitia (30°N, 30°W) due to the expected near surface water supply, being in the northern lowlands (and thus closer to the expected depth of liquid water) with relatively high measured soil water content. In addition, these locations are considered to be a reasonable compromise between such aspects as the ease of landing and launching vehicles into orbit near the equatorial regions and high incident light levels, and the higher risk and disruption of more frequent dust storms as facilities are located closer to, or south of, the equator.

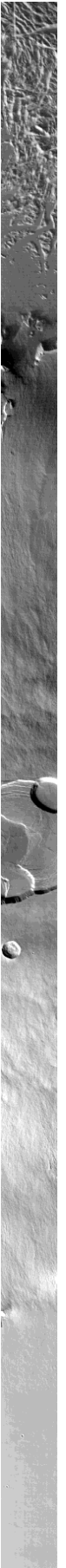
Both areas have similar climatic conditions, low elevation (relatively thicker atmosphere) and an abundance of flat terrain, although Chryse Planitia is more prone to local dust storms. Both regions have access to significant areas of scientific interest, if this was a major purpose for the habitat's establishment. The final location would be selected following a detailed assessment and local testing of many factors including the quantity and accessibility of in-situ resources (particularly water), local climatic conditions and geological assessment to name a few.

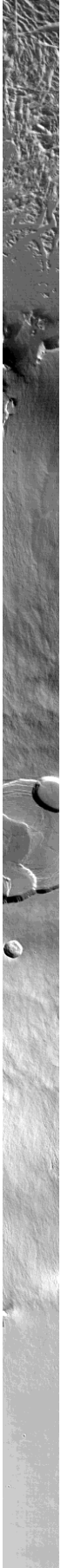
The proposed habitat design is to be modular to allow for expansion and also to provide redundancy of critical systems and compartmentalisation in the event of

decompression, fire or other event in one of the modules. The habitat could be composed of approximately 20 modules arranged in a grid pattern, allowing airlock personnel and vehicular access to the Martian surface from the perimeter modules. At least some of the modules will be entirely buried to provide for the maximum radiation protection for seeds and breeding stock of livestock and also to provide solar flare shelters in the event that some modules are not protected from such radiation events. Living space and greenhouse areas will be separated to facilitate the tailoring of atmospheric conditions to individual greenhouses and also to allow the monitoring of the effectiveness of individual greenhouses in the life support (atmosphere regeneration) processes.

It is suggested that the initial habitat be constructed using imported materials, in the form of inflatable domes and volume variable chambers to accommodate the expansion of the atmosphere without causing leakage or unacceptable pressure changes. This will provide for a relatively fast establishment of suitable living and working areas to accommodate the further expansion of the habitat. Expansion of the habitat will be by way of locally produced brick, plastic liners, etc. to minimise the cost of establishment and risk of reliance on imported materials, particularly for additional ad hoc expansion and maintenance requirements. The self sufficiency of expansion will increase with the development of various industries, however, it is anticipated that significant importation, particularly of technological systems and highly specialised materials will occur on a long term basis.

The amount of habitat space per person could be 200 square metres, based on large population studies discussed above, including 100 square metres for food production per person. Such living space can be incorporated into multi-storey designs, where practical or desirable, and equates to 2,000,000m² to accommodate and sustain the proposed 10,000 people. This can be provided with approximately 20 by 100,000m² modules. 250m wide, by 400m long semicylinders are preferred over hemispheres due to the flexibility of location and size of module interconnections when arranged in a grid pattern. The size can be reduced if internal structures, built from local resources, are multi storey. It is considered that this space will allow ample redundancy to survive in the event of the total loss of one or two modules. Habitat facilities are to include areas for habitation, commercial, retail, industrial and recreational purposes to satisfy the needs of a fully functional community.





Research indicates that the majority of power used by a Martian habitat is consumed by ISRU processes, with some estimates suggesting that this could be as high as 80%. It is suggested at this early stage that a power supply of approximately 50kW per person be provided plus an additional 20% contingency and 100% redundancy. This equates to 60kW of active power generation per person, or 10 times the average Earth consumption, and including total redundancy, a total of 1,200MW of power generating capacity across a minimum of two generation facilities, preferably more for risk mitigation purposes. Detailed power draw calculations must be undertaken on the equipment contained in the final design to verify the actual capacity required.

Base load power generation must be provided by a generator that will operate irrespective of environmental conditions, day/night cycle or other factors. Nuclear generation is currently the only viable solution in the Martian environment, is well developed and tested, and is the 4th largest power supply source on Earth. Such a system must be remotely located from the habitat for safety reasons, but will provide a reliable system that is economical and based on proved technology. Current knowledge dictates that fuel (as well as the majority of the plant's equipment) will need to be transported from Earth. Whilst this does pose environmental and safety concerns in launching nuclear from Earth, it is the only initially viable power supply until a renewable source is identified on Mars and/or new technologies are perfected. Such new technologies could include the beaming of power from several solar power generating satellites.

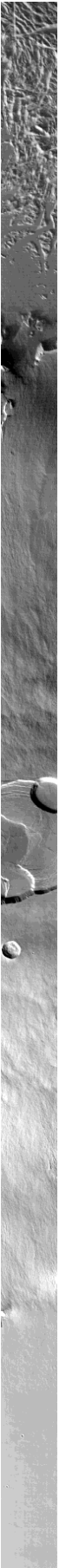
Non-base load power can be generated from the base load generators or from alternative, renewable sources, thus conserving the fuel of the nuclear generators. Solar power is feasible, subject to environmental conditions and site location, with excess power that may be generated used in the production of fuel (such as methane) for conversion back into power through fuel cells at other times. Further, the storage and combustion of methane as a backup supply is feasible, and preferable to the use of other fuels due to its ease of manufacture and simple, low energy, storage methods. It would also be appropriate for power generation for mobile equipment/vehicles.

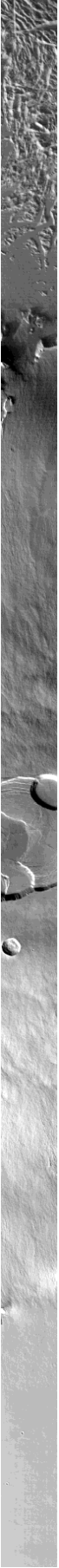
Subject to investigation into the availability of different water sources, initially the habitat would source water from ground ice or water reservoirs as it is expected to be most readily available. Ice could be melted using microwave heating (selected due to its low energy consumption) and pumped to the habitat. Where molecular sieves were being

used for other ISRU purposes they would also capture atmospheric water. Such sieves are also good for replacing system losses as the atmospheric water supply, whilst being in low concentrations, is essentially inexhaustible. A comprehensive water recycling system must be incorporated into the habitat to maximise recovery of water and minimise the need to replace losses. Recycling will include traditional filtration, chemical dosing (where available) or reverse osmosis and other methods such as plant transpiration with post-treatment UV filters.

The water reticulation system will incorporate dual plumbing to collect and distribute potable and non-potable water (allowing waste potable water to be used for non-potable purposes, such as toilet flushing, prior to recycling). An allowance of 10 litres per day per person is considered to be the minimum requirement for life support, however, larger quantities would provide for psychological benefits and additional reserves. It is suggested that 100 litres per person per day be made available, equating to a reservoir of 10 mega-litres (10,000m³), assuming a ten day recycling cycle time, for a population of 10,000 people. Additional water reserves would be required based on specific industrial needs, depending upon the habitat's industry development, processes undertaken, etc. Water recycling will be essential to minimise system losses and reduce the energy used in obtaining replacement water. A 5% loss will be considered acceptable, requiring a resupply of 50 kilolitres per day, based on population of 10,000.

The habitat's oxygen can be supplied from the thermal decomposition of carbon dioxide (utilising waste heat from the nuclear generator) due to the abundant and easily accessible supply, or from the electrolysis of water (subject to the identification of an adequate supply). Following the initial generation of the atmosphere leakage, sequestration and other losses will require the ongoing regeneration of oxygen, and other atmospheric components. This can be undertaken using the same methods as those used to create the initial supply, as it is assumed that the gradual generation of the original supply will be acceptable as the habitat is likely to be progressively expanded to the design capacity. Further, the oxygen will require a reliable recycling system to convert carbon dioxide back into oxygen. Using the greenhouses for such recycling, with a back-up chemical regeneration system is a viable solution. As basic human life support requires 0.83kg of oxygen per day the recycling system must generate at least this 8.3 tonnes of oxygen per day. On the basis that basic human life support requires 1.22kg of food (dry weight plus water content) per day, and given that 0.72g of oxygen is typically





produced per gram of plant matter, the edible crop portion of plant matter produced in the green houses, for 10,000 people, will generate in the order of 8.8 tonnes of food per day. Given the waste portion of the crop it is evident that oxygen will be produced in excess of the life support needs and is also likely to compensate for any system losses.

A mix of nitrogen and argon will be used as buffer gas in the atmosphere due to the relative ease of extraction from the Martian atmosphere. There is no need to take the additional steps required to separate the two gasses as either, or both, are suitable for the purpose. Once the initial atmosphere has been generated the buffer gas will only need regeneration to compensate for system losses. This can be undertaken using molecular sieves.

The habitat and greenhouse pressure could be different to optimise crop growth, however, this will create complexities in transitioning between these two zones and, possibly, cause health or other access issues, depending upon the selected pressure differences. As such, it is proposed that the pressure in each area be equal to simplify transition between and provide shelters in case of decompression in some zones. This can be modified later based on operational preferences and crop optimisation requirements.

The removal of dust, from the local atmosphere used as a feedstock to any systems, will be necessary to prevent fouling or damage to equipment, and such removal must be incorporated into any system design.

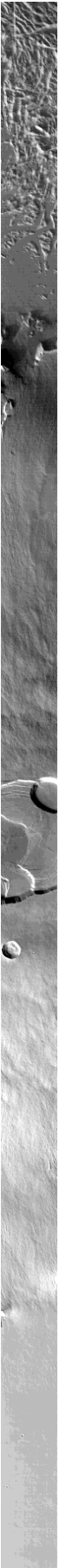
As previously discussed, greenhouse atmospheres will generally be physically separated from other habitat areas to assess and monitor their contribution to the life support system and allow their individual environmental conditions to be tailored to suit the particular crop. Greenhouse lighting will be designed to simulate the Earth's UV environment and illuminated with LED lights (for energy efficiency) to varying levels and wavelengths tailored to benefit the yield of the particular plant/crop. Greenhouse heating, as for the habitat in general, will be from waste heat generated from the nuclear reactor and the greenhouse will be insulated by a soil layer, also providing radiation protection. Greenhouses will be 'thin walled' with atmospheric pressure supporting the soil layer and shall occupy around half of each habitat module, spreading the production to prevent catastrophic loss in the event of the loss of several dedicated greenhouse modules. Plants, including crops, will be an integral part of the life support system for

food and oxygen generation and water purification. This will assist in the reduction of reliance on technologies and their associated consumables that may not be readily available locally. Crops will be grown in treated Martian soil (washed of salts, nutrients added, etc.) subject to further investigations or, where found to be impractical, will be hydroponically grown. Fast growing plants, like bamboo, will also be used to generate building materials and furniture. Some of the plant wastes can be used to produce papers, cloths, plastics, etc. The area allowed for in the habitat's living space calculations provides sufficient redundancy in food production and will allow for storage of reserve food.

In addition to crop growth in greenhouses, food within the habitat may include fish, honey (from bees that will also pollinate crops), chicken, pigs and goats, providing variety and contingency in the event of specie specific disease.

Methanol is proposed as the most suitable fuel for vehicles, remote power generation and for launches of space vehicles due to its ease of manufacture, compatibility with current technology and relatively simple storage requirements (methanol is liquid under ambient Martian conditions and so does not require energy intensive cryogenic equipment) and its versatility as an input into many industrial processes. Methane will be generated using the Sabatier process and convert to methanol.

The life support system still requires extensive investigation and experimentation prior to selecting a viable option, however, it will include bio-regenerative atmosphere regeneration, locally grown food and water purification, and local waste treatment. The system is expected to be similar to that proposed by Meyer & McKay in Figure 17 and Figure 18 and Nitta, Otsubo and Ashida, 2000 in Figure 20, requiring ongoing energy supply, but otherwise self sufficient using recycling and in-situ resources.



4. CONCLUSION

4.1. General

It has been demonstrated, through numerous measurements, observations and investigations, that Mars contains all of the essential elements for the maintenance of life and sustenance of an established habitat.

Virtually every region of Mars has been proposed as being suitable for locating a habitat, from the poles to the equator, above or below ground, each with its own advantages and disadvantages, and each being viable for various proposed designs. Regional characteristics, such as temperature, wind speed, dust storms and ground conditions must all be considered in any design. Particularly, a renewable supply of water is essential. Further, the method, and materials, of fabrication must be considered; utilising local materials, or imported; constructed or inflated; also considering things such as radiation protection, safety, living space, insulation, ease and speed of construction, and redundancy.

Facilities required in the habitat include all those necessary for living, recreation and working. Living facilities include life support systems, sleeping environments, meal preparation and ablution facilities and other such areas. Recreational facilities include lounge and reading areas, entertainment facilities and other such facilities to allow relaxation and diversional activities. Working facilities will include laboratories, office space, industrial areas (power generation, etc.), workshops, food and other production areas.

Power supply options on Mars are many, depending upon the power demand of the facilities, which varies with the population and industrial requirements. Nuclear is considered to be the most viable, due to the reliability and the power generation capability, however, this will require resupply of nuclear fuel, launched from Earth, and has environmental and safety considerations associated. Solar (surface or orbital), wind and possibly geothermal energy sources appear to be reliable and viable systems of power supply, although each has its drawbacks. Options for power storage must also be considered, including fuel cells or natural gas (such storage of power is through the manufacture of the fuel, hydrogen or methane, respectively). Emergency power

generation, through mechanical (human-powered) or other means, must also be provided.

All significant materials required to support life and industry are believed to exist on Mars. Processes for mining, extraction or concentration, as may be required, must be developed and proven, however, this is considered feasible. Renewable water and atmosphere constituent sources are considered critical, as are nutrients necessary for the production of food.

Life support is, of course, a critical consideration. Significant research has been undertaken in this field, both for earth orbit and planetary expeditions. Numerous full scale experiments of closed life support systems have been undertaken on Earth, all providing encouraging results. One vital aspect of any life support system is redundancy and compartmentalisation, such that any individual failure, or series of failures, does not disable the entire system. Ideally, any life support system on Mars should be a largely closed system such that the need to resupply/refresh resources is minimised. Contamination and toxicity control also warrant careful consideration.

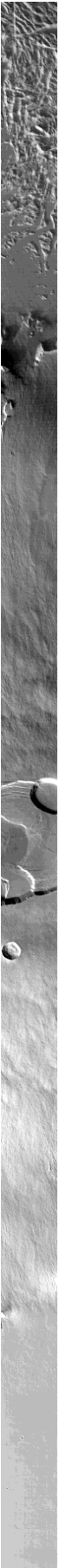
A total life support system must consider many aspects, including food and atmosphere generation and the health effects of partial gravity and possible radiation exposure.

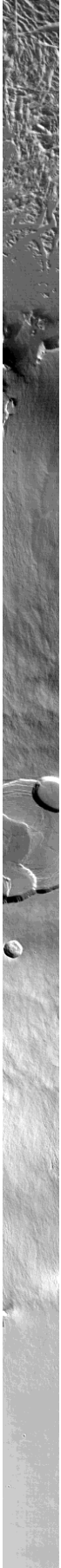
4.2. Further Research

There are many areas of research still to be undertaken before commencing the establishment of a habitat on Mars, many of which are discussed in this report. Ongoing missions to Mars will refine our knowledge of the mineralogy of the Martian crust, constituents of the atmosphere and specifics of the Martian environment in general. Earth based research will further develop and test materials, structures, systems and other aspects necessary for the establishment of a habitat on Mars.

Some of the key areas of further research required in the development of a Martian habitat, touched on in this report, included, but are not limited to:

- Detailed cost estimates for the set-up and operational costs of a Martian habitat.
- Identification of existing, or near-term, 'off the shelf' technologies suitable for incorporation into a Martian habitat to assist in minimising costs.





- Psychological investigation of astronauts, submariners and other appropriate groups to determine the acceptability of various habitat characteristics along the lines of those undertaken by Harrison, et al. (1991). Also, prediction of stresses, mitigation and effect on colonists.
- Effect of partial gravity on fluid flow should be studied on the International Space Station to confirm theoretical models due to its importance in any life support system and many industrial processes.
- Effect of partial gravity on the grain size and shape and porosity of cast metals, which will effect characteristics such as strength and durability.
- Biomedical research into the effects of partial gravity on bone density, muscle atrophy, immune system suppression and the nervous system. Partial gravity studies can be conducted on Earth using bed rest on tilt tables (Grymes, et al. 1995).
- Determination of health management system requirements for the habitat, including laboratory analysis, diagnostics, surgery, dental care, pharmaceuticals, nutrition and exercise.
- Research and development of soil bed reactors, for air purification, and soil nutrient cycles, for crop growth, specifically in regard to their suitability to a closed system.
- Determination of the salinity, alkalinity and detailed composition of various samples of the Martian regolith to determine their initial suitability as a crop growth medium and any processing that may be required to improve its suitability.
- Research into identifying the most suitable (or 'pre-adapted') plants for use in Martian greenhouses, including those that may tolerate higher than normal UV-B and UV-C doses and harsh soil conditions to use as initial crops in a bio-regenerative life support system on Mars.
- Determine the optimum atmospheric composition and pressure, light intensities, radiation environment and photo-periods, and temperatures to optimise the

productivity of crops in a bio-regenerative life support system on Mars and to best benefit the colonists within the habitation areas.

- Determination of suitable artificial lighting methods for use in food production, to accommodate the possibility of indoor growth, extended night periods at high latitudes and natural light supplementation.
- Nutritional requirements of humans when on Mars and how it differs from the requirements of Earth.
- Continued experimentation on closed ecosystems, similar to Biosphere 2 and several other current life support studies, to more accurately define the input requirements and extent of in-situ resource utilisation.
- Analysis of the integration of various life support, and other, systems.
- Development of the habitat rating system proposed by Drake, et al. (1992).

