Designing for Har Decher,

ideas for Martian bases in the 20th century

Most new ideas go through three stages. First, critics say they are totally impossible. Next, they admit that it might be done with great effort and prohibitive cost. Last, they say they knew it was a good idea all the time.

Arthur C. Clarke

Foreword

To go to Mars and settle a new planet could be one of the greatest non-military achievements humanity may ever accomplish. This view is often associated with science fiction, nonetheless a large number of people in the aerospace industry have been contemplating this possibility since the early decades of the twentieth century. The early concepts where not very concrete and were more reminiscent of H.G. Wells then of Wernher von Braun, yet they persisted and towards the end of the century the plans to go to Mars were becoming more solid as more information was gathered via telescopes and satellites. The Viking 1 and Viking 2 landers obtained even more information and in the closing decade of the last century more was known about Mars then was known about the Moon in the 1960's. No real attempt to travel to Mars however was made prior or since the Apollo mission to the moon.
So far theoretical bases are the only bases that have stood on the surface of Mars.

This paper primarily deals with the possibilities and problems aerospace scientists, designers, architects and others encountered during the *latter* part of the twentieth century when designing and planning a Martian base for the near future.

The first part of this paper is intended to show the history of man's fascination with Mars and the discoveries that have been made. It also explains the differences between the Earth and Mars. Finally a parallel is drawn with certain situations on Earth.

The second part deals with the Martian environment and the complications that this incurs on the design of a base. Possible locations for a Martian base are described and assessed. Transportation of crew and materials to and on the planet is explained.

The third part deals with the different structures and materials that have been developed for Martian bases, and details a number of semi-permanent and permanent bases.

I would like to thank Billy Lee from Horden Cherry Lee Architects, Andreas Vogler from the Technical University München and Marc Cohen from NASA-Ames Research Centre for all their information.

Thomas Dubbink, 2001

Notes

In this paper the word habitat and base are used with distinct differences:

- *Habitat* describes the core area of the base where the crew lives and works without the need for space suits.
- *Base* describes the whole of the area covered by the different facilities including but not limited to; the habitat, energy plants, storage and resource plants (oxygen). In some cases the base is so small or limited that the word base is substituted for habitat.

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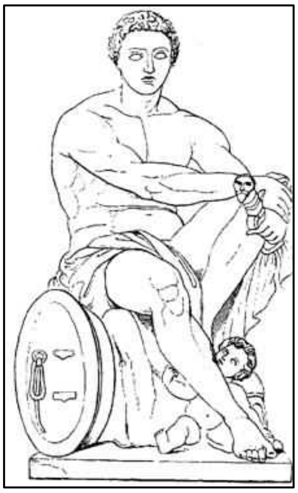
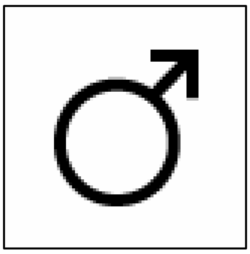
Mars, originally the god of agriculture, later the god of War. Depicted here (as the Greek god Ares) on his chariot holding his spear.
[www.exploringmars.com]



“There were few sculptures of the unpopular Ares. Most representations of him are found in vase paintings. Depictions of him ranged from a bearded and heavily armoured warrior in earlier times to later appearances as young and nude except for a helmet and spear, indicative of a softening of his character in Greek religion.”
[Thomas Gangale]



The male symbol is thought to have originated from the god Mars; the spear and shield he was customary depicted with.
[www.exploringmars.com]

[1.0] The shared history of Man and Mars

'To set foot on the soil of the asteroids, to lift by hand a rock from the Moon, to observe Mars from a distance of several tens of kilometres, to land on its satellite or even on its surface, what can be more fantastic? From the moment of using rocket devices a new great era will begin in astronomy: the epoch of the more intensive study of the firmament'

Konstantin E. Tsiolkovsky, Father of Russian Astronautics, 1896

[1.1] Ancient Times

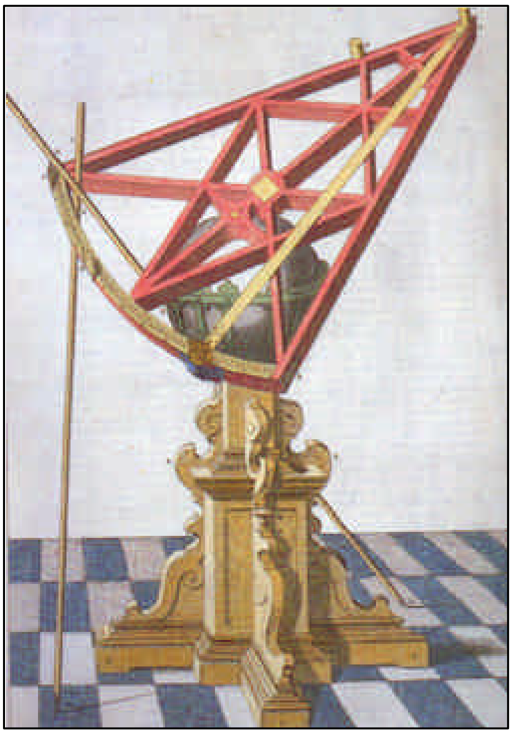
The planet Mars was probably first seen by man in prehistoric times and by his evolutionary predecessors before him. It appeared at night as a fiery red ball that followed a strange irregular loop in the sky. Mars was at times[1] the third largest object in the heavens (the moon and Venus being larger).
The planet was documented by the early civilizations of the Egyptians, Chinese, Assyrians and the Babylonians. Because of it's red colour it was often associated with strife and war.

The Egyptians, who observed it's retrograde[2] movement, called it *Sekded-ef em khetkhet* (meaning one who travels backward), it was also named *Har Decher*; the Red One. Later in Babylonia the planet was named Nergal; the great hero, the king of conflicts.

The Greeks named the planet after the god Ares[3] who was the son of Jupiter (Jove, Zeus) and Juno (Hera) but he was little worshipped by the Greeks.
"*The origin of the name is uncertain. Possibly, along with Mars, it is connected with the Sanskrit mar and the Vedic maruts, meaning "storm divinities", or the Greek root meaning, "to carry away". The Spartans called him Ares Enyalios (the warlike), while in Olympia he was known as Ares Hippios, god of horses."*[4]
His horses are said by some to have been called Deimos en Phobos. In Greek mythology he is seen as little more than a symbol of war. Ares is despised by the Greeks and seen as a coward. On a more scientific note they were also the first to position the planet exactly, Ptolemy described the position of Ares (Mars) on January 17th 272 years BC.

The Romans who adopted large parts of the Greek pantheon substituted the Roman name Mars for the Greek god Ares. Originally Mars had been the god of agriculture, later he became the god of war:
"Mars…was the god of war, the personification of the angry clouded sky, and, although but little worshipped in Greece, was one of the principal Roman divinities. He is said to have first seen the light in Thrace, a country noted for its fierce storms and war loving people."[5]

[1] Mars follows an elliptic orbit and therefore sometimes appears closer than at other times.
[2] Mars seems to move backwards sometimes, because of the difference between the orbits of Earth and Mars.
[3] The study of the Martian surface is called *areo*graphy.
[4] By Thomas Gangale
[5] Greece and Rome by H.A. Guerber, 1907, reprinted 1996



Tycho Brahe used huge sextants to map the stars using only the naked eye.
[Science Photo Library]

Nicolaus Copernicus
[Hulton Getty]

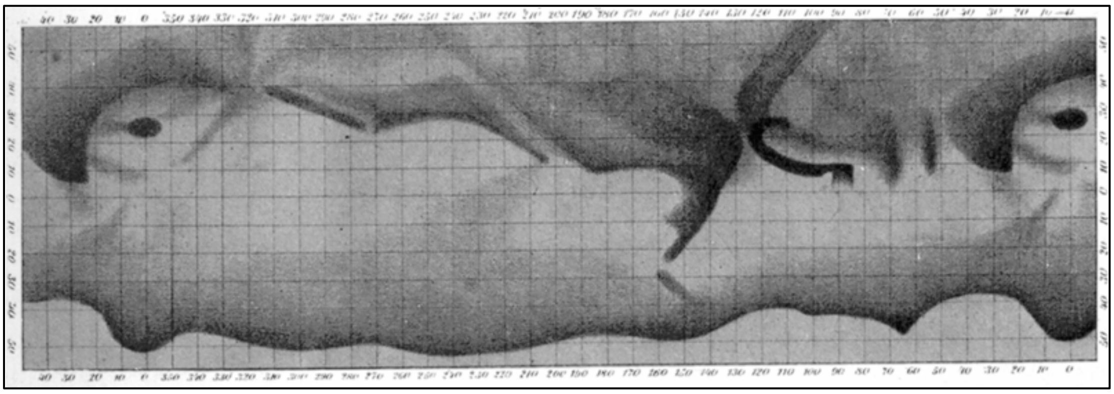
Mars became the protector of the city of Rome after it's founding by Romulus and Remus and the subsequent murder of Remus by his brother. The shield *Ancile* was dropped from heaven to protect the citizens of Rome; for as long as the shield was with them it would keep the city save. Mars' shield and spear are used in modern times as the male symbol.
The children of Mars were called Eris (Discord), Phobos (Alarm), Metus (Fear), Deimos (Dread) and Pallor (Terror).

[1.2] Renaissance and astronomy

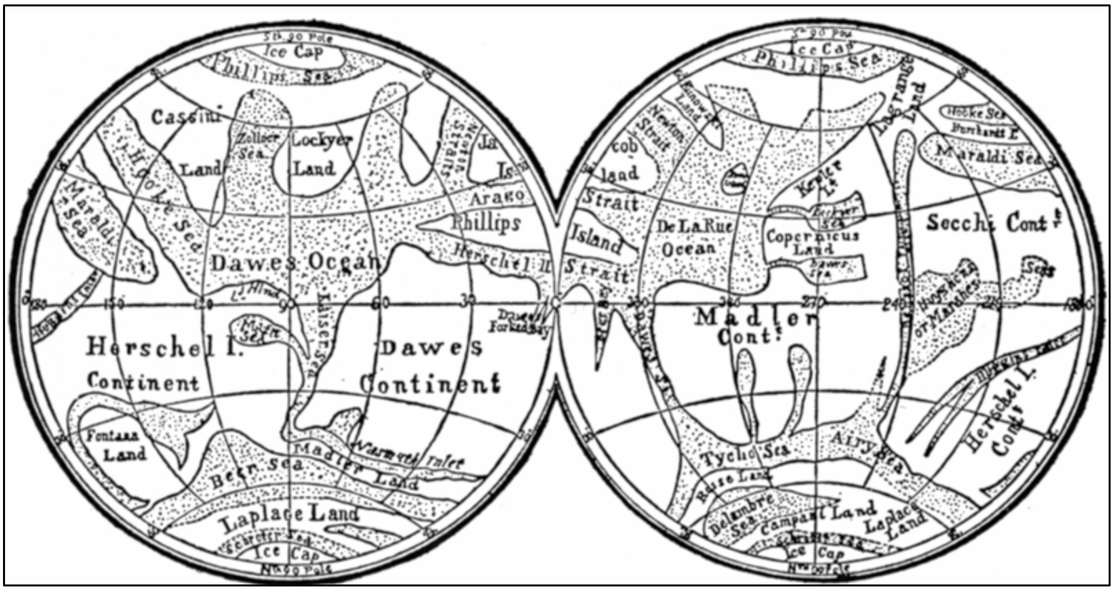
Astronomy made no major advances for a long time until the 1500's, when the heavens regained scientific interest from some of the most gifted astronomers in history. In 1543 *De Revolutionibus Orbium Coelestium* was published in the year of the author's death, it had been written by the great Polish astronomer Nicolaus Copernicus. The book described a new theory whereby not the earth but the sun was at the centre of the universe. This so-called heliocentric theory was unfortunately not widely accepted for another century. In 1576 Tycho Brahe adopted a slightly different version of the heliocentric theory and was also the first to accurately chart the path of Mars using the naked eye. The heliocentric theory was also adopted by Brahe's assistant; Johannes Kepler.

Kepler discovered the three laws of planetary motion, the first two were published in 1609 and the third was published in 1619. Kepler's first law stated that the planets orbited the sun in an elliptical path (which the observation of Mars proved) rather than a circular path that had been assumed up to that time. Mars was significant insofar as that the first two laws could only be proven in the case for Mars at the time. All other planets seemed to roughly follow Kepler's first two laws but not enough information could be gained from these movements to prove his planetary motion laws. A new device that had only recently been invented would soon be able to prove Kepler's laws for other planets too.

A Dutchman named Lippershey introduced the telescope to the world in 1608; this invention would change the world of astronomy forever. The famous Galileo Galilei soon afterwards used a telescope to observe the surface of Mars in 1610, however the telescope was too small (and impure) to be able to detect any features. In 1659 Christiaan Huygens became the first person to detect features on the Martian surface; the *Syrtis Major Planum*. Which is a dark region on Mars covering a 1.000.000 km², (these dark spots are called *albedo* spots meaning whiteness). More information was to be discovered about Mars in the following years. The rotation time of Mars was discovered seven years later in 1666 by Giovanni Cassini. The rotation time of 24h 40m was only two minutes and 38 seconds out of kilt with the actual time measured in the 20th century. Cassini was also the first to discover the poles on Mars (ea the rotation axis).
Huygens who had also seen the Antarctic of Mars in 1672, dies in 1695 and his book *Cosmotheoros* is published in 1698 three years after his death wherein the possibilities of extraterrestrial life on other planets is discussed.



Frederik Kaiser's Mars chart, created in Leiden (the Netherlands) between 1862 and 1864
[Het Mars Avontuur,1979 by Dr. A. J. M. Wanders]



Richard Proctor published this map in 1871, on which he supplied names (of astronomers) to all the known geographical features.
[Het Mars Avontuur,1979 by Dr. A. J. M. Wanders]

"Huygens deduces that though Mars will be colder than Earth, because it is further from the Sun, life there will have adapted. He also discusses what is required for a planet to be capable of supporting life and speculates about intelligent extraterrestrials."[6]

White spots are discovered on the poles in 1704 by Giacomo Filippo Maraldi, he was not sure as to whether they consist of ice or something altogether different. He discovered that these white spots did not correspond to the axis-poles, about fifteen years later in 1719 he would conclude that these poles where possibly made of ice. Maraldi also noted that the southern pole was only visible from October to July, disappearing in the months of August and September. In the summer months the Antarctic was so small as to be invisible to Maraldi (it actually shrinks to a 10th of it's size).

In 1784 William Herschel published *The Philosophical Transactions* where he also advocated Martian poles as being made from ice. Herschel thought that the dark patches on Mars were oceans because they shifted according to the decline and growth of the poles. Herschel also noted the similarity between Mars and Earth:

"The analogy between Mars and the earth is, perhaps, by far the greatest in the whole solar system. The diurnal motion is nearly the same; the obliquity of their respective ecliptics, on which the seasons depend, not very different; of all the superior planets the distance of Mars from the sun is by far the nearest alike to that of the earth: nor will the length of the martial year appear very different from that which we enjoy"[7]

It must be stated that Herschel thought Mars to be inhabited by intelligent beings and that his views of Mars were wildly optimistic. He did however discover that Mars had a thin 'onionskin' atmosphere and was even able to deduce that the pressure on Mars was vastly lower than on Earth.

[1.3] The industrial age and deception

In the 19th century a man by the name of Honeré Flaugergues discovered white/yellow clouds in the Martian atmosphere. His discovery in 1811 would later turn out to be dust clouds, which are raised during large dust storms that can engulf the entire planet for months. In 1819 Flaugergues noticed that the polar caps of Mars shrunk during spring and that the rate of decline was much faster than on Earth, he thought therefore that Mars was hotter than Earth. (Actually the average ground temperature is 15ºC for Earth and –23ºC for Mars)

A new time is set for the rotation of Mars at 24h 37m and 22.6s, this time is only a second out with the present recorded time of 24h 37m and 22.7s! The two scientists who accomplish this feat are Wilhelm Beer and Johann von Maedler. Frederik Kaiser brings the rotation time of Mars even closer a couple of years later.

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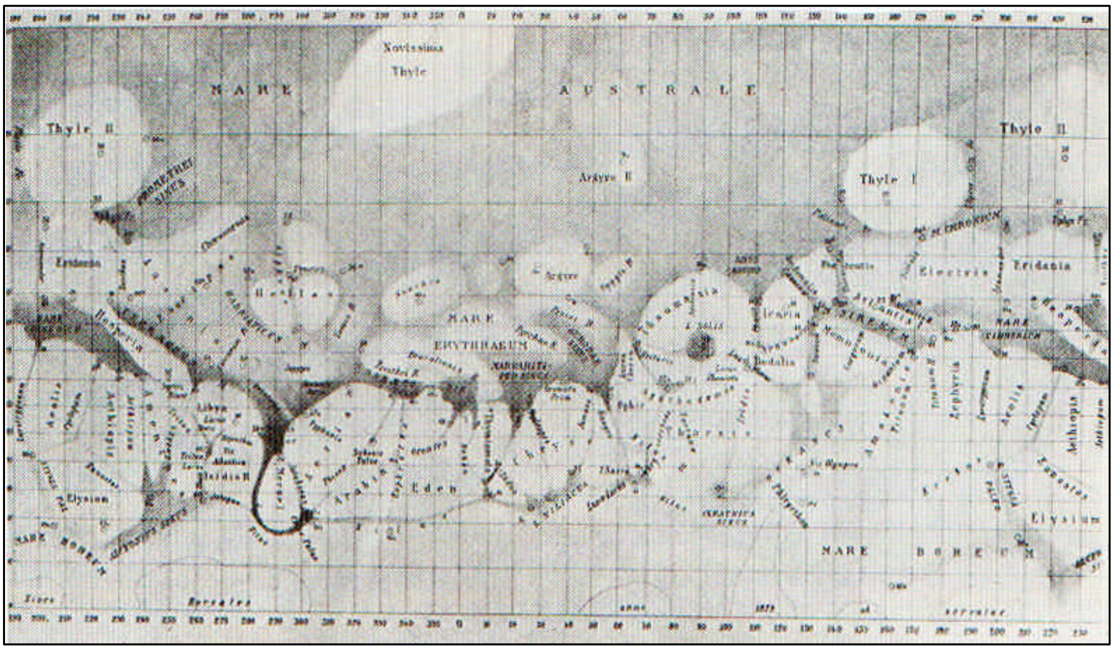
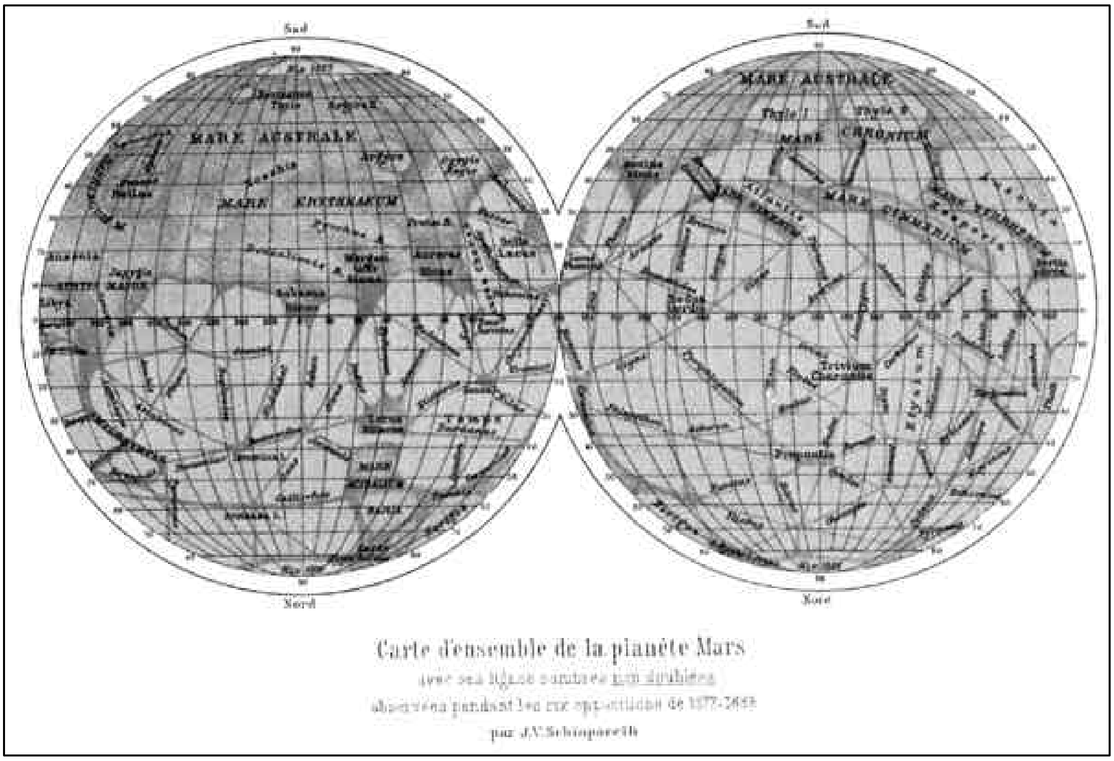
[6] www.humbabe.arc.nasa.gov/mgcm/fun/mars_chro.html

[7] From *The Philosophical Transactions* by William Herschel



Schiaparelli's map of Mars published in 1879
[Het Mars avontuur]



Schiaparelli's second map of Mars published in 1888, including observations between 1877 and 1888.
[Het Mars avontuur]

In 1859 the construction of the Suez canal is started, this engineering marvel will influence the future of Mars by inspiring people to see canals that were not really there.

A map is produced containing continents and oceans in 1867 by Richard Anthony Proctor after a Jesuit monk, by the name of Pietro Angelo Secchi, has named the dark area of *Syrtis Major*: *the Atlantic Canal* a few years earlier. This map by Proctor contains a meridian that is still used today as the Martian meridian. His allocation of astronomer's names to geographical features however was not received with much enthusiasm. It did however inspire others to do the same, with different names. The region of *Tharsis* had at one time four different names, which made it very difficult to discuss the geographical features of Mars.

Giovanni Virginio Schiaparelli put an end to all the different names on the maps of Mars by developing a new set of names. Schiaparelli named all the geographical features on Mars using the ancient Greek nomenclature for countries, seas, oceans and other features found in the ancient Greek world, he also added names from mythology. Illustrious names as *Valles Marineris*, *Syrtis Major* and *Hellas Planitia* would forever adorn Mars.

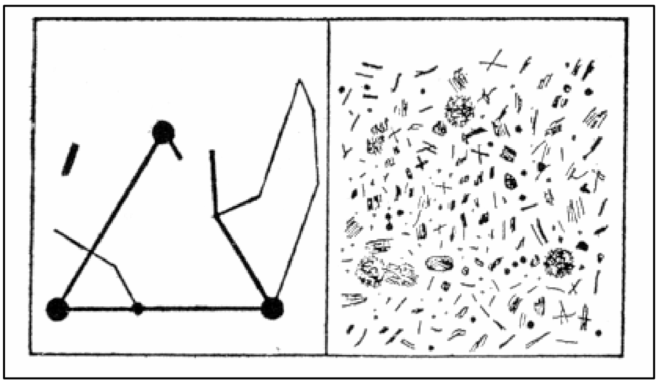
Schiaparelli had graduated at the age of nineteen as a civil engineer at the university of Turin, and became the director of the new Milanese observatory only a few years later. In 1877 Mars came into it's perihelic opposition[8] and Schiaparelli was able to see Mars very clearly, he was also the first to use a more precise method to map Mars that was derived from watching stars. During his observation he noted dark regions *'straights'* surrounding lighter areas *'islands'*, he termed these straights; *canali* (the Italian word for straights). These *canali* were translated into the English language as canals, hereby giving rise to the thought that intelligent life exists on Mars! The *New York Times* even speculates on the possibility of life on Mars. The *canali* that have been reported by Schiaparelli are later also seen by him as being actual canals, his maps in the following years show narrow straight lines on the surface of Mars (see maps). In the same year Edward Emerson Barnard notes the complete absence of these canals!

1877 is also the year that the two moons of Mars are discovered by Asaph Hall who names them; *Phobos*[9] (fear) and *Deimos* (flight)[10]; Henry Madan, the Science Master of Eton, had suggested these names to him. Speculations about moons orbiting Mars had been around for a long time: The famed writer Jonathan Swift, author of *Gulliver's Travels* (1727) had suggested in his book that Mars had two moons, Voltaire had suggested the same thing in his book *Micromégas* (1750).

[8] In it's perihelic position Mars is at it's closest position to Earth.

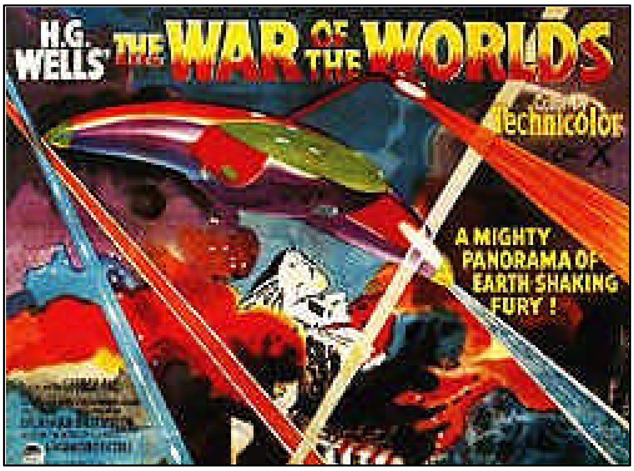
[9] Phobos is about 30km at it's widest point, orbits Mars every 7½ hours and is roughly 9.000km from Mars. (It's orbit is so close to Mars that it will be pulled into the Martian surface in a billion years)

[10] Deimos the smaller of the two is only about 10km diameter (although irregular formed 11kmx12kmx15km) orbits Mars every 30 hours and is roughly 24,000km from Mars.



J. Comas Solá thought that the canals seen by some astronomers were optical illusions. To check his theory he drew part of the Martian surface and added a number of random objects. To his surprise this map, when projected through a small screen looked very similar to a canal and oasis system. (See the picture above; both look similar from a distance of ten meters.)

[Pickering, Mars]



H.G. Wells' *The War of the Worlds* first appeared in 1897 and was published in hardback in 1898. A dramatized radio version by Orson Wells was aired in 1938. In 1953 a film adaptation was created.

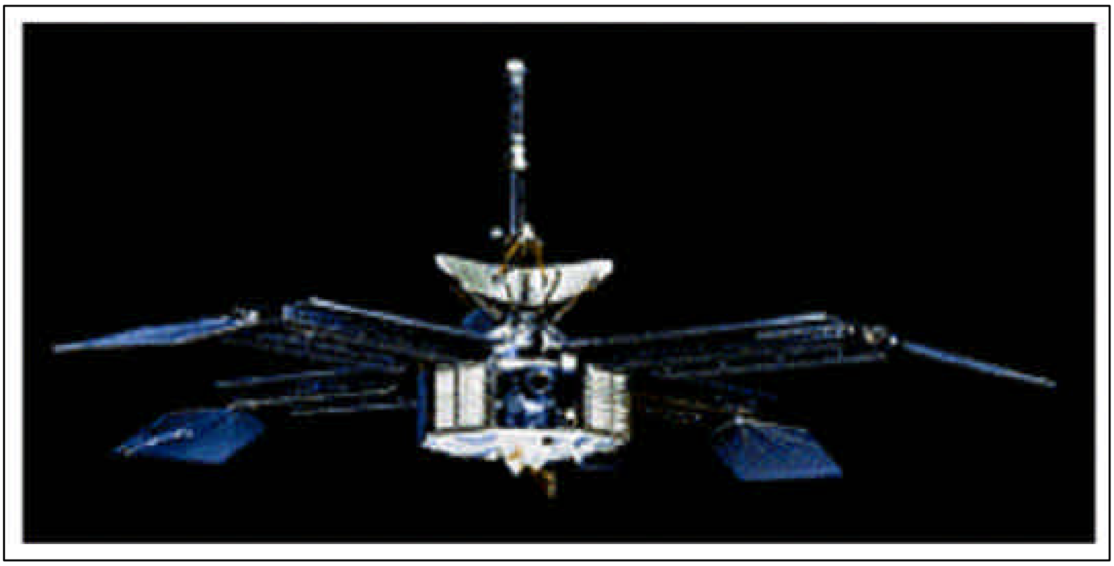
The canals that had been seen by Schiaparelli appeared to have doubled in some cases! This phenomenon, first seen in 1879, was called *gemination* other observers also noted this occurrence. In 1894 Percival Lowell, who was interested in Schiaparelli's work, started observing the sky at Flagstaff, Arizona. Lowell published his work *Mars and its Canals* a year later, in this book he deals with the surface features found on Mars such as canals and oases[11], which seem to indicate intelligent life. A couple of years later in 1897 *the War of the Worlds* by H.G. Wells is published, setting a trend for Martian fiction.
In the beginning of the twentieth century intelligent life on Mars seems to be an obvious certainty to most people. So much so that in 1900 a prize was awarded to the first person to make contact with another worlds, Mars was excluded however as that would make the competition to easy! Various articles in papers around the world discuss the possibility of (intelligent) life and in 1908 Lowell publishes *Mars as the Abode of Life* wherein he defends his theories on intelligent life on Mars.

New and larger telescopes were appearing in observatories and the Martian canals somehow disappeared from the observations. Only the smaller telescopes seemed to pick up the canals, this indicated to many people that the canals were optical illusions.

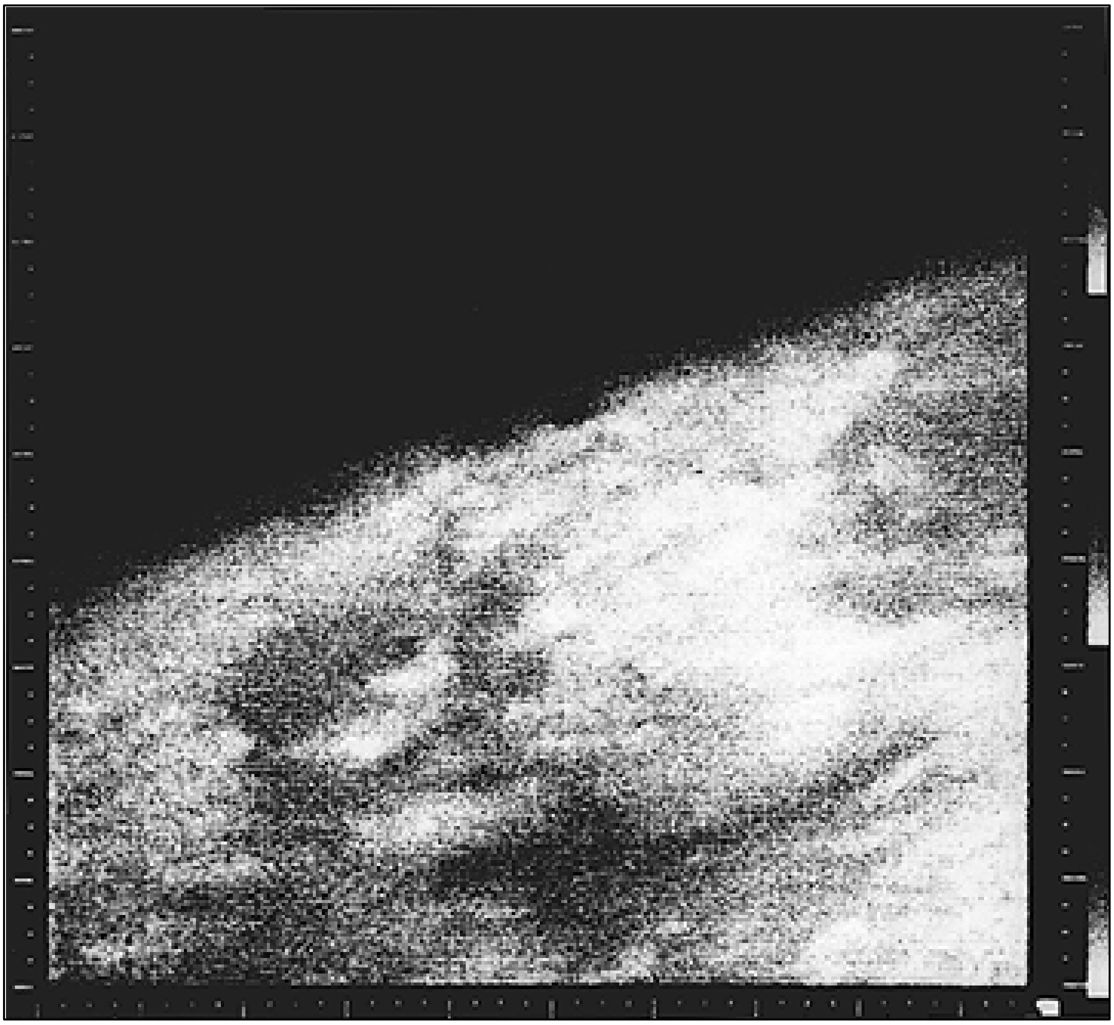
In 1909, a meteorite strikes the Earth[12], later it is identified as a *SNCmeteorite*[13] of which only 16 have been found to date (the most famous now being ALH84001, in which scientist (may) have found life).
New novels appear in 1911 about Mars; *A Princess of Mars* by Edgar Rice Burroughs spawning ten sequels that interestingly is the first book in which the Martians have a green skin.

During the First World War nothing much is undertaken about Mars, with our own world at war the interests in other worlds takes a back seat. The first new impulse towards Mars may be seen as *Holst's the Planets*, whereby the ancient element of Mars returns, for the part of Mars is titled: *Mars, the Bringer of War*. On a more scientific note the impact of asteroids and meteorites on the surface of Mars is accurately estimated in 1922 by Estonian astronomer, Ernest Julius Opik and a couple of years later the Martian atmosphere is measured as having a pressure as low as 26 millibars[14]. This research is the first to show that the Martian atmosphere has a drastically lower pressure than Earth. In 1926 Walter Adams concludes that Mars has very little water vapour in the atmosphere. The thin atmosphere found by Opik is reinforced by measurements made by William Coblentz and Carl Lampland at Flagstaff in 1927, they also put the average temperature between 15ºC and 30ºC[15]. The high temperature, which they had estimated as being roughly

[11] Large dot-like features which are found at canal intersections
[12] It actually strikes a dog first, the only known casualty by a meteorite.
[13] SNC meteorites are fragments from Mars they were called SNC because of the places they had been found on Earth (Shergotty-Nakhla-Chassigny). Because they have also been found in other areas they are now called *Martian Meteorites*.
[14] The actual pressure is 6 millibars, compared to Earth with 1013 millibars
[15] This is the temperature at the equator, the actual **ground** temperature at the equator is



Mariner 4, sends back the first pictures from Mars
[NASA]



First close-up pictures sent back from Mars by the Mariner 4.
[NASA]

± –35°C the atmosphere temperature is -70°C

similar to Earth gave rise to the thought that life existed on Mars, this thought lasts until the first space explorations to Mars.
In 1930 *La Planète Mars, 1659-1929* is published by Eugenios M. Antoniadi, this work about the surface of Mars includes many detailed maps, it's maps remained some of the most accurate for more than twenty years. In the same year all tests to find oxygen on Mars fail. The radio version of *War of the Worlds* by H.G. Wells, despite continuous announcements about it's fictional nature, causes massive panic in the United States were more than six million people listened to it's broadcast.

In 1947 the Dutch astronomer Gerard Peter Kuiper measured the amount of carbon dioxide on Mars to be more than two times the amount than the carbon dioxide levels on Earth. Years later (1964) he would discover even larger quantities and it would become apparent that carbon dioxide is the predominant atmospheric gas. The new observations and measurements made in the previous years are starting to make the possibility of life a lot less probable, the only form of life that is still thought to exist are lichens.

[1.4] Telescopes no more

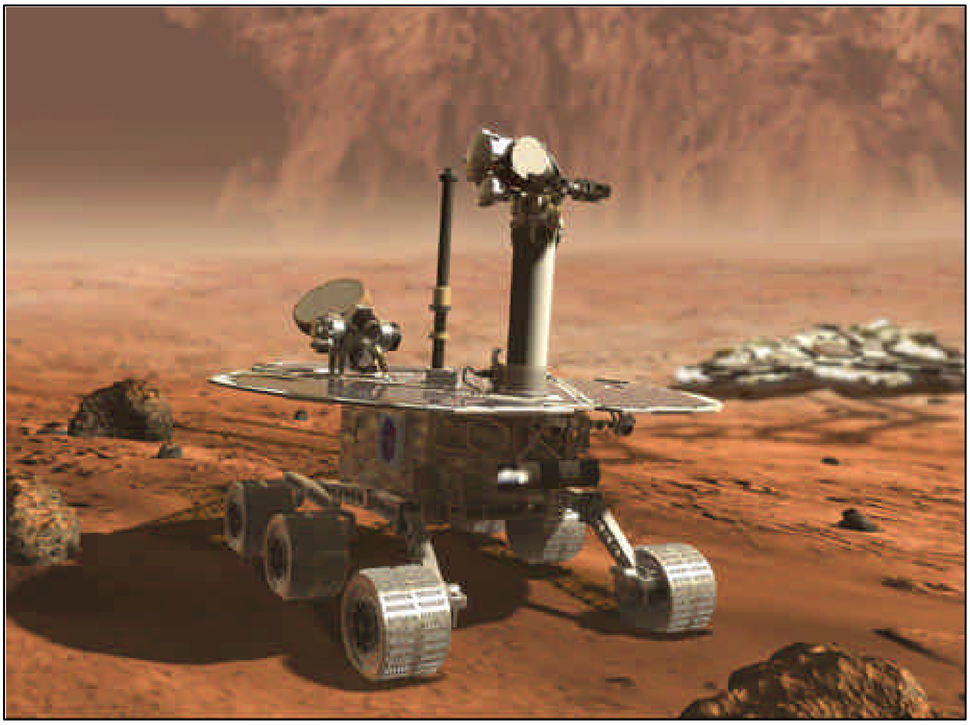
The eminent Wernher von Braun publishes his *"Das Mars Projekt"* in the magazine Weltraumfahrt in 1952 and this is later published as a book a year later. This project proposes the creation of *"ten space vessels manned by not less than 70 men."* When asked in 1962 how far away the realization of the project is he replies that he thinks it will be possible to get the project up and running in fifteen to twenty years. This huge scale project never matures beyond the strictly theoretical.

In 1957 the USSR launches the sputnik making it the first object to leave Earth's atmosphere. The space age has now made it's official start; in the coming years it will deliver a multitude of probes and satellites to observe Mars from a distance and from close, touchingly close.

In total more than 23 missions will be flown between 1962 and 2000, for the most part only the USSR and the US are able to afford the huge costs of building and launching space missions. The missions that are sent to Mars are listed below:

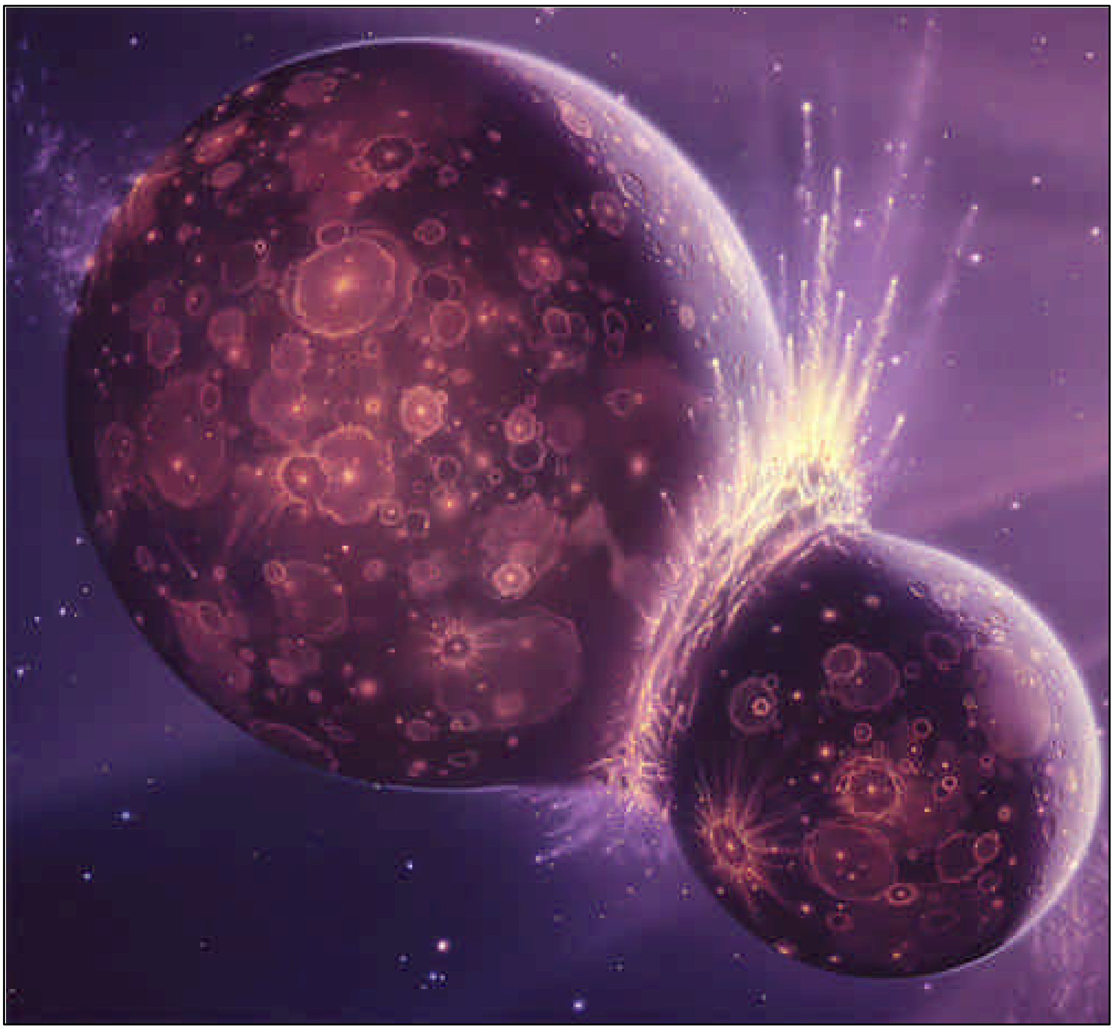
Mars 1 (USSR) is launched in 1962 by the USSR, as an imaging mission but fails, contact is lost with the probe at 106 million km. The earlier Sputniks 29, 30 and 31 also fail to reach Mars.
Mariner 3 (US) is launched in 1964 by the US; it is lost as it orbits around the sun.
Mariner 4 (US) is launched in 1964 by the US; it is the first probe to send back images (21) from Mars at an altitude of 10.000 km.
Zond 2 (USSR) is launched in 1964 by USSR, contact is lost a year later on it's approach to Mars
Mariner 6 (US) is launched in 1969 by the US; it passes the planet over the equator at a height of 3.390km and sends back 76 pictures of the Martian surface.
Mariner 7 (US) is launched a couple of months later, it passes over the southern hemisphere at an altitude of 3.500km it sends back 126 photographs

Mars, as seen by the *Mars Global Surveyor* .
[NASA]



Mars Sojourner, which was delivered by the Mars Pathfinder module.
[NASA]

Mariner 8 (US) is launched in 1971 but it is an abject failure as it crashes into the Atlantic Ocean after the launch.
Mars 2 (USSR) is launched in the same year as Mariner 8 and arrives on Mars in the same year, the orbiter successfully orbits around Mars, the lander becomes the first man made object to reach the surface of Mars albeit at such high speeds that it is destroyed on impact.
Mars 3 (USSR) is subsequently launched in 1971 the orbiter also successfully orbits around Mars and the lander makes a successful landing but contact is lost with the lander after 20 seconds.
Mariner 9 (US) is launched in 1971; it orbits around Mars for nearly a year sending back over 7.300 photographs. Contact is lost in 1972.
Mars 4 (USSR) is launched in 1973 but overshoots the orbit curve of Mars and is lost.
Mars 5 (USSR) is launched in the same year and successfully orbits around Mars and sends back pictures for ten minutes before losing contact.
Mars 6 (USSR) also launched in 1973 and successfully lands on the planet, however no communication is received after touchdown.
Mars 7 (USSR) is the last launch in 1973 but it also overshoots the orbit curve of Mars.
Viking 1 (US) is launched in 1975 and it successfully lands in 1976 on the surface. (Chryse) The lander does sample research and sends back colour photograph images to Earth, the Viking missions can be considered as the most accomplished missions to Mars ever.
Viking 2 (US) is launched a month later; it also lands on Mars (Utopia) and does the same research as the first lander. Neither landers find conclusive evidence for life. The amount of information that both Vikings send back is enormous and is still being used today.
Phobos 2 (USSR) is launched in 1988; it photographs Phobos but disappears shortly afterwards.
Mars Observer (US) is launched in 1992, and is supposed to orbit Mars and map the planet, but is lost before it reaches the planet.
Mars 96 (Russia / EU containing EU instruments) fails at launch, the instruments are redesigned and will be used for the most part in the Mars Express mission 2003.
Mars Global Surveyor (US) is launched in 1996, it orbits around Mars mapping the planet, it covers the entire planet every twelve days. The Mars Global Surveyor sends back an enormous amount of data and photographs, reviving interest in the planet around the world.
Mars Pathfinder and Sojourner (US) are launched in 1996 and land the following year. Pathfinder lands successfully and deploys the Sojourner rover, Sojourner is remotely controlled from Earth. Via broadcasting and the Internet it is possible to see the live images from Mars around the world.
Nozomi Orbiter (JP) is launched in 1998; it researches the atmosphere of Mars.
Mars Climate Orbiter (US) is launched in 1998; it burns up as it enters the Martian atmosphere. A navigational error is blamed for its demise.
Mars Polar Lander and Deep Space 2 (US) are launched in 1999, both loose contact with Earth.



Collision between two proto-planets
[www.space.com, Joe Tucclarone]

[2.0] What is Mars?

'No celestial body has generated more heat and less light than Mars. Its most important and tantalizing secret—life—is the subject of surprisingly bitter controversy.'

Gilbert Levin President and CEO of Biospherics Incorporated, 1999

[2.1] Origin and composition of Mars

Mars and all the other planets (and the sun) in our Solar System were created from a cosmic gas cloud that contracted under it's own gravitational pull. A huge flat disk was created by this gravitational pull whose centre was occupied by what is now the Sun. The remaining nebula cooled slowly whereby more and more minerals started to solidify turning the spinning gas cloud into a wheel of debris. Over the aeons this debris conglomerated into proto-planets which exerted even more gravitational pull collecting even more debris (accretion) which resulted in the nine planets we know of today. For millions of years large impacts would continue to occur, until all the large debris had been accreted.

The Martian landscape can be divided in three major landscapes; cratered ground, volcanic provinces of Tharsis and Elysium and the lowland plains. The highlands are the oldest parts and are found in the south, they date back to a time when the planet was being hit by large debris parts. The younger lowlands are found in the north. The origin of the lowlands is unclear, but the orientation of massive flood features indicates that huge amounts of water were released into the northern lowlands. Some researches have even suggested that seas once covered the northern part of the planet. [16]

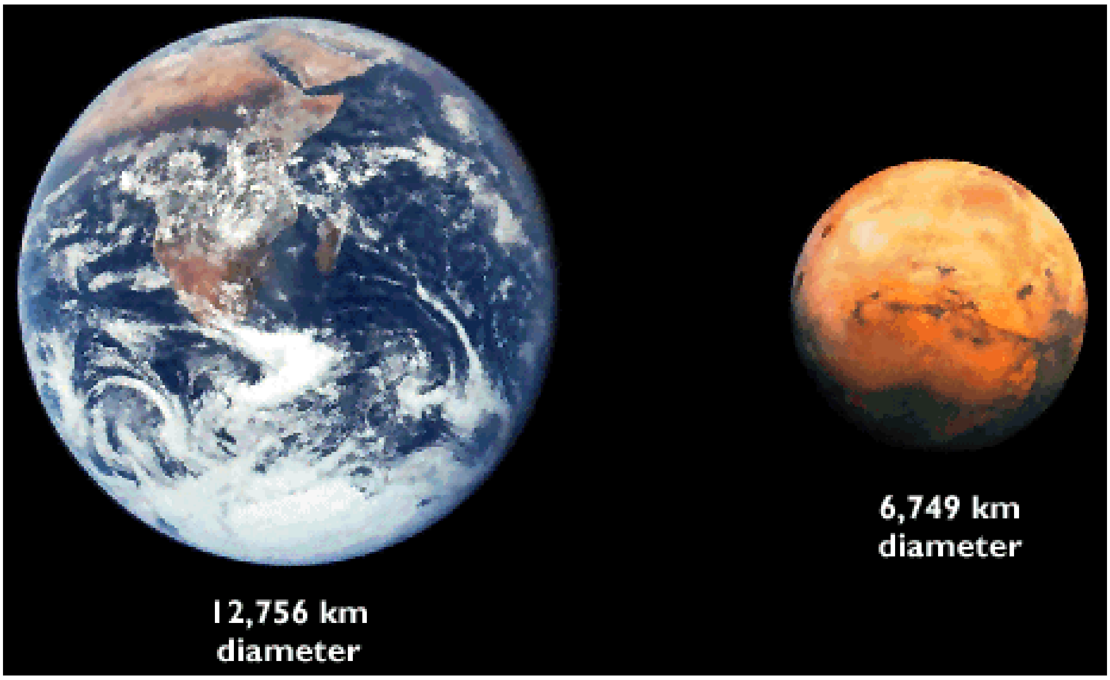
The planet has some of the most extreme topological features; including the largest volcano in our Solar System which is more than 21 km high. Mars, like the Earth, has two polar icecaps. The southern polar cap consists mainly of carbon dioxide, the northern polar cap consists of water ice.

The planet is covered with rocks, soil and drift material. Whereby rocks are made up of amassed mineral matter, the soil or regolith is mainly loose broken up material found on the surface and the drift material can be categorised as fine-grained windblown material. The Viking and Pathfinder missions indicate that these sites have ten percent of their surfaces covered with rocks. The composition of the ground is mainly made up of SiO_2, FeO, Fe_2O_3, Al_2O_3, MgO, CaO, Na_2O, K_2O and TiO_2. The atmosphere is mostly composed of CO_2 (carbon dioxide)

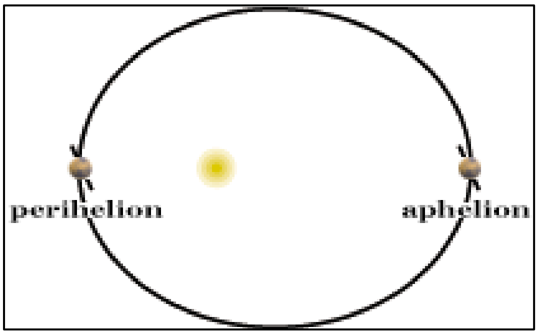
[2.2] Mars / Earth comparison [17]

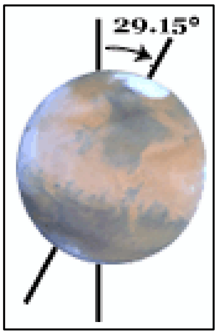
We relate everything to our own environment, to understand a different environment it is therefore useful to make a comparison with our own world

[16] From Human Spaceflight, Mission Analysis and Design
[17] See supplement [s.1] for more extensive information



The Earth and Mars
[NASA]





"The orbit of Mars is not quite circular, it is slightly elliptical. The sun is not in the center of this ellipse, but is offset to one side. As a result, there is one point in Mars' orbit where it is closest to the sun (called perihelion) and one point where it is farthest (called aphelion).

Mars has seasons because its axis is tilted (just like Earth's), 29.15° to be exact. Mars is at perihelion during the southern summer, making it slightly more intense than the northern summer"

[www.ex ploringmars.com]

when talking about Mars. In this way we can get a feeling for the differences that are imposed by a radical new setting.
Mars is the fourth planet from the sun; at times it is now the fourth brightest object in Earth's night sky (Venus, the Moon and the I.S.S.[18] are brighter). It is located one and a half times further away from the Sun than Earth. Like Earth it has satellites surrounding it; where the Earth only has one moon, Mars has two; Phobos and Demios. Mars also has an axial tilt resembling that of Earth and a rotation time which is similar to Earth's. So Mars has a day/night cycle and a seasonal cycle, however it's orbital period around the sun is more than twice that of Earth (687 days). Mars is much smaller however than Earth, it is ten times smaller in volume and has a surface that is three times as small. With gravity that is a third of that on Earth, no substantial magnetic field and no liquid water. However as planets they are very alike, the origin of the planets is the same and this explains a lot of their similarities. The biggest difference is that no life has been found on the Martian world so far.

Planetary mass:
The planetary mass of Mars is $0.642 \cdot 10^{24}$ *kg*, which is roughly ten times less than that of the Earth, which has a mass of $5.97 \cdot 10^{24}$ *kg*. This means that the planet cannot retain an atmosphere as easily as Earth, because the escape velocity for some atoms is low enough to allow them to escape into space. The escape velocity on Mars is *5.0km/s* on Earth it is *11.2km/s*

Planet size:
The diameter of Mars is *6794km* compared to the diameter of Earth, which is *12,756km*. The surface area of Mars is comparable to the total landmass of all the continents on Earth. The total area is roughly $145 \cdot 10^6 km^2$.

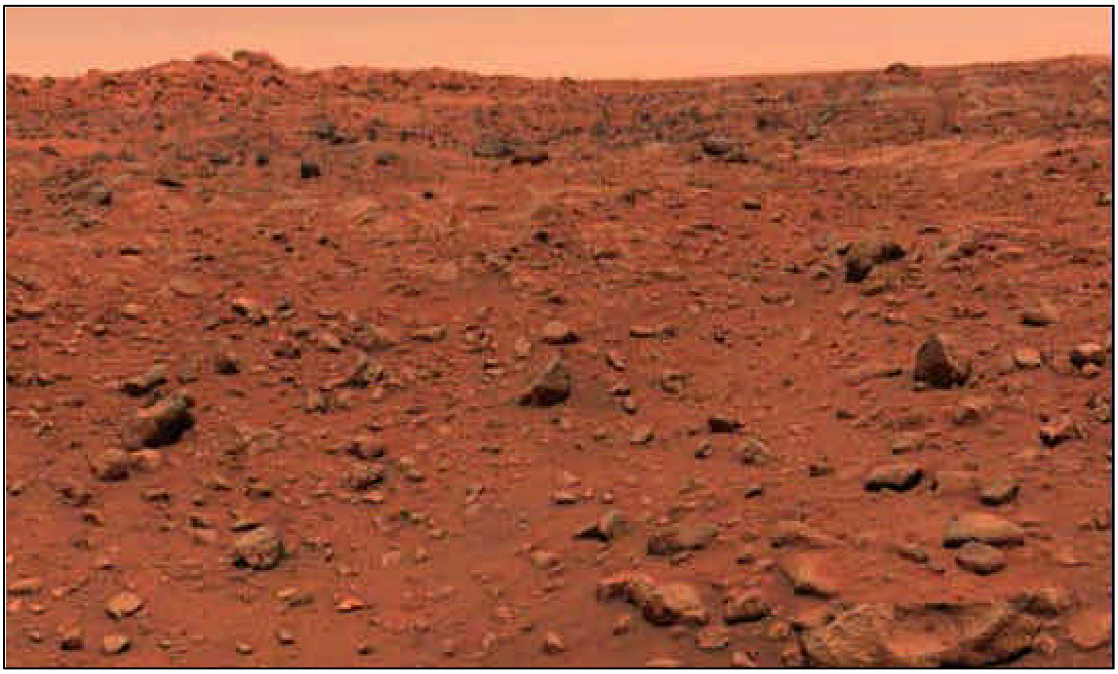
Gravity:
Because of the smaller size of Mars the gravity is also lower than the gravity on Earth. The gravity is only *0.36* of the Earth's gravity; the actual gravitational pull is $3.7 m/s^2$. Which means that the gravity on Mars is only a third of that what is felt on Earth.

Rotation period:
The rotation period of Mars is similar to the Earth's. It is so similar as to be eerie. The Earth has a rotation time of *23h56m*; Mars has a rotation time of *24h37m*. For convenience the day/night cycle on Earth has been rounded up to *24h00m*.

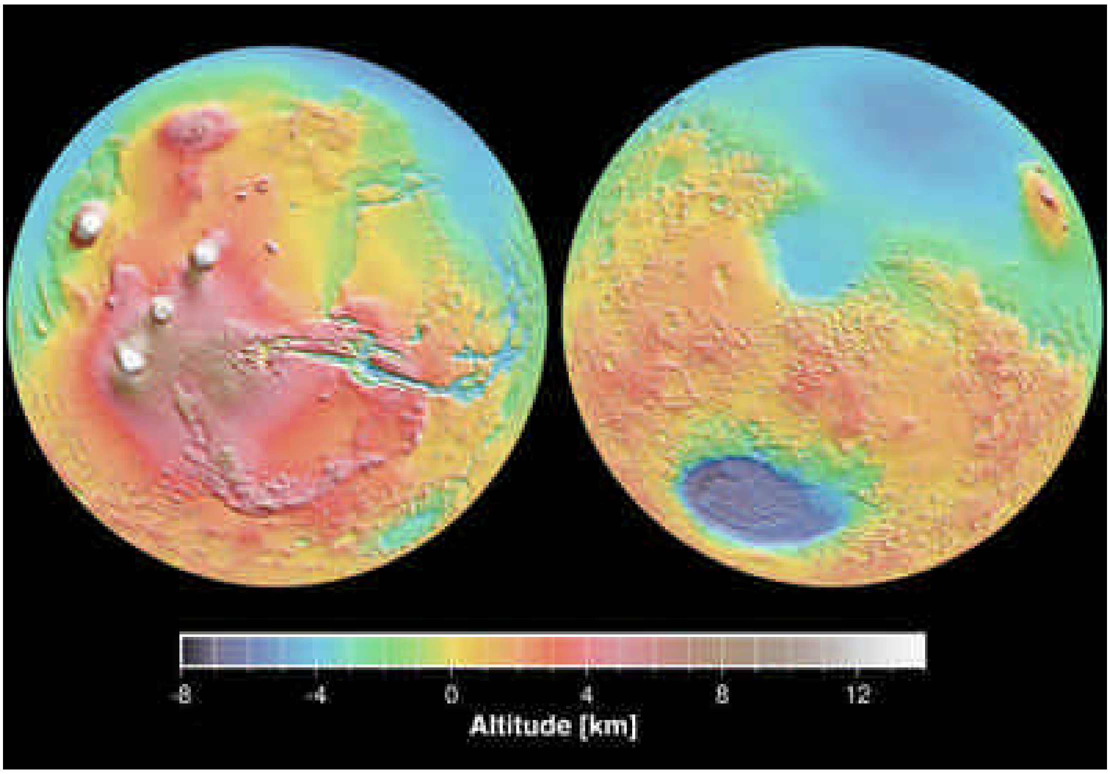
Distance from the sun:
Mars is the fourth planet from the sun; Mercury, Venus and Earth are closer to the sun. Mars is on average $227.9 \cdot 10^6 km^2$ away from the sun; in comparison Earth is $149.6 \cdot 10^6 km^2$ away from the sun.

Axial tilt:
The orbit around the sun in combination with axial tilt is necessary to create seasons, just like the rotation period is necessary for the day/night cycle. The

[18] I.S.S. International Space Station



Martian landscape
[NASA]



Map showing the differences in altitude.
[NASA]

axial tilt of Mars is *25.2* degrees; in comparison the axial tilt of the Earth is *23.5* degrees. This means that Mars has seasons similar to those on Earth.

Orbital Period:
The Martian year is nearly twice as long as the Earth year, measuring respectively *687.0* days and *365.2* days.

Mean Temperature:
On average the Martian ground temperature is *–23ºC* (250K) vs. a ground temperature on Earth of *+22ºC* (295K). The ground temperature on Mars ranges from *–143ºC* (130K) at the poles to *27ºC* (300K) at the tropics in the summer months. Because the Martian atmosphere is so thin it's 'air' temperature is much colder than it's ground temperature, so we would expect an average *air* temperature of *-63ºC* (210K)

Surface pressure:
One of the most crucial differences is the surface pressure that is found on Mars, the pressure at sea level on Earth is 1013mb whereas the pressure on Mars is only 6mb. This is the same pressure we find on Earth at an altitude of 40km!

Atmosphere:
The Earth's atmosphere is composed of gasses that are hospitable to life; they include large amounts of oxygen and nitrogen. There is also a lot of water vapour in the Earth's atmosphere. The Martian atmosphere contains nearly only Carbon Dioxide and very little water vapour.

Mars		**Earth**	
Carbon Dioxide (CO_2)	- 95.32%	Nitrogen (N_2)	- 78.08%
Nitrogen (N_2)	- 2.7%	Oxygen (O_2)	- 20.95%
Argon (Ar)	- 1.6%	Argon (Ar)	- 0.93%
Oxygen (O_2)	- 0.13%	Neon (Ne)	- 0.002%
Carbon Monoxide (CO)	- 0.08%	Helium (He)	- 0.001%
Water vapour	1 –2 km^3	Water vapour	13,000 km^3

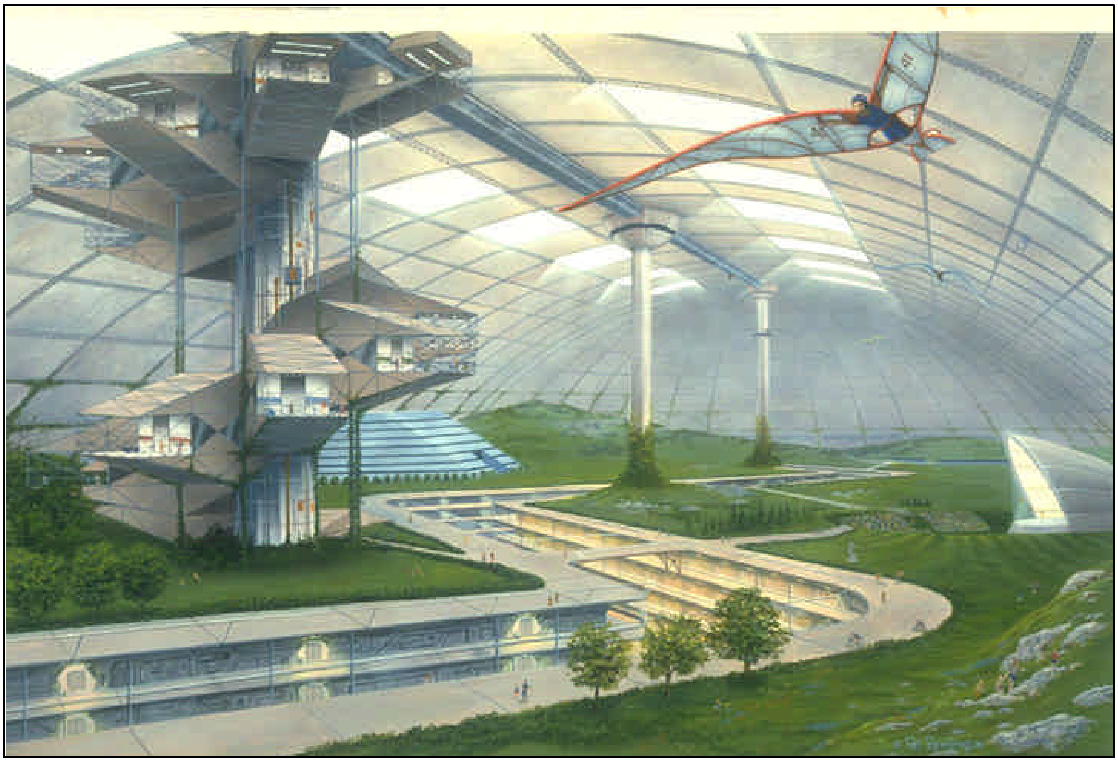
)[19]

Water
The Earth is covered by vast amounts of water (more than two thirds is covered by water), has two huge polar caps containing masses of water in the form of ice and the atmosphere is laden with it. Mars has no surface water, a small polar cap in the north that consists of water ice and only minute amounts of water vapour in the atmosphere.

Magnetic field:
Mars has no magnetic field like that surrounding the Earth; this means that navigating by compass is not an option. The gravity filed that can be detected on Mars varies significantly. Recently the Mars Global Surveyor has detected magnetic anomalies, which are not fully understood.

[19] From Human Spaceflight, Mission Analysis and Design

Biosphere2; a closed microenvironment
[Robert DeMicco, CERC 2000]



Projects like the Biosphere2 might pave the way for future microenvironments and habitats on other worlds.
[Pat Rawlings]

[3.0] Learning for Mars

Mars habitats and bases are for now theory, but a lot of practical knowledge can be gained from certain sites on Earth. These sites are in some ways similar to what we may expect to find on Mars, either by way of a hostile climate, prolonged isolation or a self-sufficient microenvironment. The most obvious and useful examples are: bases located on the Antarctic, remote military installations (missile silo's and submarines) and *Biosphere2*[20].

Of all of these a base located on the Antarctic is the most interesting in terms of; human psychology, remote and inaccessible location and in terms of designing for extreme environments. As a technical and psychological study the *Biosphere2* also has relevance on how people live in a closed self-sufficient microenvironment.

Research on the human condition within these types of surroundings has been collected by Jack Stuster and his conclusions and recommendations for these sites and any future Martian habitat are[21]:

- Humans can endure almost anything
- Behavioural problems will occur
- Trivial issues will be exaggerated
- Relations between headquarters and remote-duty personnel will become strained.
- *Zeitgebers*[22] are important.
- The larger the group, the greater is the tendency for subgroups to form.
- Self-selection is preferred to predetermination.
- Humans tend to thrive on variation.
- Most people like to be informed.
- Performance is facilitated when designs conform to human expectations.
- The longer the duration, the more ire privacy and personal space.
- Some individuals require tangible results.
- The integration of activities can improve productivity.
- Unplanned events will occur.
- There are paradoxes in designing for habitability.

These are the lessons we can learn for Mars and that need to be dealt with, and when possible (or applicable) implemented. The alienating effect of being on a different world will only add to the pressure normally felt by any crew in an isolated and hostile environment and anything that increases this stress must be removed.

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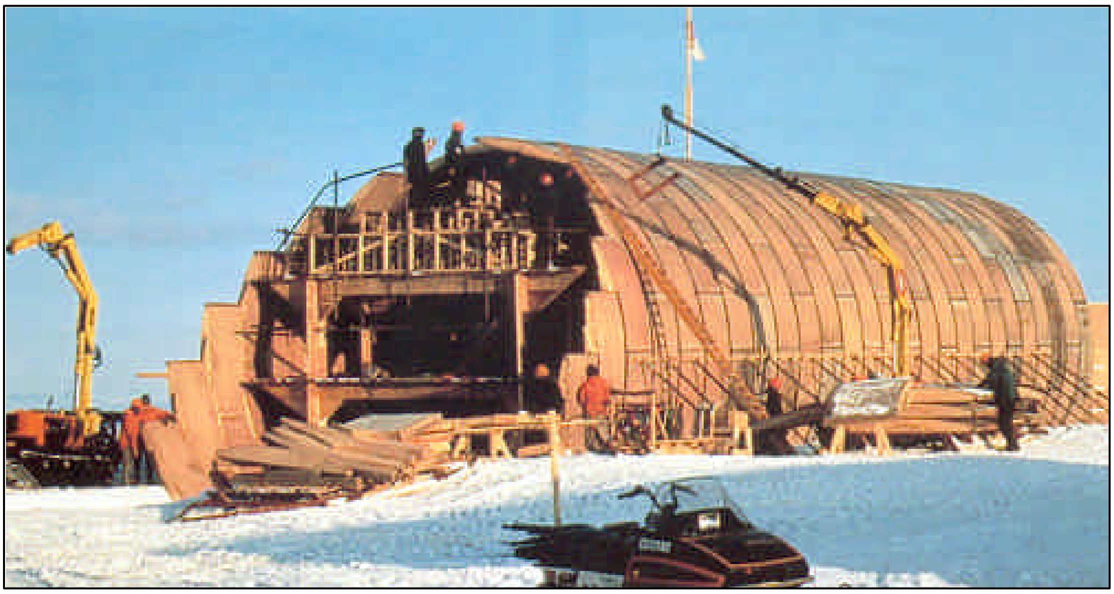
[20] Biosphere 2 is one of the largest living laboratories in the world. It is an air tight greenhouse covering 3.15 acres and 7.2 million cubic feet of volume. Within Biosphere 2 are several different biomes which researchers use to experiment on Earth systems on a relatively large scale. Inside Biosphere 2 is a rainforest, a million gallon salt water ocean, a coastal fog desert, and four other wilderness ecosystems. In 1994 Biosphere 2 was converted from an experiment to test the feasibility of humans living in a closed eco-system to a large scale ecological laboratory and Western branch campus of Columbia University.

[21] From Jack Stuster; Bold Endeavors –Lessons from Polar and Space Exploration

[22] Regular external stimuli, (dark/light cycle, mealtimes etc.)



Construction of the Halley 4 Research Station, built in 1983
[Doug Allen, British Antartic Survey]

Site of the Halley 4 Research Station, 2001: the crushed habitat lays buried meters deep under the snow.
[British Antartic Survey]

Halley 5 Research Station built in 1992 and still in use
[Natural Environment Research Council - British Antarctic Survey 2001]

[3.1] Antarctic, Halley Research Station

The Halley research station has existed on the Antarctic since 1956 when it was decided that a permanent base was needed that would allow researchers to stay there all year round. The base is built on the Brunt Ice Shelf, Coats Land and it is one of the most isolated places on Earth:

'Halley is the UK's most isolated station and is afloat on an ice shelf on the mainland of Antarctica. In winter there is darkness for 105 days - darkness relieved by magnificent auroral displays. The relief of Halley is a major undertaking with supplies being landed twice a year by ship onto the ice shelf and then towed on sledges by Snow-cats to Halley, some 12 km distant from the ice edge.'[23]

This site demonstrates the hostile environment and the isolation that a crew will have to deal with on a magnified scale in a Martian base. The difficulty in getting people and products to the facility and the limited construction possibilities that are available are all analogous to a base on Mars. The construction workers will have to be protected from the environment, and all construction/transportation vehicles will have to be able to endure the harsh environment during the building of an Antarctic research station. Planning and logistics will also have to be carried out very carefully, as there is often not a second chance to deliver extra goods due to the weather and ice that is formed in the winter.

The current Halley Research Station is the fifth that has been built in this region, the other four have perished with the third station surviving the longest; twelve years. The stations have all been crushed by the large amounts of snow that gathers over the years on the roof and sides of the buildings. The buildings were designed to last only for a decade or so as the designers knew of the crushing snow effect. The first two buildings were shed-like constructions that lasted respectively eleven (1956/57) and seven (1957/64) years, by the time they collapsed the structures were buried under more than ten meters of snow. The third building was placed inside a corrugated steel tube; a prefabricated timber building sat inside a cylinder with a flattened base. This allowed the tube to more easily bear the loads that it would suffer from the snow. Eventually the floor buckled, under the load; the wider radius of the floor made it the weakest point and the base had to be abandoned sixteen meters below the snow after twelve years of service. The fourth base was constructed from simple prefabricated wooden elements that formed a cylinder in which a secondary wooden structure was placed. Having learned from the previous failures it was constructed in such a way that the interlocking wooden panels would allow the tube to absorb and flex under the varying loads of the snow, rather then fight the snow loads it used them to strengthen the structure. Finally this structure also perished in part through design flaws after ten years (instead of the originally planned fifteen years).

[23] From www.antarctica.ac.uk/Living/Stations/Halley.html

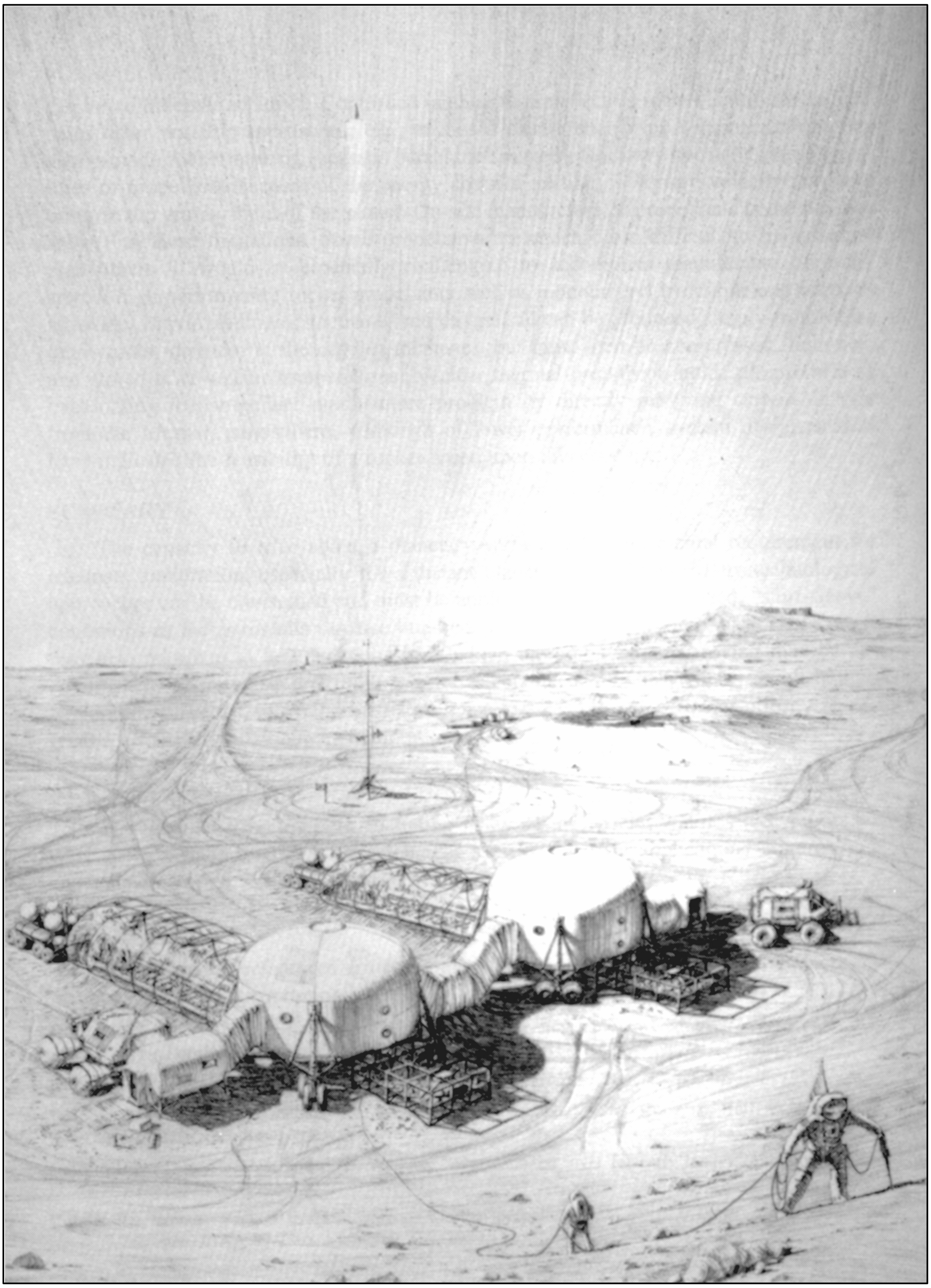
If a crewmember is severely injured or part of the habitat fails the life of the crew may depend upon a good contingency plan.
[Carter Emmart, NASA]

The latest Halley station is a completely different design that is comprised of prefabricated containers that are joined together and stand on legs above the snow:
'Halley V contains a mix of building technologies. Three buildings are located on platforms on steel legs, which are jacked up annually to keep them clear of the accumulated snowfall. An accommodation building and a garage weighing over 50 tons are mounted on skis and towed each year to a new position. Halley I to Halley IV were built directly on the snow and were each abandoned within ten years, having been crushed by the overlying ice.'

Although a Martian base will not be crushed under heavy snow loads the Halley Research Station example does show how concept and design flaws can drastically reduce the life expectancy of a base (and it's crew in the worst case). Mars is an even harder place to reach then the Antarctic and a concept for a habitat should be approached from different angles to ensure that the best possible solution is chosen. It is not possible to ensure that a habitat or base will be failure-proof; to this end a backup for the crew must be implemented in any design for a Martian base.

'..at the surface of Mars, where the pressure equals that found at 100.000 feet (33km) or higher above the Earth, a man thrust suddenly from a protected environment into the cruelly thin air would die a terrible death.
Air within his body would rip away with skin-slashing force. His lips and cheeks would flutter wildly from the tremendous blows of air tearing away from his nose and mouth. His body would bloat outward much more violently(…); he would be like a rubber balloon expanded explosively . Blood vessels would rupture, and crimson froth would spew from his eyes, ears, nose, mouth and other bodily orifices. His lungs would fill instantly with a bloody foam and this alone would kill him. Within seconds he would be unconscious. Seconds later he would be dead.
Mars, no matter what else it may be to science, to man is a bleak and deadly desert where the unprotected human will die swiftly.'[24]

[24] from Mission to Mars, Chicarro, A.F.



Any work that is done outside of a sealed environment must be done in a pressure suit that is insulated from the Martian atmosphere.
[Carter Emmart, National Center for Atmospheric Research]

[4.0] Martian settings and complications

As has been stressed before Mars is a very different and hostile place when compared to our own world. To visit it is a hard task, to settle there an even harder task. Construction of any kind has to take place in near vacuum, with cosmic radiation raining down on unprotected workers. Materials, machinery, people and other products brought from Earth are worth their weight in gold[25] and must be treated in that way. Large machinery must be shipped in parts and assembled on site and is so expensive as to be practically impossible to deploy. Robot factories and power plants must be put to service and semi-permanent habitats must be available during construction for workers to live in. The location and environment must be understood, as must logistical and transport difficulties, construction problems and design consequences.

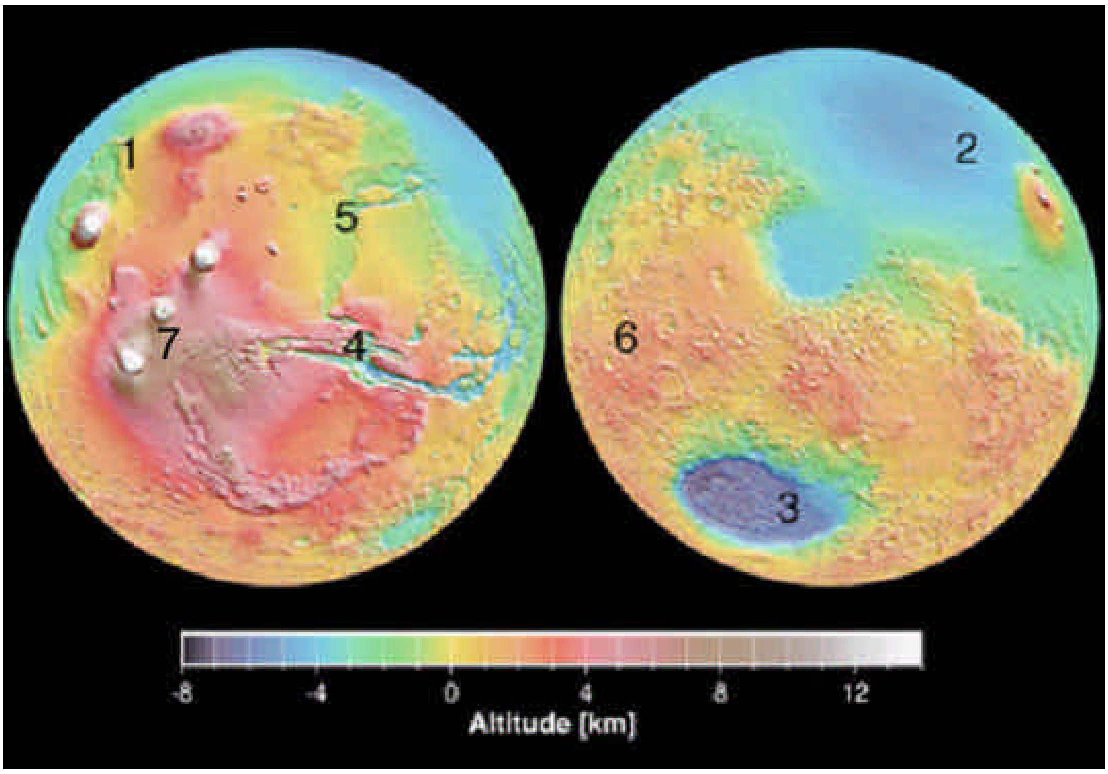
[4.1] Location and global settings

The location has a great impact on any building, so too for any permanent base that is placed on Mars. The Martian environment varies greatly from what we find on Earth and is extremely harsh even when compared to the most extreme environments found on Earth. Furthermore the Martian settings such as a thinner atmosphere and reduced gravity will also play a vital role in the placement and construction of such a base. Easy access to the base from space, expansion possibilities, research possibilities, access to water, useful natural formations (caves, gorges etc.) are among some of the most important factors that will influence the location of the base. Finding a site that can fulfil all these demands will be difficult. A choice must be made as to which factors are critical and a site located that can achieve as many of these factors as possible.
Earlier missions that rely on short to medium stays on the planet will probably also dictate the placement of the permanent base. The habitats from previous missions that remain on the planet can so serve as temporary shelter for those that will build the permanent base. However some elements such as geothermal water will be vital for a permanent base but can probably not be capitalised upon in earlier bases. (Locating the water however would be important)

[4.2] Location

When a site is selected it must adhere to a certain set of criteria, by weighing the different options a suitable site can be found. Different locations will be suitable depending on what the base or habitat is intended for:
'The criteria for site selection will be of extreme importance. A first cut at what these criteria might be was addressed by the Workshop… The first and most obvious is that of accessibility. We must be able to conveniently reach the surface site chosen for the base from reasonably expectable arrival trajectories…Next in importance is the presence of the necessary raw material. This must be absolutely certain prior to the commitment to a landing.

[25] In comparison: To deliver a kilogram of material to the International Space Station with the current launch vehicles costs US $20.000,-.



1 Eastern Arcadia Planitia/Tharsis Plateau
2 Eastern Utopia Planitia
3 Eastern Hellas Planitia
4 Candor region of the Valles Marineris
5 Kasei Valles
6 Southern Arabia Terra
7 Pavonis Mons

[www.mars.jpl.nasa.gov]

…. A third very desirable characteristic is low elevation of the base site simply because this allows us to take much better advantage of the Martian atmosphere in final deceleration….Another factor of substantial importance is our ability to communicate with earth. It is desirable to have a site which will be in contact, that is to say line of sight, through the Martian year for at least part of the day…. Of medium importance would be the ready availability of solar energy which would tend to dictate a lower latitude site… Since presumably various means of transportation will be available to the crew to visit sites of scientific interest, it is not of maximum importance that the base site itself be a highly scientifically interesting site.
But of all the valuable resources needed to support manned expeditions there, water heads the list in value and in required amounts[26]

A number of sites have been located by different parties to situate Martian bases. A study done by G. James, G. Chamitoff and D. Barker for the Johnson Space Center identify three sites for possible permanent bases. The NASA Special Publication 6107 sees the *Candor* region as a suitable place for an outpost; and a more permanent NASA base is to be located south of *Pavonis Mons.* The Obayashi Corporation places their habitat in the *Kasei Valles*. While Robert Zubrin plans a string of temporary bases along the southern edge of the *Arabia Terra*.

- *Eastern Arcadia Planitia/Tharsis Plateau*, 120 degrees west longitude, 45 degrees north latitude. Here an area with a 500-kilometer radius has been selected. The site contains evidence of recent surface water and permafrost[27], volcanic activity in the last 250 million years indicating possible active geothermal sources which can be used for heating and electricity. The soil appears to be very fine meaning it can easily be used as radiation cover or construction material. Wind speeds are relatively high indicating a possible use for wind energy. The Tharsis Plateau is located in the northern hemisphere, where the summer and spring last longer than in the southern hemisphere allowing for better solar power.

- *Eastern Utopia Planitia,* 220 degrees west, 45 degrees north. Here an area with a 500-kilometer radius has been selected. Has the same resource possibilities as the *Tharsis Platea*u site and the Viking 2 lander is located within this area as are huge outflow channels possibly created by Martian floods in the past. The wind speeds are also high as the winds blow down from the Elysium volcanic rise. The atmosphere is thicker here than most places elsewhere on the planet as the site is located in a basin. A thicker atmosphere makes the site especially attractive for wind power and water vapour extraction from the atmosphere.

- *Eastern Hellas Planitia,* 275 degrees west, 45 degrees south. An area with a 500-kilometer radius has been selected. The site lacks the fine

[26] From Boulder conference by the "Mission Strategy Workshop"
[27] Permanently frozen subsoil.

Olympus Mons is a mountain of mystery. Taller than three Mount Everests and about as wide as the entire Hawaiian Island chain.
[NASA]

soil found at the other two sites and no volcanic activity is thought to have occurred recently (within the last 250 million years). Another problem with this site in comparison with the other two sites is the amount of solar power that can be harnessed as the *Hellas Planitia* is located in the southern hemisphere the summer and spring are much shorter. Dust storms are more frequent in the *Hellas Planitia* and this can also impair the amount of sunlight that can be used for solar power. Outflow channels and permafrost can be found at this site and so water should not be a problem. The *Hellas Planitia* is more than eight kilometres lower than the average Martian surface; it was created when an asteroid collided with the planet. The air pressure is higher here by more than 44% because of this lower altitude. A higher pressure means that wind energy is more profitable and that the atmosphere can absorb more water vapour, thus making it possible to extract more water from the atmosphere.

- *Candor region of the Valles Marineris*, 70 to 75 degrees west longitude, 2.5 to 7.5 degrees south latitude. NASA also sees the *Candor* region in the *Valles Marineris* as a possible location for what they call an outpost:
  "It offers a unique opportunity to sample rock layers and their interbedded soils that would reveal the petrochemical history, age dates, and the environmental changes that may correlate with episodes of channel formation and the history of solar variations preserved in the rocks from the time when they were exposed at the surface."[28]
  Located just south of the equator it is at the same longitude as the *Kasei Valles*. The altitude of the site is low as the *Candor* gorge is located in the *Valles Marineris*, which is the deepest, and the largest canyon on the planet. Exact wind speeds and soil composition are not known but are probably roughly similar to those found in the *Valles Marineris*.

- Gorge situated south of *Pavonis Mons*, is located 100 degrees west longitude, 0 degrees south. It has the same benefits as other sites located on the equator: relative long summers, and not too many dust storms. The lower altitude of the gorge means that the atmosphere is relatively thicker and wind energy should be applicable because of the winds coming down from the *Pavonis Mons*. The location is near the Valles Marineris which is positive for research:
  'For that reason, the "Big Valley" [Valles Marineris] is obviously science's number one choice when it comes to the firs human footsteps on Mars[29]

- *Kasei Valles*, 56 to 75 degrees west longitude, 18 to 27 degrees north latitude. The Japanese corporation Obayashi created a Martian design for a base that could be built in 2057. They choose the *Kasei Valles* (Kasei is the Japanese word for Mars) as their location. The *Kasei*

[28] Hal Masursky, JPL 1980
[29] Report of the Mars Exploration Study Team – Paris European Space Agency 1989

TABLE 4-12. Design Guidelines for Dealing with Mars's Surface Environment.

Concerns	Guidelines
Can soil support landers, stations, rovers?	Yes. Footpad or wheel dimensions must be sized according to load.
Can structures be anchored in soil for additional stability against seismic events, wind, etc.?	Wind loading relatively low (maximum velocity ~30 m/s). Seismic hazard probably minimal.
What is the effective shielding against radiation?	~ 0.5 m to 3 m
What is the effective shielding against micrometeoroids and orbital debris?	~ 0.5 m
What is the physical effect of soil and dust on mechanical or electrical systems?	Long-term effects unknown. Mechanical devices will need lubrication and sealing.
What is the chemical effect of soil and dust on mechanical or electrical systems?	Long-term effects unknown. The presence of unknown types of oxidants may pose a problem. The type and nature of oxidants must be determined.
What is the size distribution of rocks near the landing site?	Site specific. Sites must either be imaged at scale appropriate to certify lack of hazard or design must fit the current database.
Can the surface be used as an electromagnetic ground?	Yes.
How much heat load will the surface provide (independently of the direct solar flux)?	Ground temperature depends highly on the albedo and thermal inertia of surface material. Latitude and seasonal effects are also important.
Does the local geology contain usable quantities of critical resources, such as oxygen, carbon dioxide, and water?	Carbon dioxide can come from the atmosphere. Water can also come directly from the atmosphere. Whether alternative sources of water are necessary depends on the required quantity and production rate.

Table 4-12. Design Guidelines for Dealing with Mars's Surface Environment.
[Human Spaceflight, Mission Analysis and Design]

Valles is located just north of the *Valles Marineris* at roughly the same latitude as *Olympus Mons*. Having located their base in the northern hemisphere they gain the extra solar energy from the longer springs and summers. The *Kasei Valles* is located just of the *Tharsis* highlands that should give them high wind speeds although the high altitude should negate this effect partly. Outflow channels are also present here. The Viking 1 lander touched down on the *Chryse Planitia* which is adjacent *to Kasei* Valles and soil measurements might be assumed to be similar. In this case there would also be very fine soil present at the *Kasei Valles*.

- *Southern part of Arabia Terra*, 60 to 315 degrees west longitude, 5 degrees south latitude to 10 degrees north latitude. Robert Zubrin's temporary habitats are placed along the meridian, where fine soil should be present. Reasonable long springs and summers can be expected. Exact wind speeds and soil composition are not known.

It is clear that the sites that have been chosen by the various teams are not small areas that specifically fulfil all the necessary requirements. Rather they are areas wherein enough demands can be met to set up a (semi) permanent base. However it is clear that there are a number of benefits that can be gained from certain locations, such as; geothermal energy, ground water, atmospheric water, wind energy and construction soil.

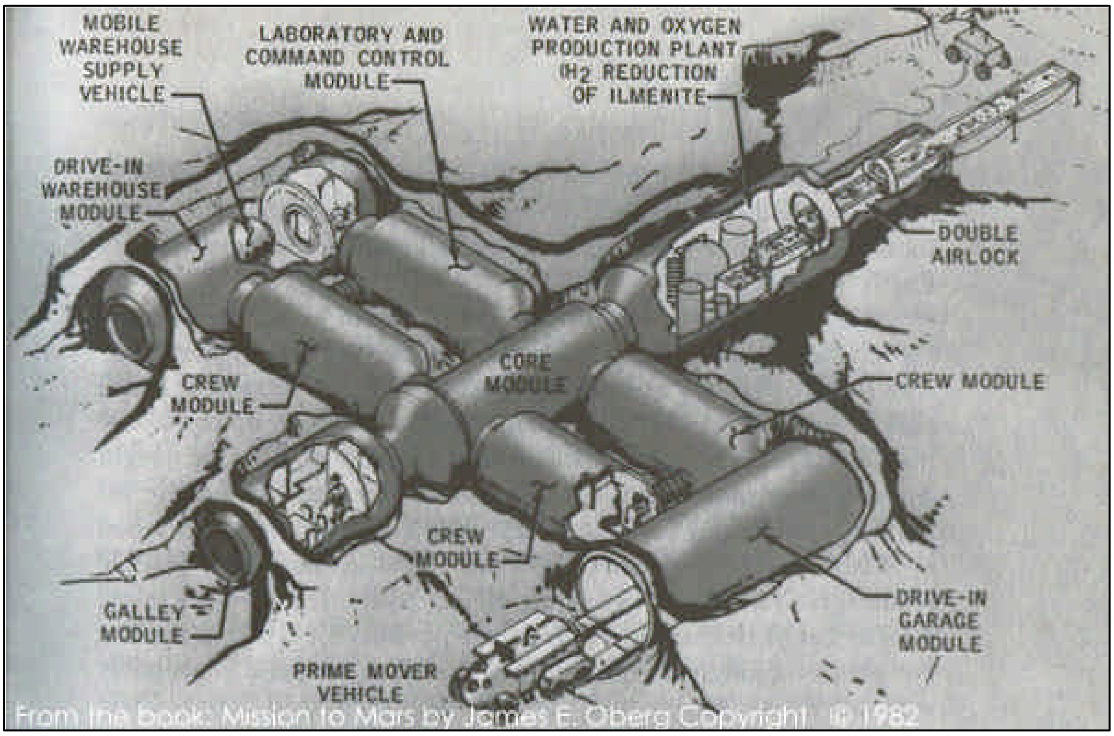
Geothermal energy, this can be produced through the use of geothermal water that might reside in the ground.

Ground water, *'Water is also present in the surface material as absorbed water and within the structure of hydrated minerals. Thermal processing of such surface material could release large quantities of water but would require a lot of material and energy. To get more water faster, crews may need to locate and use subsurface aquifers. Unfortunately, we understand virtually nothing about the subsurface hydrosphere or even whether it exists. Tapping any existing aquifers would require crews to find it at particular sites drill for it, and then extract it, possibly having to melt ice to recover the water.*[30] Water is expected to be found in the northern hemisphere at 45 degrees North latitude[31].

Atmospheric water, there is a minute quantity of water in the atmosphere that could be condensed. Parts of the planet that are at a lower altitude will have a thicker atmosphere which will absorb more water making it easier to extract large quantities from the atmosphere.

Wind energy, as wind is nearly always present on Mars it makes sense to use it as a source for energy. Because of the thin Martian atmosphere the (force) pressure is very low, even though there are often very high wind speeds. In total the pressure exerted by the atmosphere during windy conditions is about 0.25Pa. Locations that are close to elevation differences often have higher wind speeds.

[30] From Human Spaceflight, Mission Analysis and Design
[31] Carr, et al., 1986



To protect equipment and personnel from radiation the base can be completely dug into the ground. In this case it is also possible to use the weight of the material on top of the base as a counterweight for the pressure difference.
[Mission to Mars, by James E. Oberg]

A small amount of sandbags has been used as a radiation shield for a semi-permanent base.
[Touchstone]

Solar energy, the day/night cycle on Mars is fairly short (comparable to that of Earth) this means that excessively large batteries are not necessary to store energy during the night (compared to the moon which has a 354 hour night). As the springs and summers are longer in the northern hemisphere it will allow for more solar energy to be produced at the sites located there. Dust storms can obscure the solar collectors and reduce their output, however long-term dust build-up should not occur, as the soil is so fine that wind will blow it away over time.

Useful surface material is soil that can easily be scooped up and used for either; the covering of structures or as production material. It is possible to distinguish in[32]:

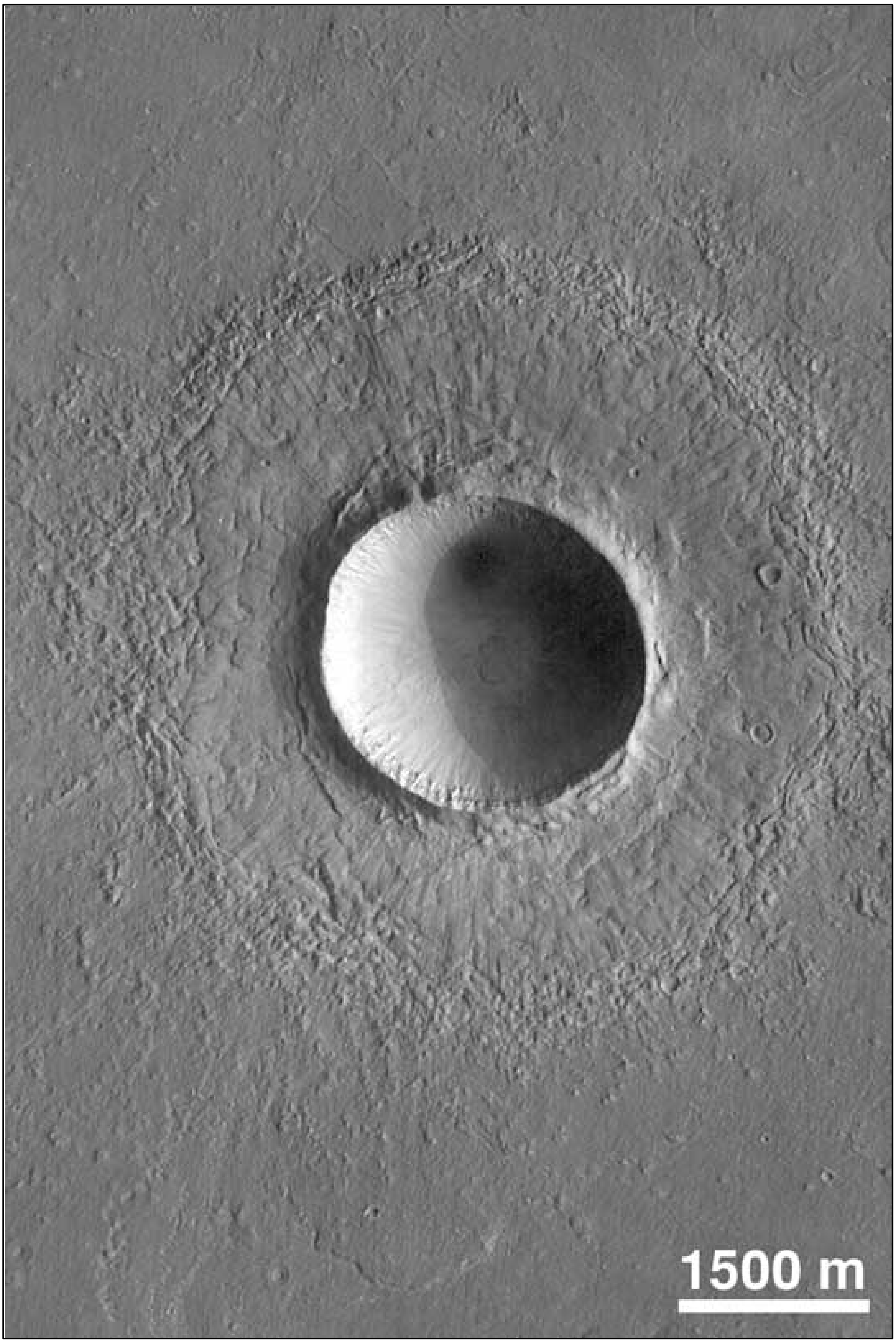
- Rocks, solid aggregate of mineral matter
- Soil, loose unconsolidated material
- Drift material, fine grained and transported by wind, this material could be used to fill sandbags that can be used as radiation shielding.

In addition to the locations and benefits set by these groups PAX[33] and NASA have defined a number of requirements that any site should adhere to. Some of these requirements have also been included in most of the locations mentioned earlier in one way or another.

- The base should be located in a geologically varied region.
- Base should be near possible water locations.
- Base should be located at a low elevation.
- The base should be located in the northern hemisphere.
- The habitat should be shielded from dust contamination and wind.

These requirements are for any type of bases including the initial habitats. Permanent habitats will require extra measures, as these will want to be able to expand and take full benefit from the surroundings. According to PAX these measures include; locating the base within rover distance of a volcano (scientific interest), flat terrain to assist in launch and landing of space- and planetary-crafts, base expansion and the recognition of the base as a village, Outpost or home. The latter is important for crew moral, *…to have a recognizable image of their home on Mars.*[34]

[32] From Human Spaceflight, Mission Analysis and Design
[33] PAX Permanent Martian Base, Space Architecture for the First Human Habitation on Mars.
[34] Hansmann and Moore, 1990



'This crater on northern Elysium Planitia is a little more than twice the diameter of the famous Meteor Crater in Arizona, U.S.A. It formed by the impact and subsequent explosion of a meteorite. Picture from MOC in July 1998.'
[NASA/JPL/Malin Space Science Systems]

[4.3] Global settings

Besides these local settings there are also global settings that must be taken into account. In chapter 2.2 the differences between Earth and Mars have been discussed, a number of these differences pose a threat to any habitation built on the planet. The most important of these factors concerning the building and placing of a habitat are: radiation, micrometeorites, seismic activity, atmospheric pressure/temperature/wind speed, and global dust storms.

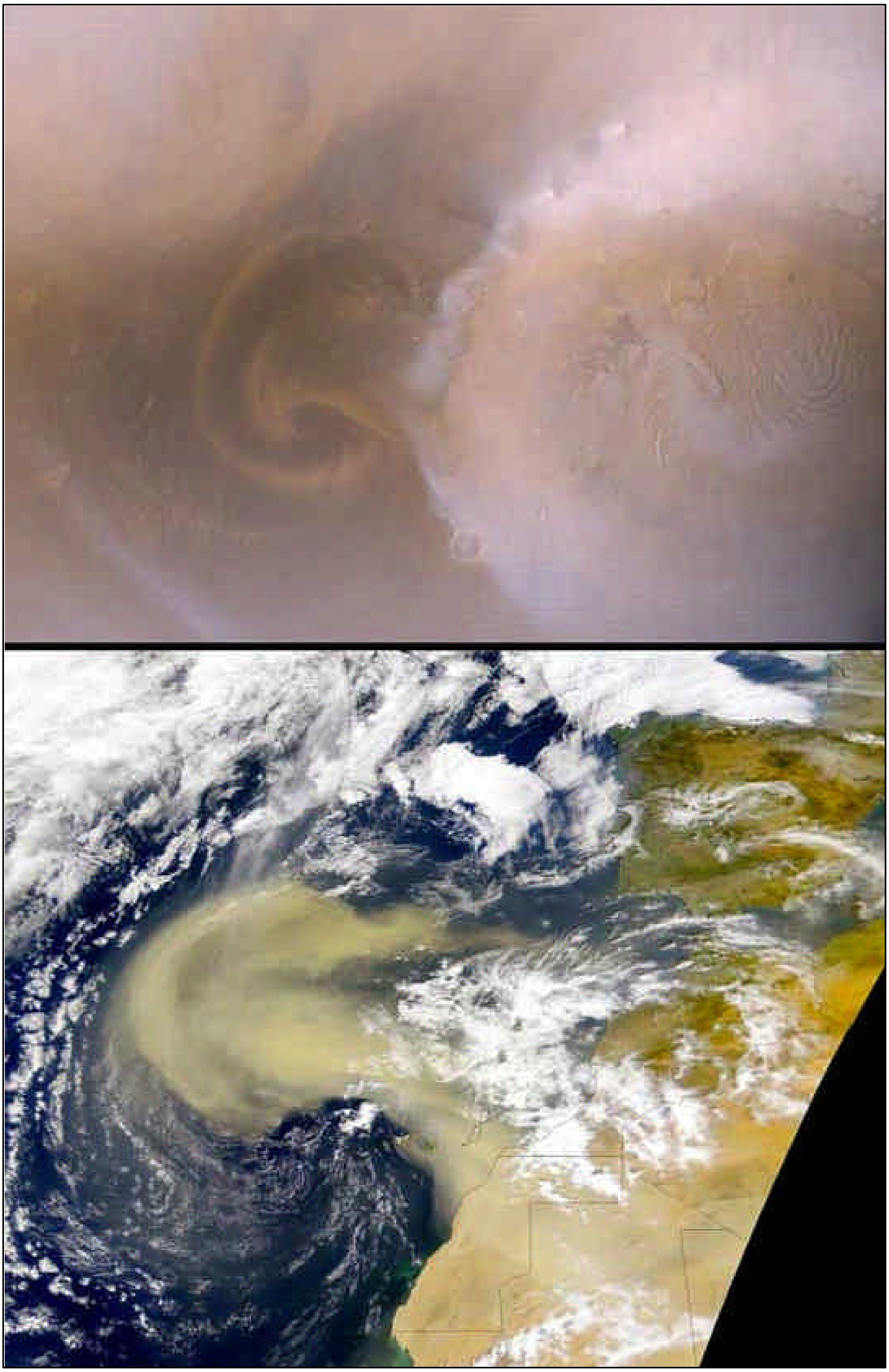
- Radiation in the form of *solar particle events (SPEs,* which are highly energetic particles that originate from ejections of coronal mass on the Sun) is for the most part blocked by Martian atmosphere. Shielding against this kind of radiation can be accomplished by 0.5m of Martian surface material. The radiation received by *galactic cosmic rays (GCRs)* that are present as a low-level background of highly energetic particles also need to be blocked by 0.5 of Martian surface material. To shield from any occasional dose of radiation such as activated thermal neutrons it would be wise to shield *permanent* habitats with several meters of Martian surface material. Or create shelters that can hold the entire crew for small periods of time.

- Micrometeorites are very small meteorites; the Martian atmosphere usually protects the surface from these types of meteorites. However some shielding would be advised, the same type of shielding can be used as is used against radiation.

- Seismic activity is of no great concern on Mars; at this moment the timescale of a Richter magnitude 4.0 event occurring from a surface fault would be 71 years.[35] No threatening seismic activity is expected on the surface. *'If crews locate operations far from geologically young faults, the risk from seismic shaking is probably low enough so they wouldn't need to seismically strengthen any structures.'*[36]

- Atmosphere pressure, temperature and wind speed have been discussed above in part for the local settings. Globally speaking the atmosphere changes a couple of Pascals during a Martian day (sol). The condensation of the carbon dioxide atmosphere at the winter pole and its sublimation during the summer causes a seasonal variation of roughly 2.50 mb. The average pressure at the Viking1, Viking2 and the Pathfinder landing sites was respectively 7.8mb, 8.7mb and 6.8mb. To keep any structure from imploding it will have to be able to withstand the difference between the inside pressure (which we need for humans and plants to survive) and the lower outside pressure. If a structure is buried deep enough then piling back some of the Martian surface material on top of the habitat will be enough for it to withstand the pressure:

[35] Golombek et al. [1992]
[36] From Human Spaceflight, Mission Analysis and Design



Dust storms on Earth and on Mars work in much the same way. *'The rare, global storms alter the planet's total heat balance and promote variations in seasonal frost formation and dissipation, and greatly affect the distribution of water vapour'.*
[NASA/JPL/Malin Space Science Systems]

'If we stick with our proposed Martian standard of 5 psi the vaults will experience a pressure force trying to explode them upward of about 3.5 tonnes per square meter. Assuming that Martian soil has an average density four times that of water, this would mean that a layer of dirt about 2.5 meters deep on top of the vault would be enough to keep the whole structure compressed.'[37]

The average *air* temperature of *-63ºC* (210K) and a ground temperature of –*23ºC* (250K) make Mars a cold place. Temperatures can vary during the day by 20K to 60K and from summer to winter nearly 100K. Designing a habitat with regards to the temperature should not be an insurmountable problem even though the differences in temperature are higher than on Earth. (See chapter 2.2)

- Global dust storms, which cover the entire planet, occur in the southern spring and summer. These storms have never been observed during northern spring and summer. Global storms develop when local storms expand in the right season. Although the storms can last for a long time they do not pose a serious problem. Although they can obscure solar panels cutting back their efficiency, however the storms would never impair the amount of energy a solar panel can deliver to an insufficient level. The pressure that a dust storm delivers is calculated at 0.0025mb, which does not call for a dramatic over-dimensioning of structures placed on the planet.

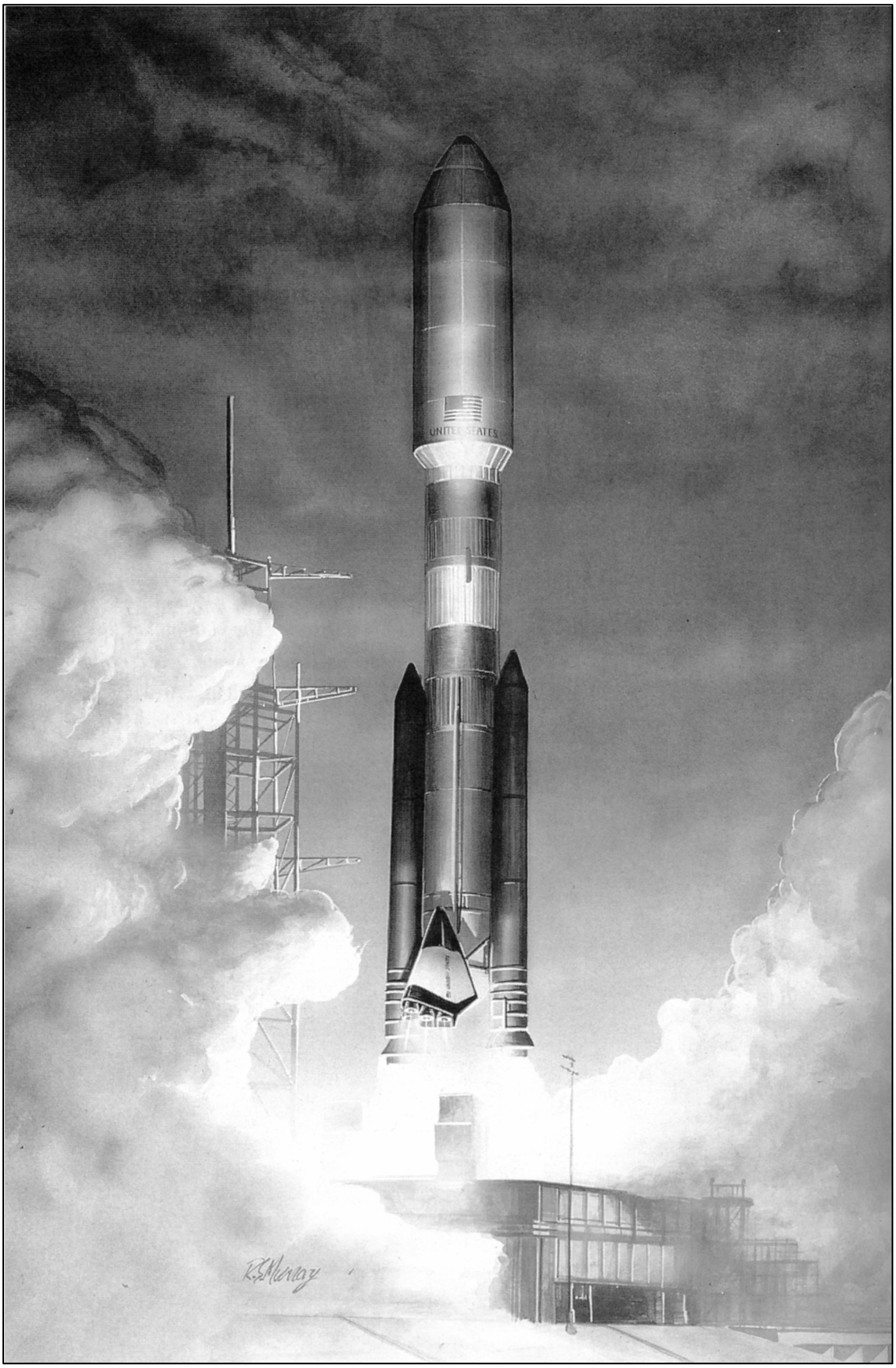
[4.4] Transport and construction obstacles

'The expansion of human civilization into space will be paced by our ability to transport goods. A Mars base, for example, may require as much as 500 metric tonnes of material, not including propellants, to be delivered from Earth to the surface of Mars. An additional 1000 metric tonnes of propellant may be needed to land this payload on the surface.'

As has been mentioned earlier in this chapter it is very costly to bring materials to the Red planet and a lot of ideas have been proposed by a number of people to solve this problem. As this paper is not meant to be an exercise in aerospace technology I will only regard these ideas for their merits in what they can deliver to the planet; how much they can deliver and how fast. Besides the vehicles themselves there is also the trajectory by which an interplanetary vehicle travels between Earth and Mars that must be considered. Different trajectories allow for a shorter time to travel between the two planets. However these trajectories do have a consequence in that certain trajectories are only possible at certain times. In considering the vehicles or engine drives we have to make a distinction between two classes of vehicles; those that exist now and those that are theoretically possible at this time or in the near future.

Once payloads have landed on the Martian surface they might require transportation to the building site. Assembling and unpacking of materials and

[37] From the Case for Mars, by Robert Zubrin



Ares heavy lift booster, comprised of shuttle parts, enabling 135 tonnes to be lifted into space.
[Robert Murray, Lockheed Martin]

products brought to the planet will pose problems, as initially at least there will not be a sheltered area to aid in this process. So the three points that need to be looked at are; the transport vehicle, the trajectory and the assembly possibilities.

[4.5] Transport vehicle

Looking at the transport vehicles that exist today there are a number of possibilities; it is possible to launch a number of rockets from Earth and assemble them in Earth's low-orbit (LEO) from where they move to Mars. In this way larger ships can be created to carry more payload, except that all the rockets that leave Earth to create this big ship still have a maximum dimension that the payload must fit within. Even NASA's idea of creating inflatable spaceships cannot solve this problem as ultimately the size of the rocket that leaves Earth still determines the maximum dimension of the payload.)[38]

The maximum dimensions of a single object that can be launched from Earth today can be determined by the maximum payload, diameter and length of a rockets cargo hold:

Name	**weight carried**	**diameter**	**length**	)[39]
Ariane-5	6.8 tonnes	4.57m	10.35m	
CZ-3B	4.5 tonnes	3.80m	6.00m con 4.00m tap	
Energia	*22.0 tonnes*	*5.50m*	*37.00m*	
H-2	4.0 tonnes	4.60m	9.20m	
Space Shuttle	*5.9 tonnes*	*4.70m*	*18.60m*	
Titan III	5.0 tonnes	3.65m	11.00m dual	
Titan IV	5.2 tonnes	4.57m	12.20m con 4.0 tap	

From the vehicles that exist today the American Space Shuttle and the Russian Energia are the vehicles that can carry the largest payload. The Space Shuttle has the advantage of being reusable, however the Energia can carry nearly four times the weight of the Space Shuttle and is twice the length of the Space Shuttle. The Energia can carry a crate of 3.8m by 37.0m to Mars; of course a crate would not be a very efficient shape within the available space.

The economical cost of shooting a large number of these rockets to Mars will be astronomical, every launch would be a multibillion-dollar event, a Space Shuttle launch costs between $500 million to $1 billion. To this end there are a number of new possibilities that can reduce the amount of launches or that can drastically cut the cost of a launch.

There are a few alternative modern technologies and new technologies that could bring a payload to Mars in the future. Increasing the size of the rockets is probably the easiest option; there are a number of ideas in the pipeline that might be used, two examples are:

- The *Ares* as proposed by David Baker using Space Shuttle engines and fuel tanks can deliver a payload between 121 tonnes and 135 tonnes into a Mars trajectory, (not LEO!)

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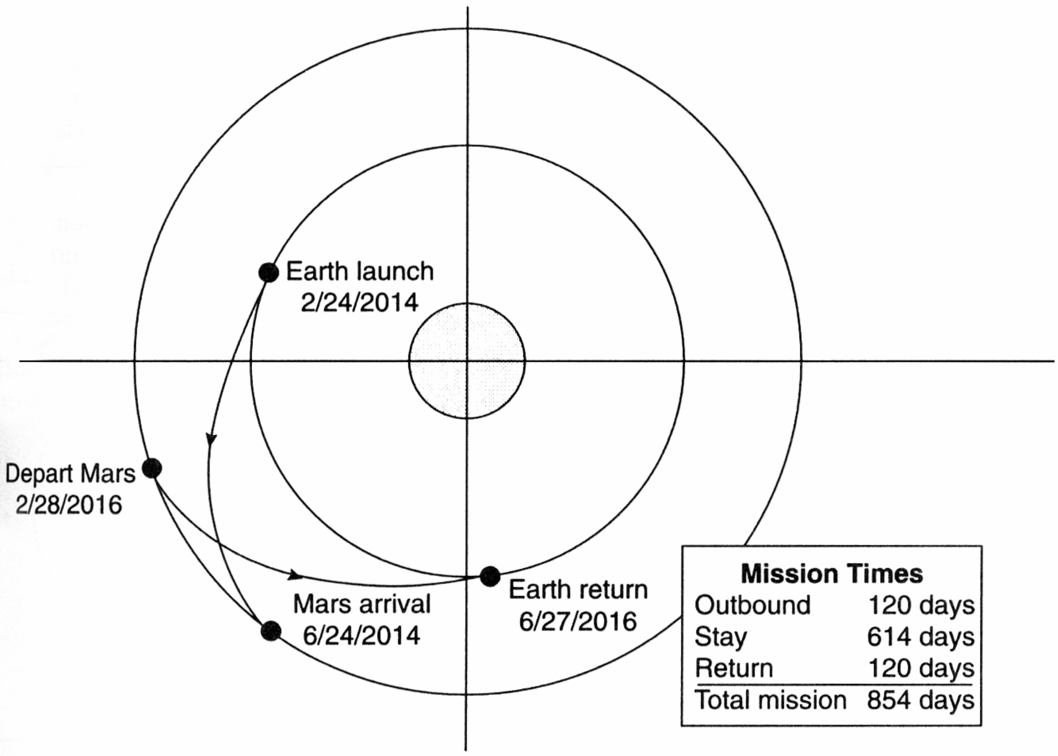
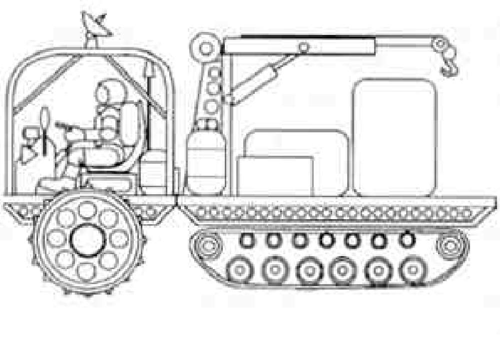
[38] Of course a spaceship that is assembled in LEO will be able to more payload with it, the dimension of a single object will always first have to fit in the rocket that lifted it from Earth.

[39] From Isakowitz 1995, compiled in Human Spaceflight, Mission Analysis and Design

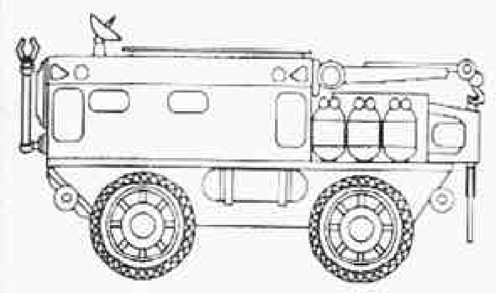


Typical Fast-Transit Trajectory between Earth and Mars. This figure shows actual launch and arrival dates as well as relative locations for this type of trajectory. This variation of the conjunction-class trajectory uses more propellant to reduce the outbound and return flight times.

A trajectory showing the possibility to travel between Earth and Mars in 120 days or 4 months.
[NASA, From Human Spaceflight, Mission Analysis and Design]



Flat-Bed, Open-Cab Utility Vehicle



All-purpose Pressurized Utility Vehicle

Vehicles will usually be multi purpose as this diminishes the need for more vehicles. The choice for pressurized or unpressurized vehicles depends on their radius of operation. Unpressurized vehicles do not need the large habitat shell and can have more equipment on board while the total weight stays the same.
[From Human Spaceflight, Mission Analysis and Design]

- The *Energia – B* design should be able to lift roughly 200 tonnes to LEO

A rocket with a payload of 140 tonnes would be able to deliver 28.6 tonnes to the Martian surface. According to Robert Zubrin this should allow the delivery via an Ares rocket of containers with a diameter of 10m and a length of 5m, which have been nicknamed *'tuna can's*.

By using nuclear propulsion the amount can be increased, however no test flights have yet been done with NTR (Nuclear Thermal Rockets). A 140 tonnes NTR would be able to deliver 46.3 tonnes of cargo to the Martian surface.[40]

Using nuclear propulsion allows rockets to travel to Mars much faster. The use of nuclear propulsion allows for 60 to 70 percent more payload delivered to the Martian surface. Another possibility is the use of a STR (Solar Thermal Rocket) for the interplanetary part of the mission, which would allow 30 to 40 percent more cargo to be delivered to the Martian Surface.

- A large nuclear powered freighter could be used between the orbits of Earth and Mars if an alternative can be found for bringing payloads to LEO. A freighter using a nuclear electric propulsion (NEP) engine would be able to carry a payload in the order of 182 tonnes.
  One alternative would be to use laser propulsion for Earth to LEO launches, these would be relatively cheap and with mass restrictions of 150 kg per time could still deliver a million kg a year to LEO. Preferably a larger set-up would be desirable to allow for larger objects to be moved to LEO.

It is clear that however near new technologies may be that it will remain expensive to move cargo from Earth to Mars. For now it is reasonable to assume that in the near future **45 tonnes** of cargo can be delivered to Mars by a single rocket.

[4.6] Trajectory

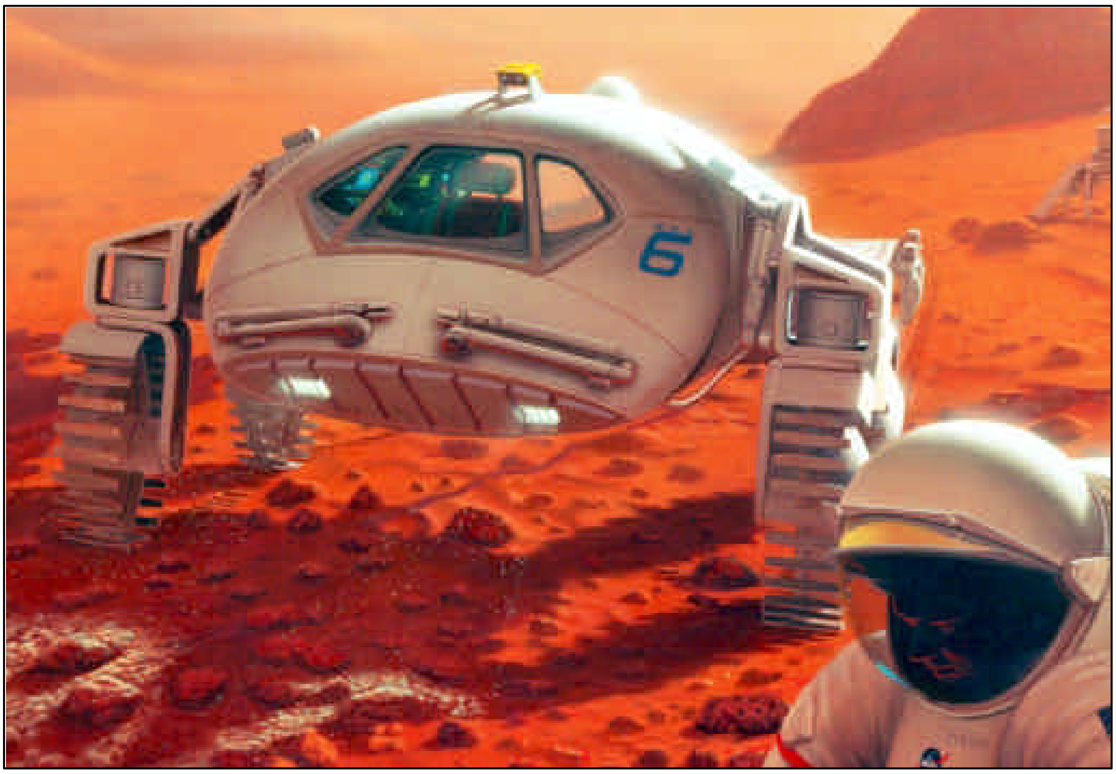
There are a number of trajectories that have specific advantages and drawbacks, however this paper will look only at the duration of a trajectory. Because of the limitations in fuel and the gravity of the Sun the total distance travelled from Earth to Mars will be more than 400 million km, which is the maximum distance that Mars is from Earth. At times Mars is only 53 million km from Earth but it is not possible to escape from the sun's gravity well to take advantage of this close proximity. Depending on when a mission leaves from Earth it will have to travel at least 120 days or four months.

[4.7] Local assembly and transport possibilities

The assembly possibilities will mostly deal with what options there are for the crew to construct a base. Once crew and cargo have been delivered to Mars it will be

[40] From The Case for Mars, by Robert Zubrin

necessary to move the crew and cargo across the hostile Martian terrain. Transporting a crew over larger distances will require the vehicles to



be pressurized, for vehicles that are only meant for work around the base it is possible to use unpressurized vehicles.
Construction of habitat elements and the placement of heavy loads will also require machines and vehicles. Heavy cranes and huge construction trucks will not be available(not at first anyway). Fortunately the Martian gravity is only a third of that on Earth allowing smaller vehicles to do the same as their larger counterparts on Earth. The lower gravity also means that the crew itself can lift and carry more things than they could on Earth, easing the demand on machines for construction work.

Therefore most habitats and bases could probably do without any large machinery. For transportation and construction the same vehicle will probably be used to minimize the number of vehicles needed to aid the crew in building and maintaining the base. Trailers can be added to the heavier vehicles to transport heavy loads.

The terrain surrounding the landing base will determine the type of the construction vehicle, whether it uses wheels, tracks or legs. Most probably wheeled vehicles will be used as they are relatively simple to maintain and can cover fairly rough terrain and are capable of carrying a heavy payload.

Kim Stanley Robinson advocates a huge scale approach in his fictional work Red Mars, dropping large amounts of vehicles and habitats on the planet:

"..the tractor inside the lander's crate was a Mercedes-Benz… The stacked crate walls made a ramp to drive the tractor off the lander; they didn't look strong enough, but that was the gravity again…the tractor rolled down without incident, and stopped on the ground: eight meters long, royal blue, with wire mesh wheels taller than they were. The crane prosthesis was already attached to the mount on the front end, and that made it easy to load the tractor with the winch, the sandbagger, the boxes of spare parts and finally the crate walls…The tractor itself was a real pig, with six hundred horsepower, a wide wheelbase, and wheels big as tracks."

A mature Martian base as envisioned by Tom Paine
[NASA, Strategies for Mars: a guide to human exploration]

[5.0] Martian habitats and settlements

During the last couple of decades a lot of different designs have been proposed to protect and facilitate explorers on Mars. The location, global settings and general requirements allow us to determine the necessities that every Martian habitat must conform to. The most important aspects of the location and global settings have been mentioned previously in their respective chapters. The most important factors for crew and equipment protection, and location benefits can be summarized in the following:

Protection from:

- Radiation
- Micrometeorites
- Atmospheric pressure
- Atmospheric temperature

Benefits gained by:

? Geothermal energy
? Ground water
? Atmospheric water
? Wind energy
? Useful surface material

Eckart and Koelle have collected the most important mission factors and the resulting design considerations in the following two tables.)[41] The first table discusses the influence of the environment on a base, the second table deals with crewed missions to Mars (or the Moon).

Environmental Factors	Influence on How We Design and Install the Surface Base
Partial gravity	Changes how we build equipment. Affects all fluid mechanical processes.
Low atmospheric pressure	Requires critical connections and sealing of pressurized elements. Adjusts the pressure levels in the habitat and Extra Vehicular Activity (EVA) suits.
Surface lighting	May need artificial lighting for certain operations
Thermal environment	Control temperatures and protect all surface elements
Dust environment, sand storms	Limit dust penetration and accumulation in or on surface elements. Affects availability of solar power.
Ionizing radiation	Protect crew and sensitive equipment from radiation.
Meteoroid environment	Minimize risk and effects of micrometeoroid impacts.
Surface resources	Affects availability of atmospheric or soil constituents that may be used to produce propellants, consumables, or other useful resources.
Surface features	Affects site preparation.
Surface roughness	Affects design of the surface-transportation system

[41] Eckart [1999] and Koelle [1986, 1990, 1991] From Human Spaceflight, Mission Analysis and Design

A future Mars explorer touching down on the Martian surface.
[Pat Rawlings]

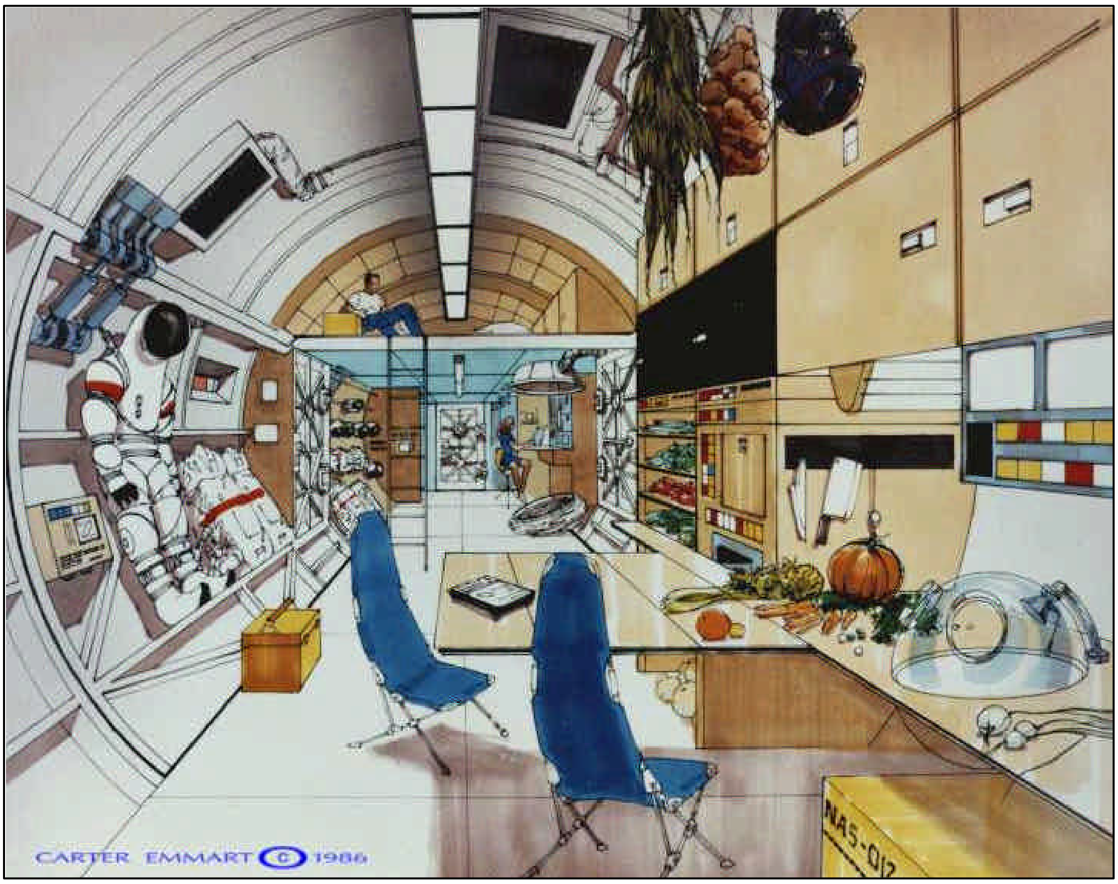
Mission Aspects	Design Consideration
Mission objectives	Required support equipment for science activities (labs, surface mobility), support infrastructure, power, and plants or facilities to develop in-situ resources.
Destination	Mars: relatively isolated (by distance) from Earth, long travel time, unknowns about environment, higher risk.
Number of crew	Amount of pressurized volume and consumables required, crew's health, effects on base mass, power requirement, and thermal load.
Mission duration	Pressurized volume required, system redundancy, spares and consumables required, type of life support system, shielding required, crew's health and medical support, crew's duty cycle.
Launch vehicles, logistics, infrastructure, and transfer vehicles	Limits on the vehicle's size and mass, fleet size, launch frequencies, turnaround times for vehicles.
Mission risk	Safety of crew, level of protection for crew, systems and equipment, system redundancies, spares required, fail operational vs. fail safe, system reliability.
Surface base evolves	Design for expansion
Mission cost	Use off-the-shelf technology vs. develop advanced technology; life cycle for design, development, test, and evaluation; crew's duty cycle.

As far as the *life support system*[42] is concerned it is assumed that all forms of habitats and bases use a closed loop system with the exception for food. Creating a closed loop system that incorporates food requires huge amounts of space to grow crops. A large permanent base should at some stage contain a true closed loop system though.

[5.1] Design principles

A number of different designs can be created even though the tremendous restrictions and recommendations for a habitation on Mars impose severe limitations. All of these designs will have to take a number of considerations into account, such as the changes in human circulation and the stair and ceiling heights due to lower gravity. One issue that should be avoided is that of *Sick Building Syndrome*[43], if it appears on Earth then it is problematic, if it appears within the habitat it could be disastrous. To this end PAX states that the environment should not cause sensory over stimulation and that the crew should have control over the environment. The design should also protect the personal rights of the crew. Whereby the environment should encourage

[42] All systems that are required to keep the crew alive and healthy.
[43] The effect that a building causes its occupants to feel stressed and or physically sick, usually attributed to the fact that occupants cannot change their surroundings with relation to temperature, sunlight and fresh air.



The interior of this habitat takes full advantage of ceiling height differences, colour schemes and visual connections between the different areas. (privacy does not seem to be particularly good though)
[Carter Emmart, 1986]

social contact but in such a way that there are degrees in personal and public space; primary, secondary and tertiary territories (much like your bedroom vs. your living room vs. your porch). Private relaxation and recreation must also be possible, one fictional example of this is the *Holodeck* which features in the *Star-Trek®* series, this is an empty room, which crew members can make use of alone or with others and which allows holographic projections to be displayed and interacted with.
Another factor that nearly all the habitats have in common is the private space for each crewmember. To this end PAX sets out a number of requirements that must be met for the interior of a habitat:

- Safe work environment
- Personalization of the workstations (whenever possible)
- Proper lighting of the work environment
- Buffers against noise
- Adequate ventilation
- Personal space for each crewman

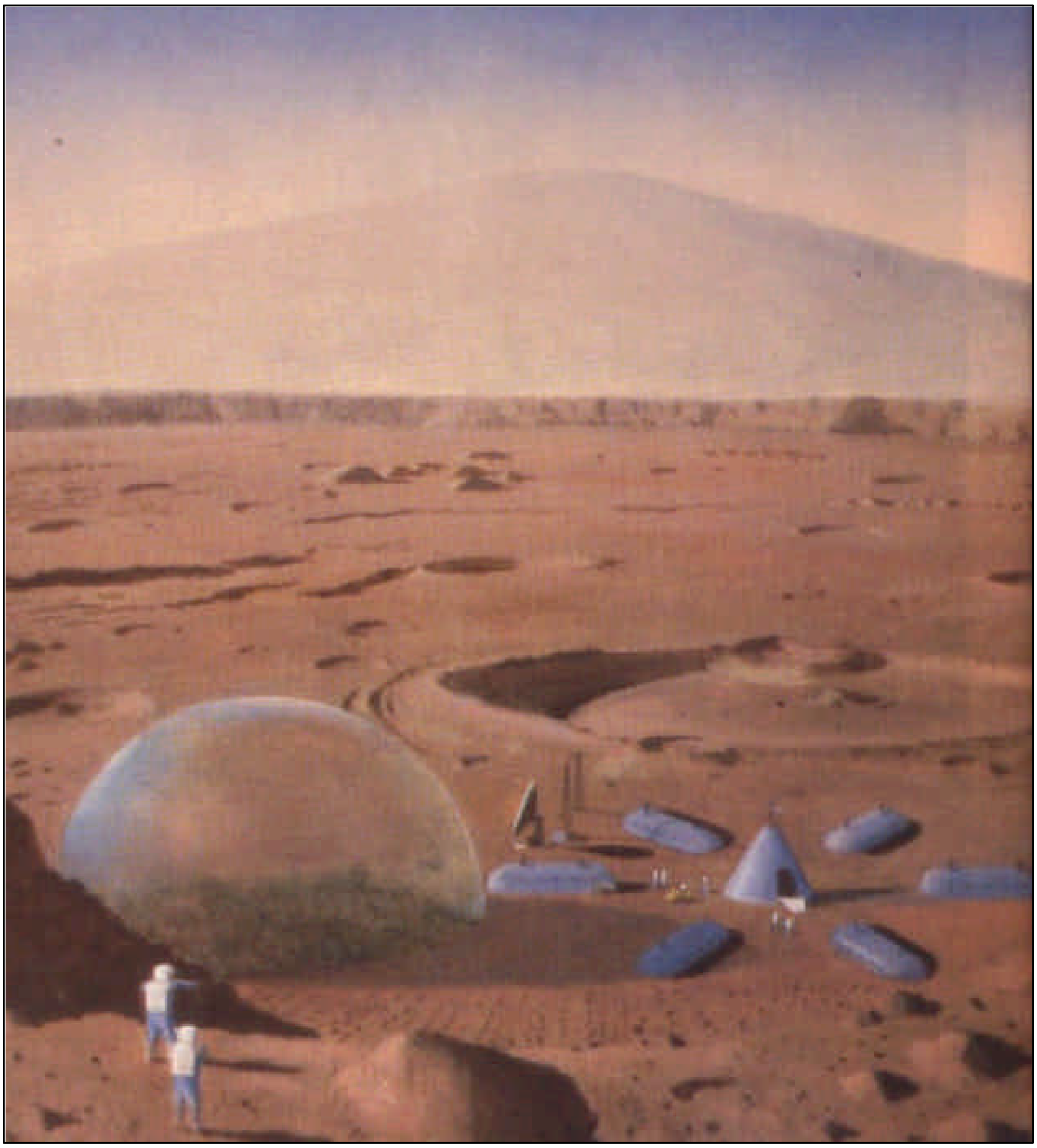
A couple of these requirements cannot be said to positively effect people, however if these requirements are *not* met they *will* result in a negative effect. *Jack Stuster*[44] also adds to this; the effect of non-personalized communal areas as this can have a negative effect on the crew as a whole. Research done in this field states that pictures of landscapes and other wide vistas seen from (what appears to be) a save vantage point is most often appreciated by crewmembers.[45]

The cost of floor space on Mars is much higher then anything terrestrial this means that excess corridors or areas with low usage are not desirable. Multipurpose use of corridors, areas and machines will have to occur; whereby circulation space should, whenever possible take place in the usable space of a room. Minimizing volume and using the same area for multiple purposes will result in modularising; this has a danger of creating monotonous spaces, which have a negative impact on crew moral. To counter effects like these it is important to create a variety of spaces and avoid easily comprehended linear spaces. Curvilinear spaces will produce rooms where not all surfaces can be seen at once making them appear larger[46]. Varying the floor heights, using light colours, creating visual connections between areas and using near excessive lighting are all methods that can be used to make areas seem larger and more spacious.

Conflicts might arise between different functions or space usage, to tackle this problem it is essential to separate some functions through the use of zoning. PAX has set (some of) the zoning requirements as:

- Base should be separated in habitat, power and launch/landing zones
- Work and relaxation activities should be separated from each other
- Habitats should be zoned from noisy to quite and from public to private

[44] From Jack Stuster; Bold Endeavors –Lessons from Polar and Space Exploration
[45] *"…in many ways replicate optimal living conditions during the millions of years of human evolution"* From Bold Endeavors
[46] Harrison, Caldwell, et al., 1988



A base on Mars. In the distance rises a broad-based shield volcano.
[From The Mars that Never Was, Chesley Bonestell/courtesy Space Art International.]

To maintain flexibility within the base it is important to use modular furnishings and where possible to create divisions using modular divisions that can easily be placed and removed to adapt to changing uses. These divisions can function as storage space (cupboards) to save room.

Depending on the type of habitat or base that is built the construction will vary, although it will most probably always be lightweight and modular, however it is also conceivable to construct with bricks baked from Martian soil[47]. As far as the materials are concerned they should at least be durable and easy to maintain.

The different designs that have been developed for Mars can be categorised by looking at the duration of the missions that they are intended for. This directly relates to how large these habitats and bases need to be and how much and for what purpose they need to use local resources. Initial surface stays up to 500 days can be done in semi-permanent bases (or habitats), longer stays of two years and more will require permanent bases or clusters of the former bases/habitats.

[5.2] Layout of a base and elements needed

A base needs to be planned and so logistics and transport play a vital role in the functioning of a base. Although the scale of an instantly deployable habitat and a permanent base varies greatly their layout can both be divided in different zones of operation. The same can be said for the elements that a base will need, even though a permanent base will have certain facilities that a temporary or semi-permanent base will not be able to support. The (primary) elements that are needed for a base[48]:

- Habitat,
- Laboratories and surface based science, pressurized rovers could be used for this task
- Extravehicular activities and airlocks
- Life support
- Power supply
- Thermal control
- Communication and navigation, line of sight is important
- Surface transportation and construction
- In-situ resource utilization
- Logistics and resupply

Very small bases and habitats can combine elements within a habitation module (such as life support, power supply and thermal control) whereas large bases will need to have large scale separate units for all these elements The layout of the base can be set up in a number of zones, whereby the habitat is placed centrally so that all other zones are easily accessible and the amount of travel that the crew must undertake to maintain the base is

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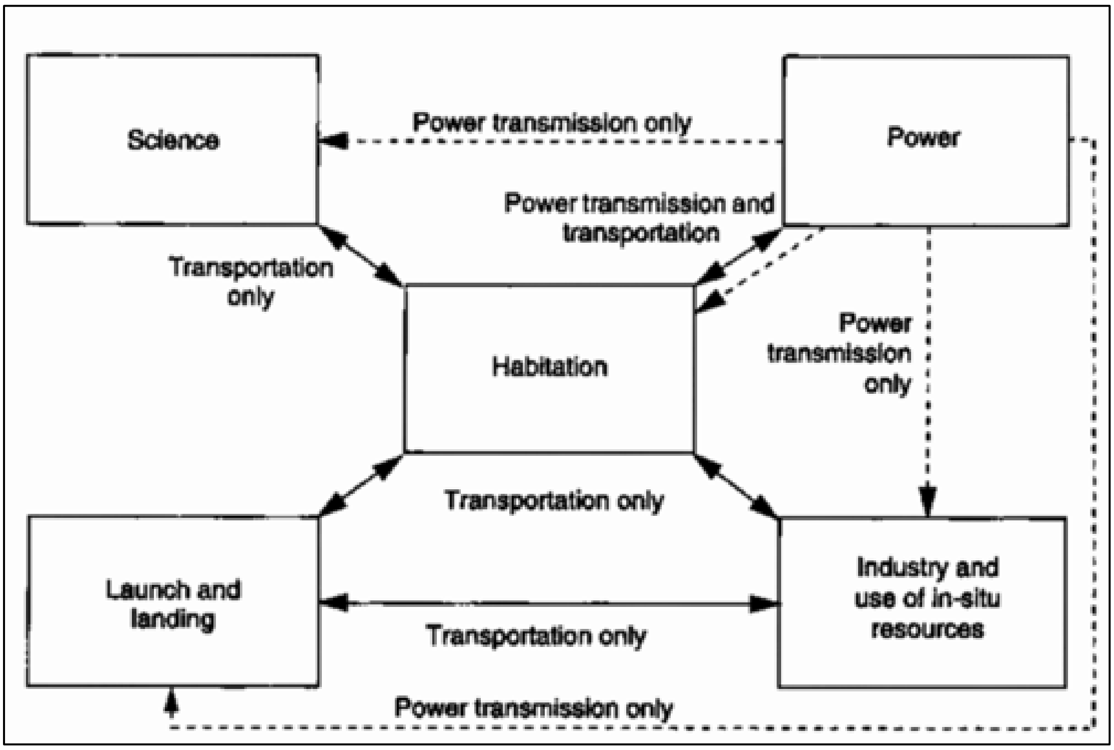
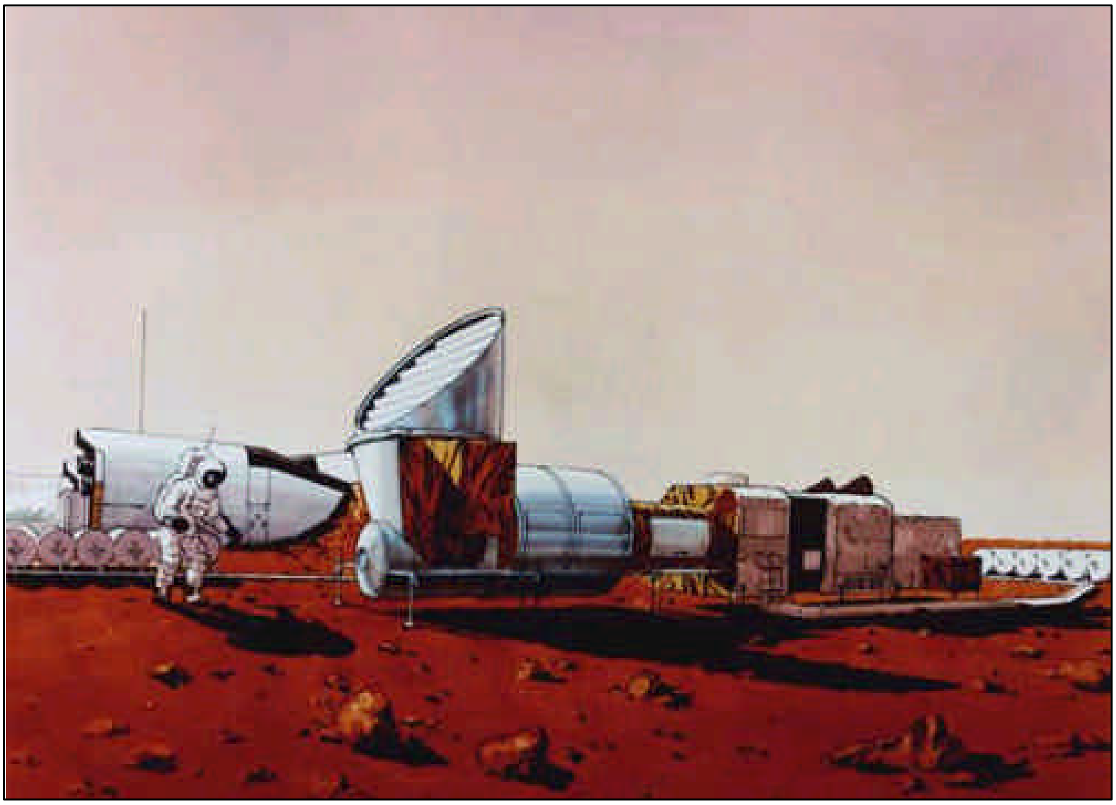
[47] See ‘Permanent Habitats’ for more information on different ways to build a habitat.
[48] From Human Spaceflight, Mission Analysis and Design



The base is divided into different zones that are connected to each other by transportation or power connections (or both).
[From Human Spaceflight, Mission Analysis and Design]



Close up of the gas extractor. This machine, operating like a jet engine, sucks in the thin Martian atmosphere safely above the surface dust. Compressing the mostly carbon dioxide air, it separates out oxygen, nitrogen and argon for breathing, and carbon monoxide.
[Carter Emmart, NASA]

minimized. Kriss J. Kennedy from the Johnson Space Centre has defined a way in which the elements are divided in zones:

- Habitat: The central point of the base where everything that has no reason to be in one of the other zones is located. Maintenance facilities, hangars for surface transport vehicles and laboratories should be located here.

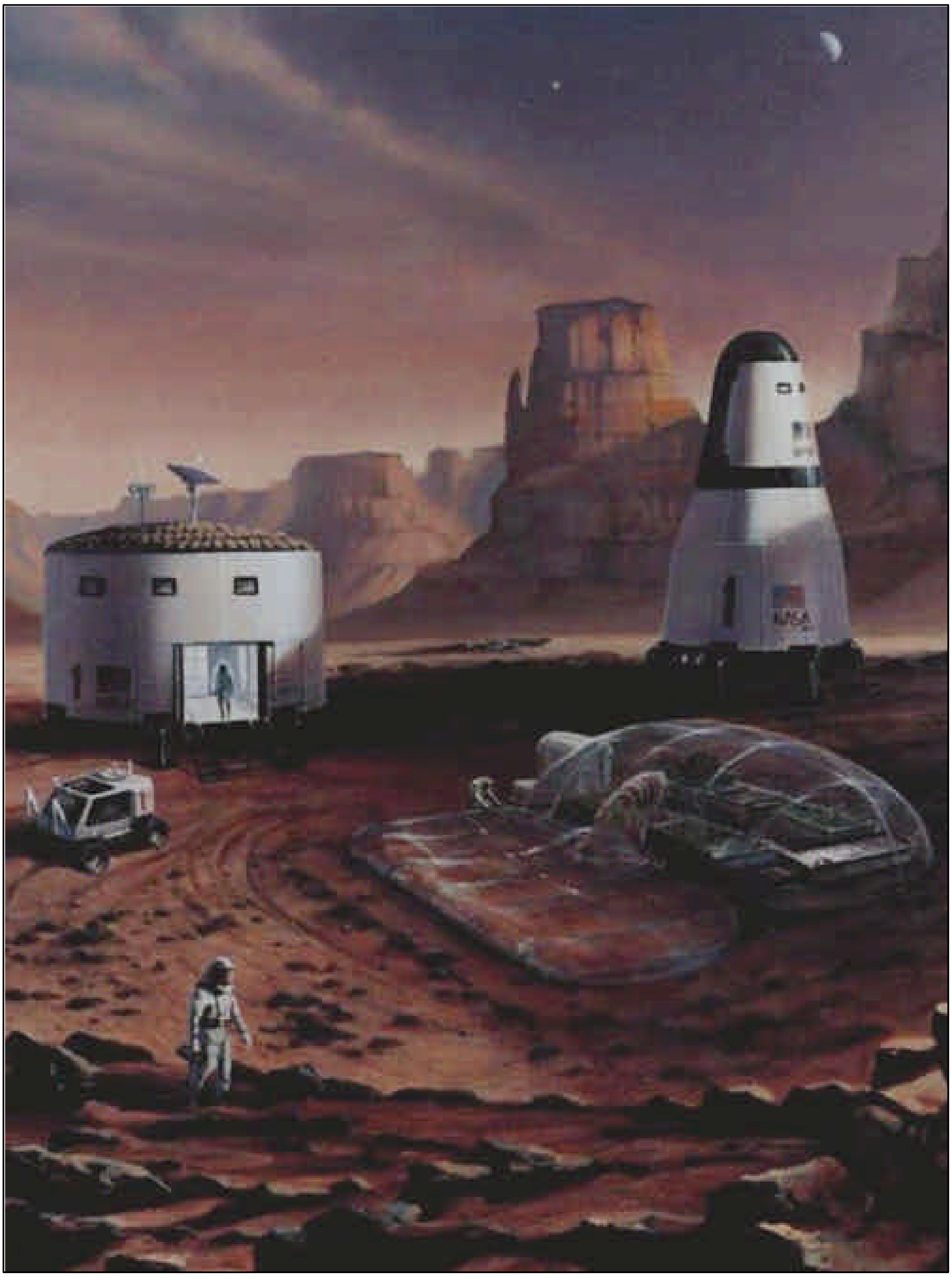
- Science: These laboratories should be located far away from the launch and landing zone and possibly near the habitat area. Contamination from other activities should be avoided. Remote power capability is a must.

- Power: The power zone is a difficult area; it has to be located as far away from the habitat and launch and landing zone as possible. Close proximity to the other zones is preferable. Contamination from nuclear power plants must be avoided; this zone must be several hundred meters from the habitat zone. Solar arrays should be placed well away from well-traversed areas and the launch and landing area to avoid dust reducing the input of the arrays. A host of regulators, storage cells, and relay stations are needed, the power must be transported to the different zones separately so a failure in one system doesn't affect another system.

- Industry and Use of in-situ resources: The production facilities should be as close to the in-situ resources as possible. This zone should be near the power zone (to reduce transmission losses), habitat zone for easy maintenance and far away from the science zone and the solar arrays. The probability of these facilities producing dust means that some form of shielding should be considered.

- Launch and landing: This area should be a hardened level area, with a navigation aid to help incoming spacecraft. The landing zone should not require trajectories that cross over any of the other zones, so as to minimize the risk of disastrous crashes. On a more advanced level refuelling vehicles and depots, cargo loading and unloading systems, surface roads and more sophisticated navigation aids will be possible.

The different zones are connected by different methods depending on the needs: The power zone for instance only needs to be easily accessible in a physical sense from the habitat zone, while all other connections to this zone do not require people to move between them. These latter connections are accomplished by power cables. (See pictures) The size of the zones is dependant on the mission outline for the base, a reconnaissance mission would require much less facilities then a large scale science base.
An example is the area that is planned for greenhouses; a small scale mission with four people staying a limited time on the planet has an experimental greenhouse of only 200m^2, while a permanent base for 300 people has 15,400m^2 reserved for greenhouses. It is therefore very hard to give a rough overall estimate on the size of zones and the elements they contain.



The *Martin-Marietta Mars Direct MSR Mission Design Habitat* is built up around a habitat and an Earth return vehicle that is fully fuelled and operational when the crew arrives on Mars.
[Martin-Marietta, Robert Zubrin]

[6.0] Semi-permanent bases

The semi-permanent bases are those habitats and bases that do not necessarily develop into permanent bases. It is very likely though that a semi-permanent base placed on Mars will grow out into a permanent base, or that the location will be used for a permanent base. Because of the large costs involved in getting it there in the first place it is unlikely that a base will be left alone and forgotten. But it might be possible that a semi-permanent base does not have a crew during it's entire lifetime, while a permanent base *will* be staffed during it's entire lifetime. The semi-permanent bases are divided into *Instantly Deployable Habitats* and *Converted Habitats*.

[6.1] Instantly deployable habitats (IDH)

These types of habitats can usually be used as the crew habitats during the voyage to the planet and are then landed on the planet where they continue to serve as habitats for the remainder of the mission. They are similar to the converted type habitats except that the latter are generally used to transport cargo during the voyage to Mars and are then converted to be used as parts of a (larger) base. The most well known instantly deployable habitat is the *'tuna can'*. The tuna can exists in three different types; all are relatively similar and differ mainly on the way they are deployed. They are all related in some way and were probably designed jointly for the most part. Other versions do exist of the *Instantly Deployable Habitat* (IDH), nonetheless all share similar characteristics except for the shape of the vehicle. The IDH's are one of the most compact forms of habitat that can be placed on the Martian surface, for this reason they will always struggle to fulfil all of the requirements yet they still manage to realise quite a number of them[49]. They are meant to be semi-permanent with the ability to be linked. The three 'tuna can' designs are:

- Martin-Marietta Mars Direct MSR Mission Design Habitat [1992]
- First Mars Outpost Habitation Strategy, by Marc M. Cohen [1992 /1993]
- Mars Reference Mission, by Hoffman and Kaplan [1997]

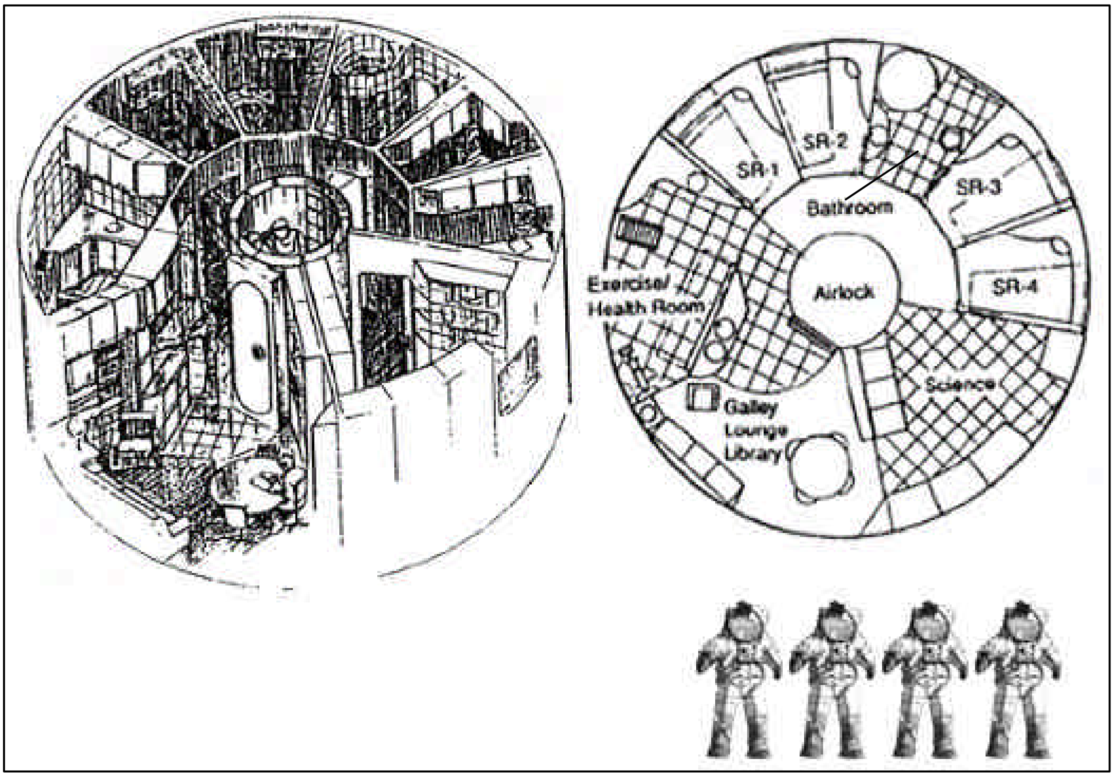
[6.2] Martin-Marietta Mars Direct MSR Mission Design Habitat

This version of the tuna can proposed by Robert Zubrin and his team at Martin Marietta Astronautics consists of a round module 5 meters high and with a 10 meter diameter. Several other modules are launched before and after this module, for backup purposes, the next mission and to provide a means for getting back to Earth. Propellant is only brought along for a small part; most is gained from the Martian atmosphere (in-situ).

The module is divided into two 2.5 meter high compartments, the total floor space is over a 100m². The module can support four people and has a closed-loop life-support system integrated which allows the recycling of water and oxygen. The habitat holds over 7 tonnes of food and water for the crew.

[49] Most of the IDH's that are described in this work have not been detailed completely so it is difficult to ascertain if they do or do not meet the set requirements mentioned above.

Martin-Marietta Mars Direct MSR Mission Design Habitat on Martian surface
[the Case for Mars]



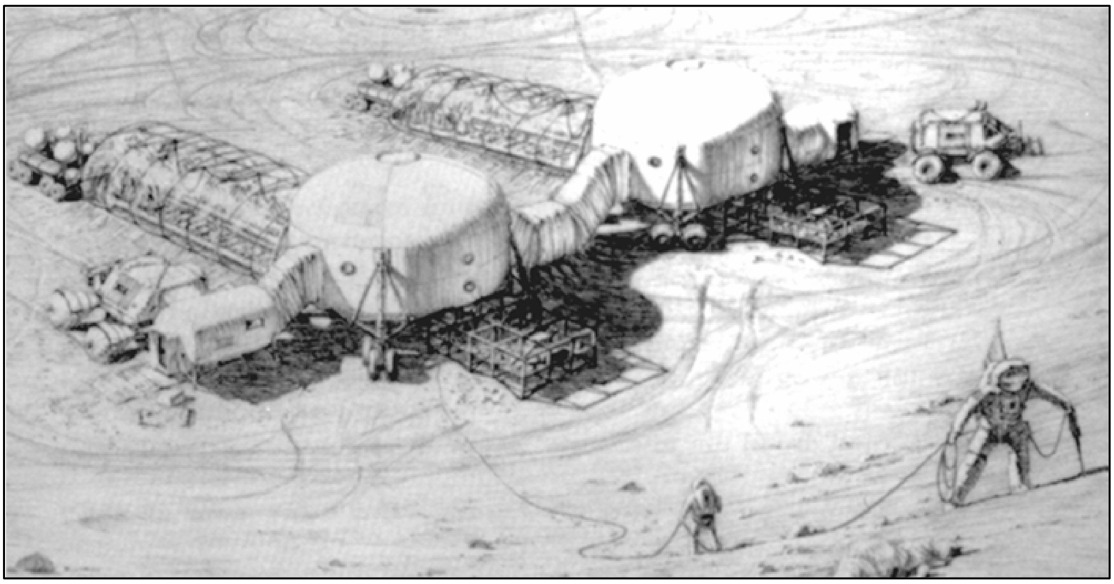
Schematic of the Mars Direct MSR Mission Design Habitat. In the event of a solar flare, the airlock could double as a storm shelter for the crew of four (4).
[the Case for Mars]

Included in this module is a pressurized rover that can be used to explore the planet, or function as another habitat should the original one fail. The roof is covered after landing with sandbags to shield against radiation The planet and the atmosphere shield the crew from most radiation and the additional sandbags will stop virtually any remaining radiation.

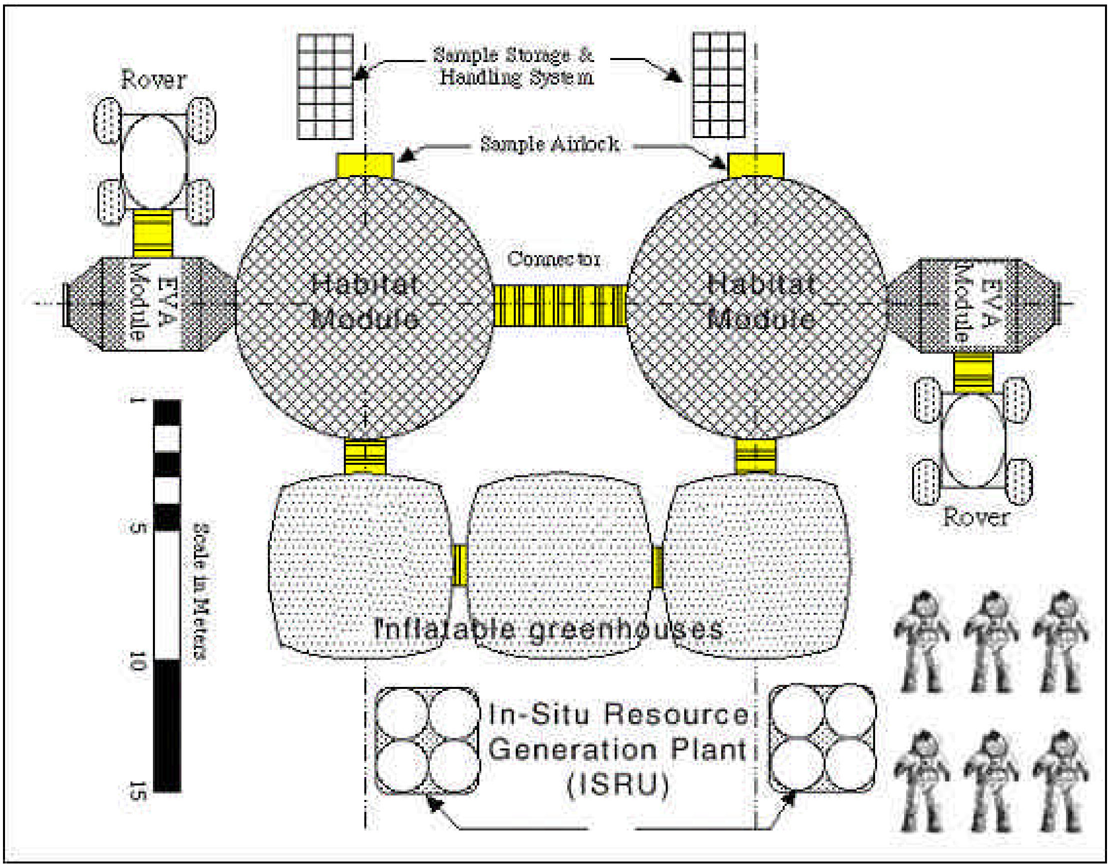
On the top level the habitat contains four private rooms for the crew. These allow the crew to have their own space, which is deemed important even though the crew will be busy most of the time with duties. The bedrooms of the crew are paired around the shared bathroom. A small hallway connects the bedrooms and the bathroom with the other facilities on this level. A galley/lounge/library is located directly opposite the bathroom and contains: *'books, games, writing supplies, and other materials to support various hobbies or amusements.'* Located to the left of the galley is a science room that can be used for science work and research. The exercise and health room is located left from the galley and is next to the kitchen. One of the most important rooms on this level is the airlock. The air lock doubles as a solar storm shelter and connects the two levels whereby the lower level gives access to the Martian environment.
On the lower level there is space for the pressurized rover another science lab and storage areas for samples. The large area below enables the rover to be repaired and fitted within a closed environment. The total weight of the fully loaded habitat is over 25 tonnes. If the habitats are fitted with wheels or other transportation devices (as is proposed by Robert Zubrin) then multiple habitats can be linked by inflatable tubes. The habitat remains on the planet as the crew leave in a separate module, this means that a base can grow mission after mission.

This design incorporates the requested zoning by placing private quarters together along a small hallway that connects them to the other facilities. No noisy activities take place on the living quarter level. Apart from the science room all the work related activities are located in the lower level. Multiple use of space does not really occur except for the kitchen, which is used to access the galley. There are no differences in floor heights or visual relations between the different areas. The small amount of space that is available to the crew however does contain private areas and recreational areas. The amount of control that the crewmembers have over the environment, lighting or ventilation is not known. The crew will spend 500 days on the surface in this habitat the redundancy system in this plan does not include a secondary linked habitat that can be used as extra space for the crew. The redundancy in this plan is accomplished by using the pressurized rover and the *Earth Return Vehicle* (that are not directly linked to the habitat) as a backup. This means less room for the crew but is more space efficient.

An inflatable greenhouse has also been brought along to grow fresh crops on the Martian surface. The inflatable greenhouse is constructed of thin UV-resistant hard plastic domes. These domes measuring up to 50 meters in diameter can be brought from Earth.



Two linked habitat modules. With two greenhouses connected, a later proposal connects three greenhouses.
[Carter Emmart, National Center for Atmospheric Research]



The habitats connect on three sides to different modules; EVA, Greenhouse and a Sample Airlock, a fourth connector connects two Habitat modules together, combined they house a crew of twelve (12).
[NASA, Strategies for Mars: a guide to human exploration, Marc M. Cohen]

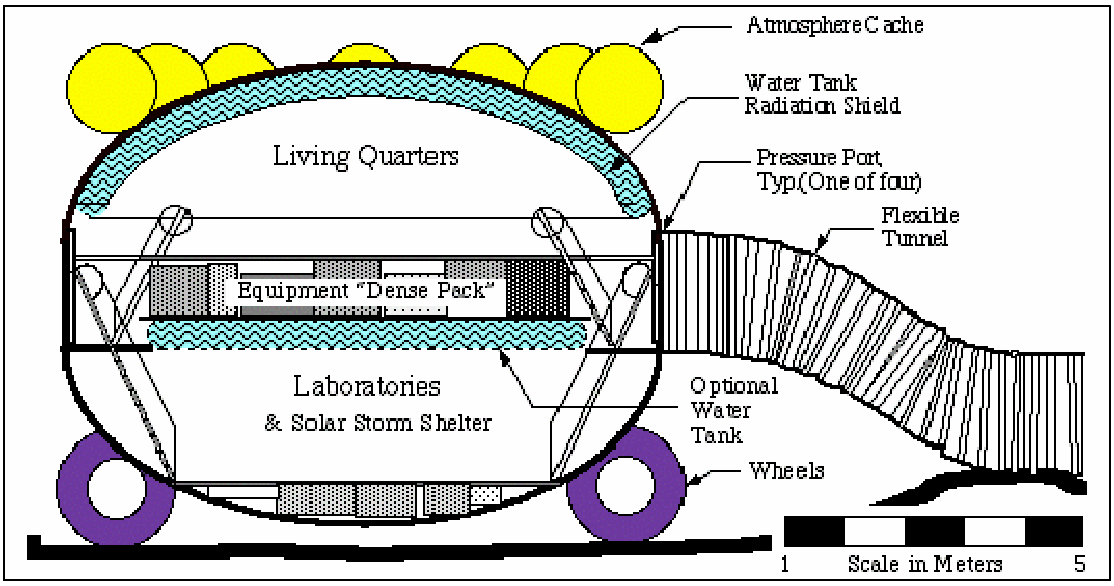
[6.3] NASA First Mars Outpost Habitation Strategy

This design is similar to the *Martin-Marietta Mars Direct MSR Mission Design Habitat*, the main difference is that the habitat module and the flight module are two different components. The reasoning for this is that radiation shielding in a flight module has to surround the module on all sides whereas a habitat module only needs to offer (less) shielding from the top as the planet blocks out radiation from all other directions. The crew habitat is therefore flown out before the flight module this means an extra launch is needed, however crew safety is heightened and the flight module can be reused. The interplanetary craft can cycle between the planets using orbital docking and deliver people to and from Mars.

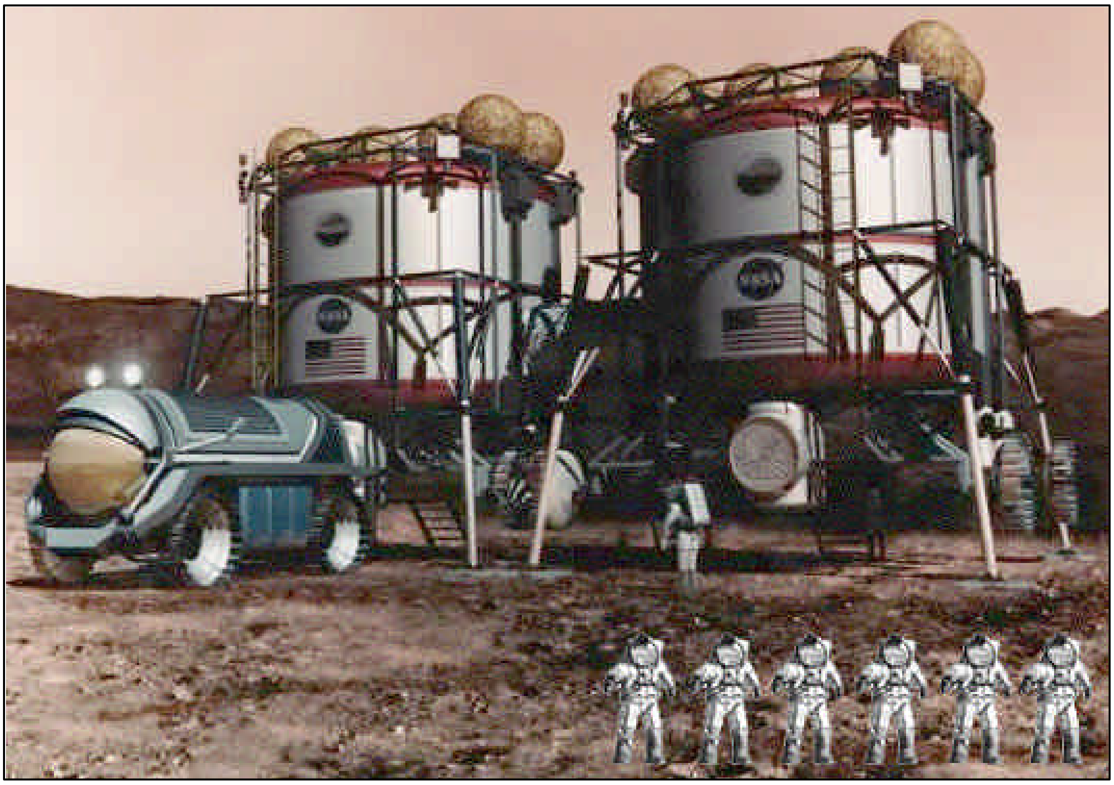
As a habitat module the main differences are the connections that allow a number of other modules to be connected. The module connects on three sides to other modules and on one side to a sample airlock, which permits samples from being accessed that have previously been deposited from outside of the habitat. The other three connections are: a greenhouse, an *Extra Vehicular Activity* (EVA) module and a second habitat. The greenhouses are similar to those of the Martin-Marietta version but are here joined together in such a way that they are the first volumes that receive oxygen from the *In-Situ Resource Generation Plants* (ISRU plants) and are used as a buffer area. The EVA module attaches to the pressurized rover or grants access to the Martian surface. The pressurised rover does not require the user to wear special clothing or equipment, any crewmember that wants to enter onto the Martian surface however must wear a Mars/Space suit. The second habitat is used as backup in case there is a fire or other major disaster. The backup on the Martin-Marietta habitat is landed further away, and is accessible by pressurized rover this means that if it isn't used for an emergency it can still be used by the next crew for new exploration. However in this strategy the crew could use the second habitat to enlarge the crew living area. This increase of the living area and the laboratory space, together with the connected greenhouses mean that it is possible to wander around the base (in normal clothing). The resource plants have been located outside the closed life support system and far away from the crew living quarters minimising potential noise problems.

The interior of the habitat is not unlike that of the Martin-Marietta habitat except that the instruments and equipment are used as additional radiation shielding. The habitat module is divided in two levels. The top level has been assigned as living quarters, instead of placing sandbags on the roof against radiation the top of the habitat modules have water compartments placed in the ceiling. Water compartments have also been placed in the ceiling of the lower level where the laboratories are located. Two water compartments, a dense pack of equipment and supplies, shield the lower level. This allows the lower level to be used as a storm shelter. The four connections on the habitat module will probably reduce the amount of efficient space available, however this is partly negated by placing all the equipment in the floor.

Wheels are not optional in this design as the habitat modules are intended to be connected immediately and precision landing is not something that can be



The habitat design for the *NASA First Mars Outpost Habitation Strategy* shows two levels protected by two layers of water, the habitat connects on four sides to other modules.
[NASA -Ames Research Center, Marc M. Cohen]



Mars Reference Mission, showing two habitation modules and a pressurized rover on the foreground. The double habitats house a crew of six (6).
[Nasa]

guarantied. The habitats are so heavy though that they can only be moved over flat surfaces.

[6.4] Mars Reference Mission [50]

This mission is a culmination of the other two missions and can be seen as NASA's official Mars habitat.[51] It resembles the *Martin-Marietta* habitat even more so than the *First Outpost Habitat*. The major difference is that it, like the *First Outpost Habitat* places two modules directly next to each other. One of the habitats (surface laboratory) is placed on Mars before the crewed module (transit/surface habitat) arrives. This surface laboratory is essentially the same as the other module but has no consumables; it effectively doubles the pressurized volume of the habitat. This laboratory module can also be used for emergency backup purposes.

The dual habitats allow for more crew space but lack the greenhouses of the *First Outpost Habitat* that creates a larger area for crew to wander around. The interior of the habitat is designed for maximum efficiency and offers the crew a spacious living quarter without wasting any space. A lot of the furniture can be compacted to allow the space to be used for different activities.

The modules are composed from cylinders with a 7.5m diameter; the cylinder is composed of two parts just as the other tuna can models. Each level is 3m high.

A similar energy source (nuclear) is used on all three of these projects and a *ISRU* plant.

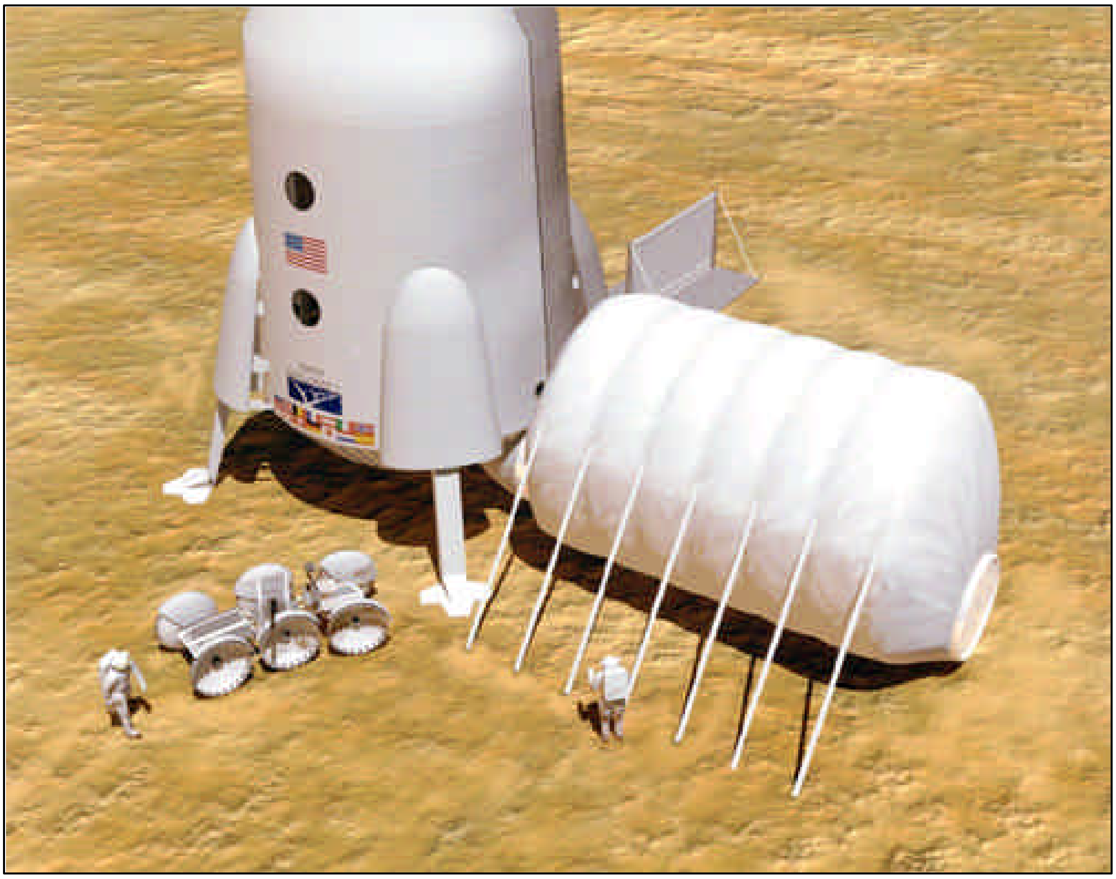
[6.5] Other instantly deployable habitats

Aside from the different *tuna can* models there have been few mature IDH concepts in the recent past. The only other concept developed by NASA is similar to *Martin-Marietta Mars Direct MSR Mission Design Habitat* except that it uses a conical shaped craft and uses an orbiting space-craft to transport the crew back to Earth. One feature that is more present in this plan is the use of pressurized (inflated) volumes; although the *tuna can* models use inflatable greenhouses, this habitat also uses an inflatable laboratory that increases the pressurized volume for the crew. Using pressurized volumes is one of the easiest ways to enlarge a habitat; the low weight to volume ratio makes it ideal to create structures with on Mars. The anchoring of the inflated structures to the surface is something that requires attention, but should not pose a problem as all links between structures are usually designed with flexible connections. Puncturing an inflated volume could pose a problem, although modern high strength plastics are extremely tough. Larger inflatable volumes can survive a puncture a long time before any serious problems occur:

"A habitation mad of rip-stop Kevlar fabric is unlikely to fail catastrophically. Even if someone shot a large-caliber bullet through a 50-meter diameter

[50] See supplement [s.2]
[51] Note: NASA currently has no formal plans for a human expedition to Mars or the Moon.

The interior of the habitat is designed for maximum efficiency and offers the crew a spacious living quarter without wasting any space. A lot of the furniture can be compacted to allow the space to be used for different activities.
[NASA]



The completed outpost on Mars includes the crew's two-story lander habitat, inflatable laboratory and unpressurized rover.
[NASA S97-07837, 1997]

dome, it would take over two weeks for the air to leak out, leaving plenty of time for repair."[52]
Off course the leak would have to be fixed much earlier to stop the pressure becoming to low for human habitation, but it does show that a large inflatable structure is relatively safe.

The older concepts such as those proposed by Wernher von Braun in the late 1960s are closely linked to the *Apollo Lunar Module* used by the first astronauts to land on the moon. The design for these early Mars modules is slightly different and the expected duration of the mission is of a much lower order (a couple of weeks at the most). However the basics are much the same as that of the tuna can modules:
"We land on landing gear, open a hatch again, get a vehicle out which provides mobile transportation. We also have quarters to accommodate the crew for maybe a stay time on the Mars surface of a month or so, so there will
be sleeping and cooking facilities and some equipment to take a first glance at samples, maybe some microscopes, maybe some infrared capability, and so forth.."
Von Braun's original mission which he described in "*Das Mars Projekt*" had multiple landing boats which were more spaceship than habitat and were only meant to stay on the Martian surface for a short time. Most of the other concepts all hinge on similar Apollo Lunar Module designs and are roughly similar to von Braun's design.

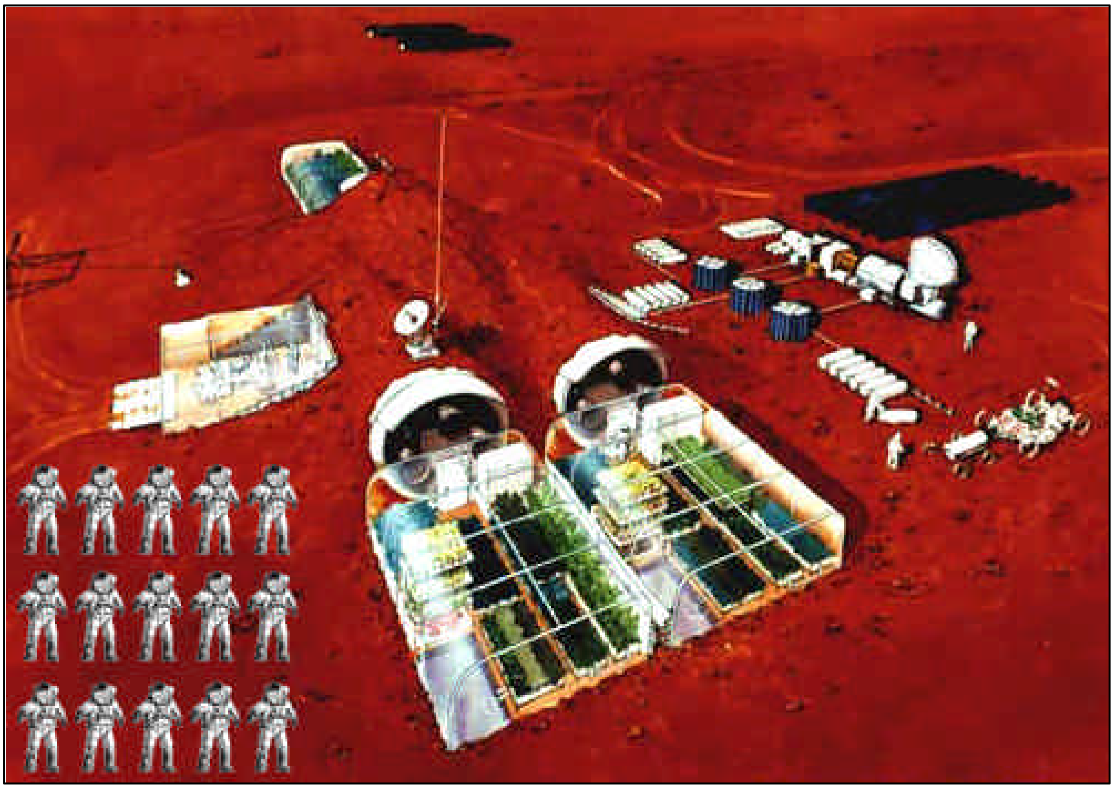
A different approach that has been suggested is to first land standard cargo modules and convert these into habitat modules.

[6.6] Converted habitats

The *Converted Habitats* involve more work on site to set up but are more flexible in their use than the *Instantly Deployable Habitats.* The converted habitats have the difficulty that they are not easy to categorise as they can either be an extended IDH or a primitive permanent base. The converted habitat described here is intended for a larger crew and for multiple uses making it much more independent then the IDH plans. This mission scenario for the human exploration of Mars was developed at the Case for Mars II workshop in Boulder Colorado held July 10-14, 1984:
Three spacecraft are docked in transit to Mars and contain a number of modules. The quarters for the crew on the planet and the quarters in transit to Mars are different; similar to the *First Mars Outpost Habitation Strategy habitat.* These space flight habitat modules (of which there are six) contain:
'… crew quarters, one of the three landers, and part of the crew transfer tunnel. Each habitat module provides the living and working volume roughly equivalent to one mobile home. Spread over six such modules, this gives the total crew of fifteen men and women adequate accommodation. The smaller compartment of the lander is nested by tanks of fuel and consumables in order to provide enough bulk shielding in the event of intense radiation from

[52] From the Case for Mars, by Robert Zubrin

Cargo landers are converted to habitat modules.
[Carter Emmart, 1986]



The landers have been converted to habitats and pressurized greenhouses and entry have been added to the design. The habitats house a crew of fifteen (15).
[Carter Emmart, 1986]

occasional solar flares. A pressurized tunnel connects the other spacecraft via the docking ports which are large enough for crew and equipment transfer. In the event of systems failing in one module, multiple module redundancy gives added safety for the long voyage beyond help.'

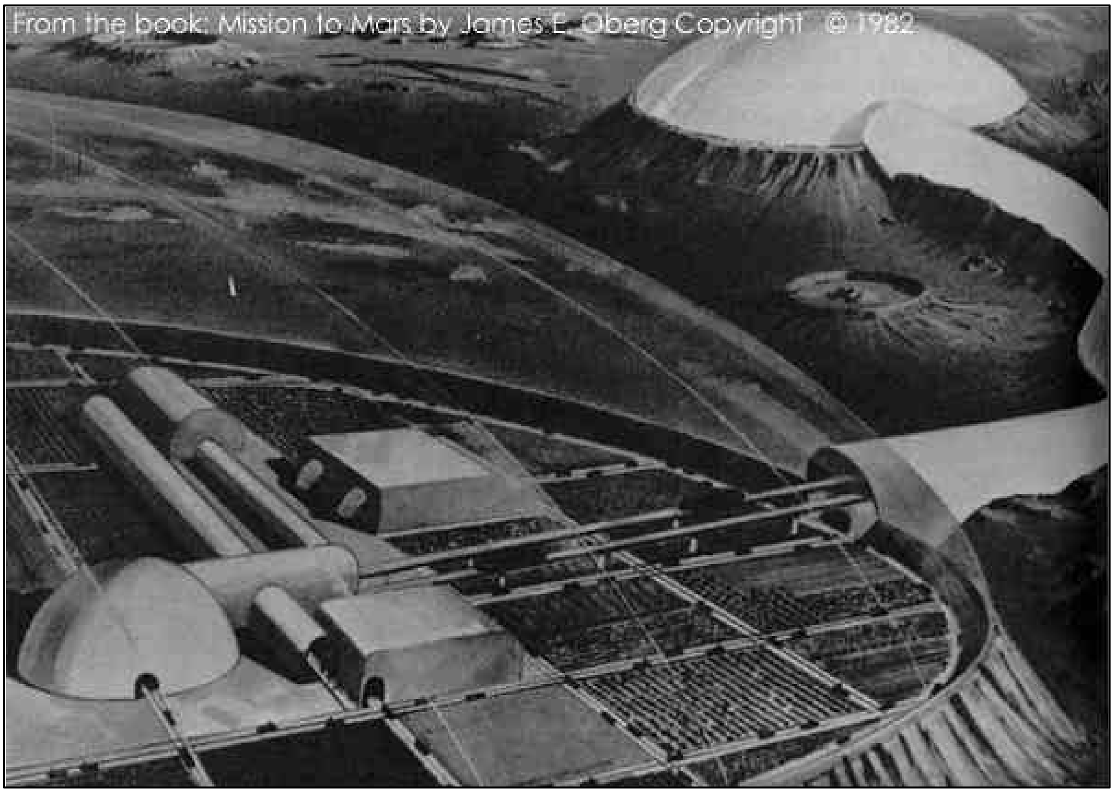
Only the landers go down to the planet, the remaining craft orbits Mars until the landers return and rendezvous in orbit to return to Earth. Once in orbit the landers go down to the surface and home in on previously deployed unmanned cargo landers. The landers that the crew landed on the surface remain upright (like a rocket) and refuel for their ascent later, the cargo landers have been landed on their sides. The cargo landers are unloaded and towed to a permanent location that is a safe distance from the crew landers (to avoid any damage when these take of at the end of the first crew's stay) but not to far away. The cargo landers are placed with their noses together, connected and pressurized (see picture) to serve as the habitats for the crew. The cargo landers will have airlocks installed and by removing one of the engines a greenhouse can be attached to each lander. Nuclear power supplies are placed at a safe distance from the habitats, the other resource utilities that create breathable air and fuel are placed near the habitat. The greenhouses are slightly pressurized and through advanced intensive agriculture can provide the crew with food and act as a partially closed biological system. Pressure differences between the habitat and the greenhouse means that airlocks are necessary.

The interior of the landers (see picture on page 56) each has a living volume that is slightly larger than a mobile home, giving the crew a reasonable amount of space to live in. The extra floor means that there is more space to store cargo. Soil is used to cover the habitats and protect them from radiation.

Eventually this habitat will be able to expand into a permanent base:
'With the support of more cargo shipments, and a continuous cycle of crew, this scenario would establish a self-sufficient, permanent, expanding, scientific outpost on Mars similar to our research bases in Antarctica. The importance of this design shows such a mission could be done soon and relatively cheaply using available technology and equipment.'[53]

[53] Carter Emmart

Possible future Martian city?
[Don Dixon, 1999]



Domed buildings and cities have long been the realm of science-fiction, but maybe they can hold the solution for large settlements in hostile terrain.
[James E. Oberg, 1982]

[7.0] Permanent habitats

These habitats will be built once a permanent presence of man on Mars is desired. A permanent habitat requires a large amount of resources and man hours to complete and maintain, but in turn allows for more research capability and can support many more people. The permanent habitat can be extended or connected to semi-permanent habitats that have been used on previous missions. Alternatively these earlier habitats can be used as living quarters while a complete new habitat is built.

[7.1] Structures and materials

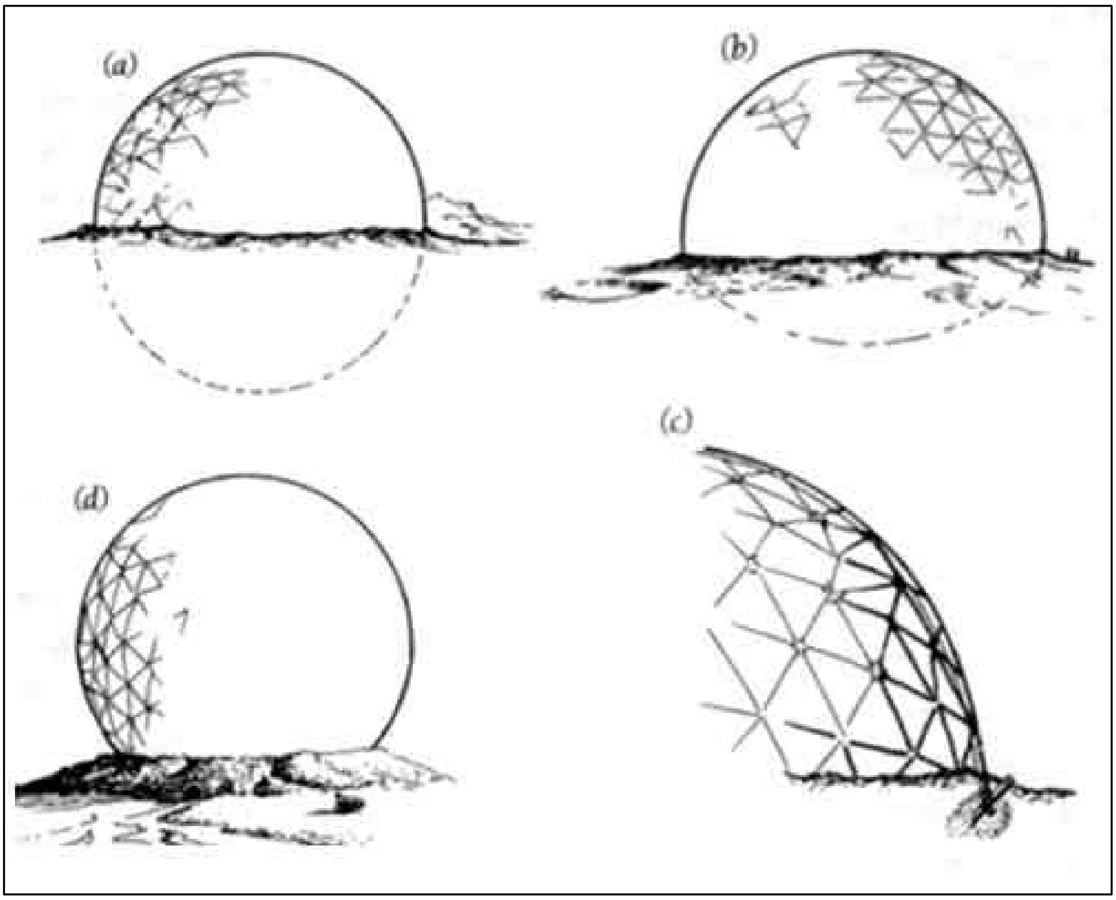
It is clear that *permanent* bases and habitats require a different approach to *semi-permanent* bases and habitats. Because they are much larger in scale they need to strive to some form of self-sufficiency and require large greenhouses and power/resource plants. The much larger scale of a permanent base means that assembling everything on Earth and just blasting it of to Mars does not make any sense as the cost per kilogram is just to high. So it becomes necessary to create structures on the Martian surface, either by using local materials or by bringing construction materials from Earth. The main difference between these two methods is the technology involved:

- Construction materials brought from Earth will have to be light and can be very high-tech as all the necessary facilities are available on Earth. Domes and other prefabricated structures are relevant examples.
- Using local materials will require relative simple techniques because of insufficient high-tech facilities available. Brickwork vaults and other on- site manufacturing methods can be employed or found in the form of caves.

[7.2] Domes

If we look at science fiction then the most famous construction type for any base situated on an alien world is probably the dome. But even in the real world the dome is seen as a realistic way of creating a controlled environment. The dome creates a space that is separated from the hostile surroundings outside and enables any chosen environment inside. Buckminster Fuller’s idea of covering Manhattan with a gigantic dome is one of the most famous examples in architecture. Maybe the biggest advantages that a dome has to offer is that it is lightweight, needs only a minimal construction and has a very low surface to volume ratio. The dome has many advantages, on Earth as on Mars:

“All domes share certain advantages, whether or not they are geodesic. Their compound-curved shape is inherently strong, giving a self-supporting clear span with no columns. Domes are resource and energy-efficient because, of all possible shapes, a sphere contains the most volume with the least surface. This holds true for domal slices of a sphere as well. The minimal surface presents the least area through which to gain or lose heat…When you double the exterior dimensions of a dome the skin area rises by a factor of four while the volume rises by a factor of eight...Larger domes are more efficient because less percent of the contained air is near of touching the skin where most heat loss or gain occurs. Doubling the size of a



Different types of domes require different construction and surface connections.

(a) Burying half of a spherical dome.
(b) Burying a dome whose lower half has twice the radius of curvature as the upper half.
(c) Anchoring a 'tent' type dome.
(d) A spherical housing complex located entirely above ground, employing Kevlar suspended decks.

[From The Case for Mars, by Robert Zubrin, Artwork by Michael Carroll]

Domed cities on Mars as seen by science-fiction writers in the early part of the 20th century.
[unknown]

dome doubles its thermal efficiency…The favourable surface-to-volume ratio is not the only reason for a dome's remarkable thermal performance; interior and exterior aerodynamics play a part , too…A dome's heat loss is further reduced by the concave interior…Moreover, like an enormous, down-pointing headlight, a dome reflects and concentrates interior radiant heat that would otherwise escape through the skin. The concave interior also bestows a less expected thermal advantage: self-cooling."[54]

According to Robert Zubrin there is no need to protect people on the surface from solar flares, as the atmosphere is thick enough to absorb them. The greenhouse effect[55] that is created by a dome is a benefit as it reduces the need for artificially heating the dome. The dome would have to be pressurized to allow humans to live inside it, meaning that in contrast to Earth the dome needs to be able to hold back the internal pressure, much like a balloon does.
Robert Zubrin would pressurize the domes to 350 mb (1/3 of Earth's atmosphere) as it is sufficient for humans to live in and the air then becomes thick enough for insects to fly[56]. This pressure from the inside out will mean a very minimal construction, as the dome will want to rise. The hard-plastic ultraviolet and abrasion-resistant geodesic dome can be created from transparent plastic. This Plexiglas® will form the outer skin and be unpressurized, it is used to stop the pressurized inner skin from being damaged by sandstorms and accidental puncturing. The inner skin can be made from Kevlar®; a dome with a 50 meter diameter would need a Kevlar skin of only 1mm[57] thick. The weight of a dome capable of covering nearly 2,000m^2 would only be eight tonnes for the inner skin and four tonnes for the outer skin. The weight to volume ratio compared to an instantly deployable habitat is huge:

- Instantly deployable habitat 250m^3 and weighs 25 tonnes
- Dome 335,938m^3 and weighs 12 tonnes

Off course the former contains everything needed for four people to survive on the Martian surface and in space for more than two years (and the latter needs to be constructed on the surface of Mars).
During construction of the base itself it will be possible to work within the protected atmosphere of the dome, only during the construction of the dome itself will the construction workers have to wear spacesuits.

The largest problem with a pressurized dome is the connection to the surface, i.e. it's foundation. A sphere is the most optimal shape for a pressurized volume, but if this shape is used it means that the lower part of the sphere has to be buried and later the excavated dirt has to be replaced (see picture *a*). It is also possible to rest the sphere on the surface (see picture *d*). The latter construction has to be lightweight or has to pierce the pressurized skin to connect it to the ground, which means large connection problems.

[54] From Bucky Works : Buckminster Fuller's Ideas for Today, by J. Baldwin
[55] Because of the thin atmosphere the greenhouse effect is much stronger as more heat through direct sunlight reaches the surface.
[56] Insect flight is necessary to pollinate plants.
[57] Kevlar has a fabric yield stress of 2,100 bar /cm^2, this is three times as much as would be applied in this case.

Crewmember working inside a pressurized greenhouse, while another crewmember works outside in the Martian environment.
[Carter Emmart, 1996]

Other ways of making the dome work is by creating two different segments with different curve spans. The lower part would have a much shallower curvature (see picture *b*), meaning less excavation work while still allowing for the same amount of volume in the top part of the dome. A fourth solution would be to only place the top part of the dome and connect the base to the ground somehow. The best way to do this would be to dig a shallow trench around the perimeter of the sphere, and using freezing techniques, stake the skin of the sphere in the ground:

"…could be accomplished with a lot less work by digging a relatively narrow, shallow circular trench, laying the skirt (the inner skin) in it, and then staking the skirt into the ground with long, deep-penetrating bared stakes. The stakes would have pipes in them through which hot steam would be sent down deep underground, where it would eventually freeze into a solid and extremely strong ring of permafrost rooting the stakes, and thus the dome, firmly in place."[58]

This last method for placing a dome on Mars requires the least amount of excavating (and replacing) and can be seen as one of the most convenient solutions, it does pose more stress on the foundation then the other methods though. NASA advises against (a single) large domes as the construction is very difficult and it would imply building vertically (to efficiently use the volume), which is more difficult then building horizontally. Smaller domes are therefore thought to be a better idea for Mars bases:

"A series of much smaller domes, connected via transport tunnels with pressure-retaining bulkheads and airlocks would theoretically be significantly easier to emplace and would be resistant to any single event causing a catastrophic failure. Privacy would also be increased (but so would isolation!) Lastly, smaller domes impose more constraints on how a colony can be configured than a larger dome would-but maybe it would be worth it"[59]

Most probably domes will find their first use in greenhouses as plants need much less pressure then humans to survive. This means that hemispherical domes (picture *d* on the previous page) can be used more easily as the stress on the foundation is much less.

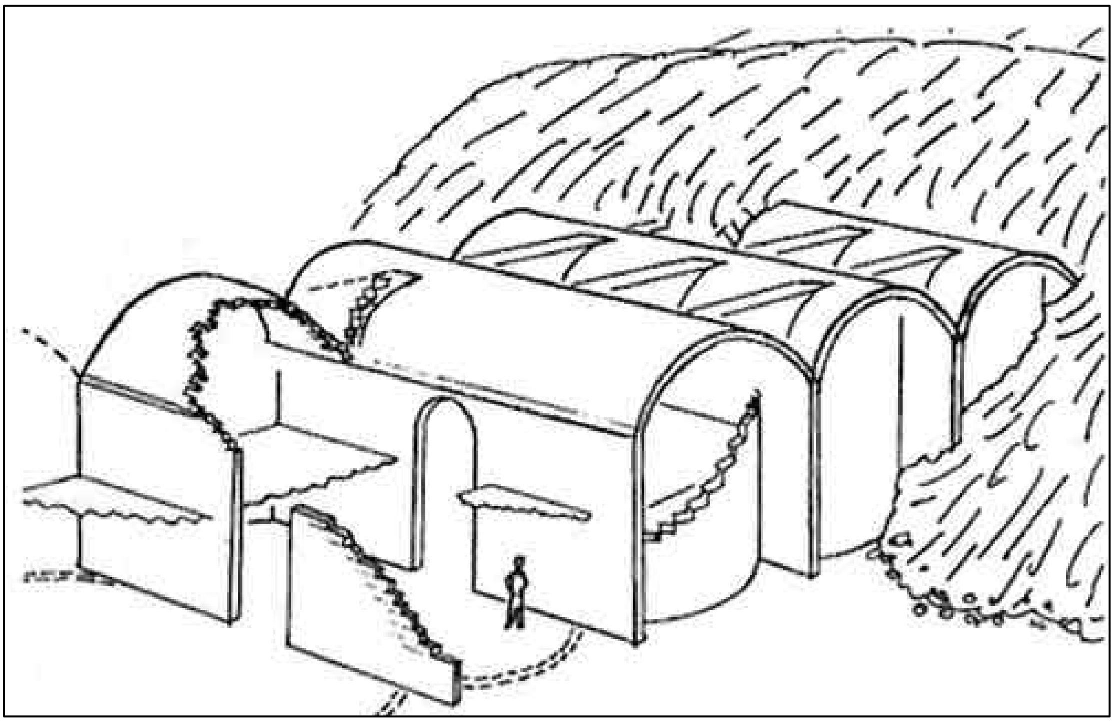
[7.3] Prefabricated elements

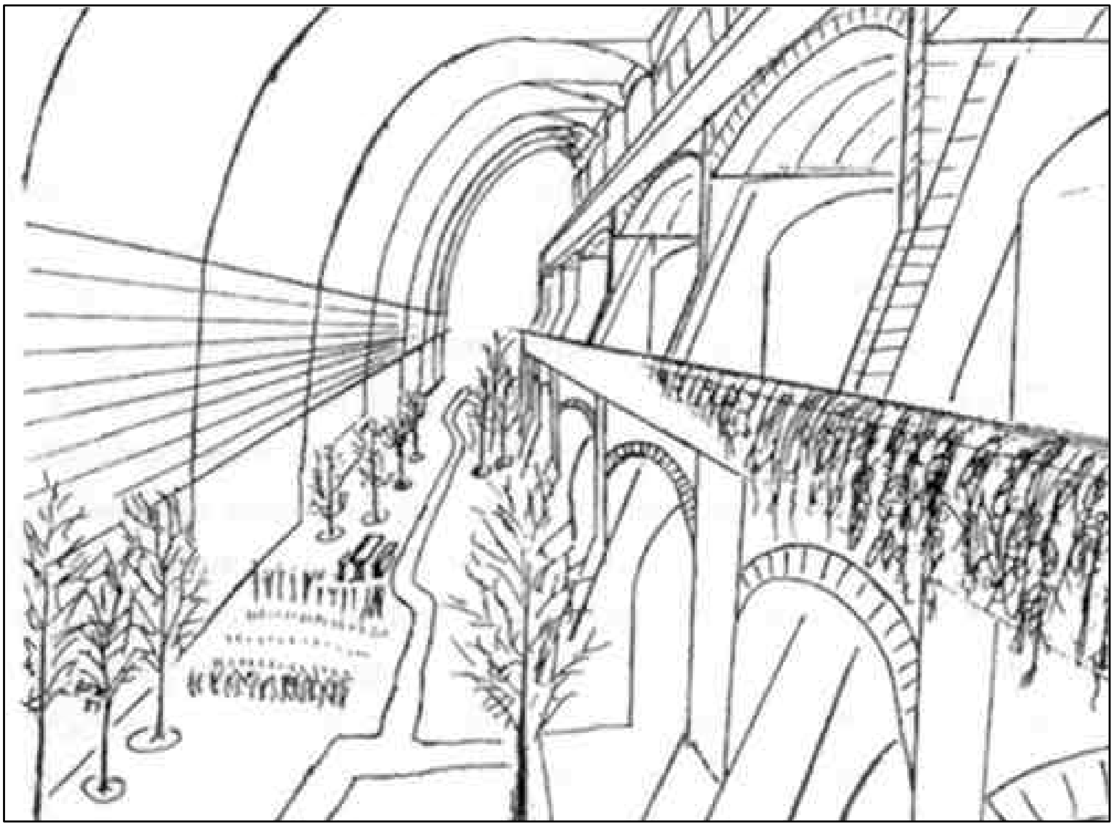
Other prefabricated elements that can be deployed on Mars are small-scaled inflated elements that are connected to form a larger base, or modular 'hard' elements that are used for a similar purpose. These elements would either have to consist of smaller elements that have to be assembled to form a closed volume, or they could be *tuna can* type elements that have been fully designed for various functions and once on the planet only have to be connected. The *PAX Permanent Martian Base*[60] is an example of this type of prefabricated base.

[7.4] Brick vaults

The optimum on-site material to use for construction of structures on Mars is brick the biggest advantage of brick is that it is very simple to make. Bricks

[58] from the Case for Mars, by Robert Zubrin
[59] from http://spaceflight.nasa.gov/mars/reference/faq
[60] see page 92 for a description of this base





can be fashioned by wetting finely ground soil, and compressing it slightly in a cast (or mould) and then to bake it.[61] Furnaces for baking the bricks can use solar reflective heat, nuclear power or combustion engines, the last option being the least favourable as the power from the first two is practically free; as the nuclear waste heat can be used to power the furnaces. One of the problems with creating bricks is that it requires water that is hard to find on Mars, however if the furnace is designed right it is possible to recycle the used water nearly indefinitely. The raw material for bricks can be found nearly everywhere on the Martian surface in the form of iron-rich clay-like dust, fibres that have been brought along could also be added to create a stronger brick. According to a test done at Martin Marietta the Martin soil[62] can be turned into *'Duricrete'* that is half as strong as normal concrete. The surface material of Mars also contains gypsum which when added to mortar creates Portland cement; this will greatly improve the tensile strength. As brick has large compression strength it is a good idea to build vaults, in this way an entire structure can be built using compression forces and only a minimum of tensile forces will occur. Furthermore brick structures have been around on Earth for over three millennia and have proven themselves (by some of them still being around today). On Mars the difference is of course that the structure has to be pressurized (from the inside) and this has to be countered in some way. The most effective way is to build vaults; Roman type vaults can be linked together to form a larger complex. The vaults have to be buried in the ground to counter the effect of the vault wanting to expand through the internal pressure. A minimum pressure of 350 mb is required, this will exert a pressure of 3.5 tonnes per m^2 on the brick walls. This means that covering the vaults with 2.5 meters of Martian dirt will be necessary, because of the lesser gravity more dirt is needed. The added advantage of this layer of dirt is it's radiation shielding and thermal shielding. By adding a powdered version of polyethylene to the brick mix it will be able to help shield against radiation more effectively. The barrel vaults can also include other elements such as small domes or inflatable structures, especially if sunlight is required.

The amount of air that leaks out of the brick vaults can be drastically reduced by using a thin layer of plastic on the inside of the walls. Slow leaks will not last long as the moisture in the air will freeze as it escapes and seal the leak automatically.

[7.5] Caves

There is also an even more primitive shelter that could be used to support human life on Mars; caves.

"A handful of proponents say caves created long ago by cooling lava would be the cheapest, largest and most protective places to expand human outposts. Mars was once volcanic, scientists say, and it shares features with Earth, which is still volcanic. Among the common features are myriad types of caves left behind as lava flowed across the landscape and then cooled."[63]

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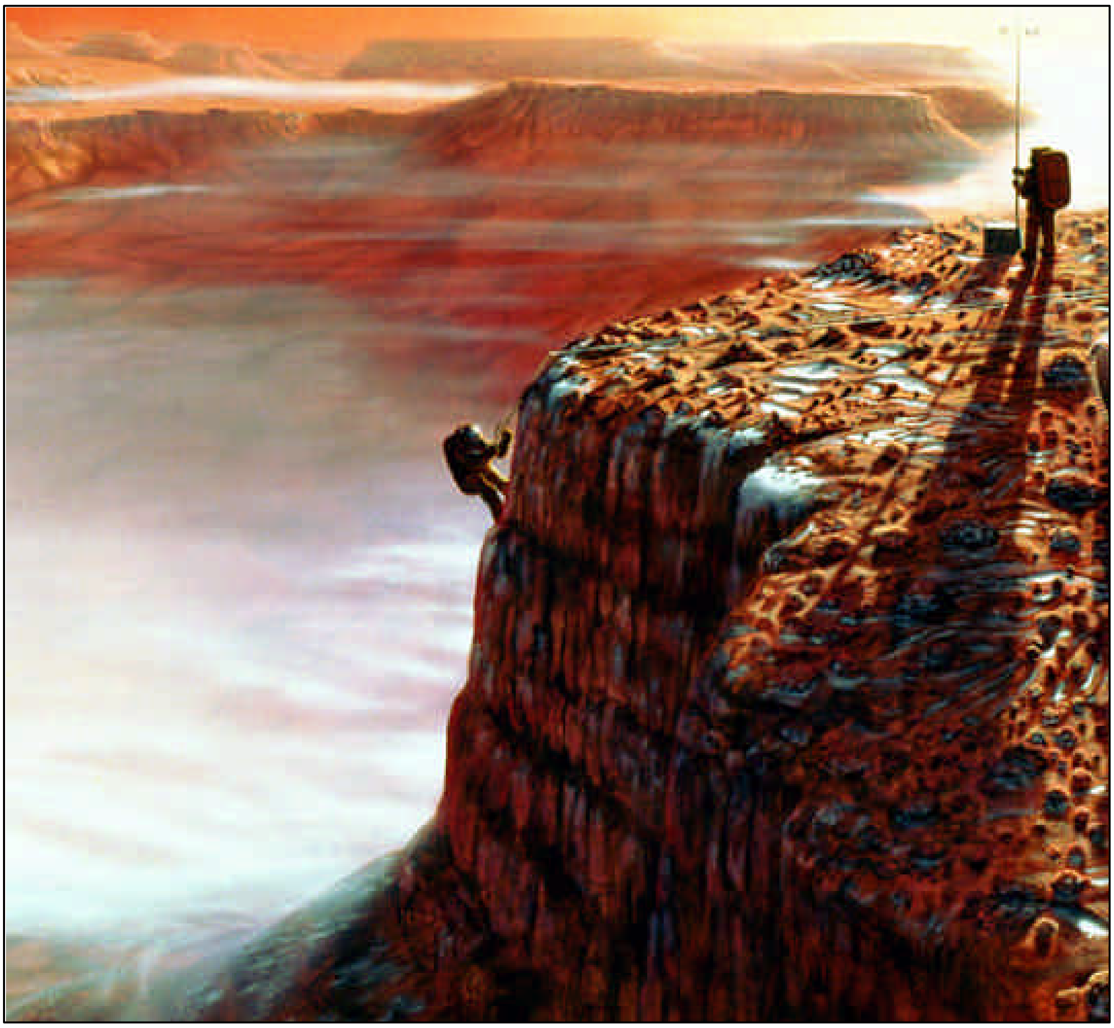
[61] Temperatures can range from 300°C to 900°C (which is the temperature used for modern baking)
[62] A substitute of the Martian soil was used.
[63] From http://www.space.com/scienceastronomy/solarsystem/mars_caves_000321.html



No matter how primitive or luxurious a base a crew might have on the planet, they will always need to do some work by hard physical work.
[Carter Emmart, NASA]

[NASA]

Locating suitable caves will not be easy, as they need to be readily accessible, correctly dimensioned and extensive enough to be able to expand the base. If caves are found they might prove to be natures home for man on Mars:
Like wax from a candle, flowing lava freezes in place. A crust forms over the top, insulating the liquid underneath, which continues flowing. When the source of magma is exhausted, the remaining liquid lava drains out, leaving the crust and a hollow interior. Frederick says some terrestrial caves resemble subways, with ceilings more than 20 feet (6.1 meters) tall. Where the crust is thin, a portion sometimes collapses and creates a skylight. Such holes, Frederick says, not only provide a way into a cave but could also serve as a place through which to direct sunlight. Frederick says photos of Mars show lava-flow landforms that are similar to those on Earth, indicating the possibility of caves, which he says are probably larger than earthly caves.[48]
The lack of sunlight in caves can be overcome by holes in the ceilings covered with transparent elements that supply direct sunlight in the caves.

A number of options are possible, a combination of structure types might be the optimum way of building a base. Combining caves or brick vaults with domes for instance. For the foreseeable future the high quality and complex products will have to be brought from Earth. This includes things like; airlocks, furniture, clothing, tools, machines and vehicles. In the future it might be possible to create these things on Mars, for now Mars will have to depend on the Earth until enough people and/or large scale (robot) factories are possible on the Martian surface. Every kilogram that does not have to be lifted from Earth means a huge financial saving and makes the Martian base less dependent on the Earth. For this reason structures created from local material have an advantage, which can be negated though by the amount of man-hours these structures require. A design for a Martian base should be clear on it's function, and weigh the costs and benefits of a structure type.

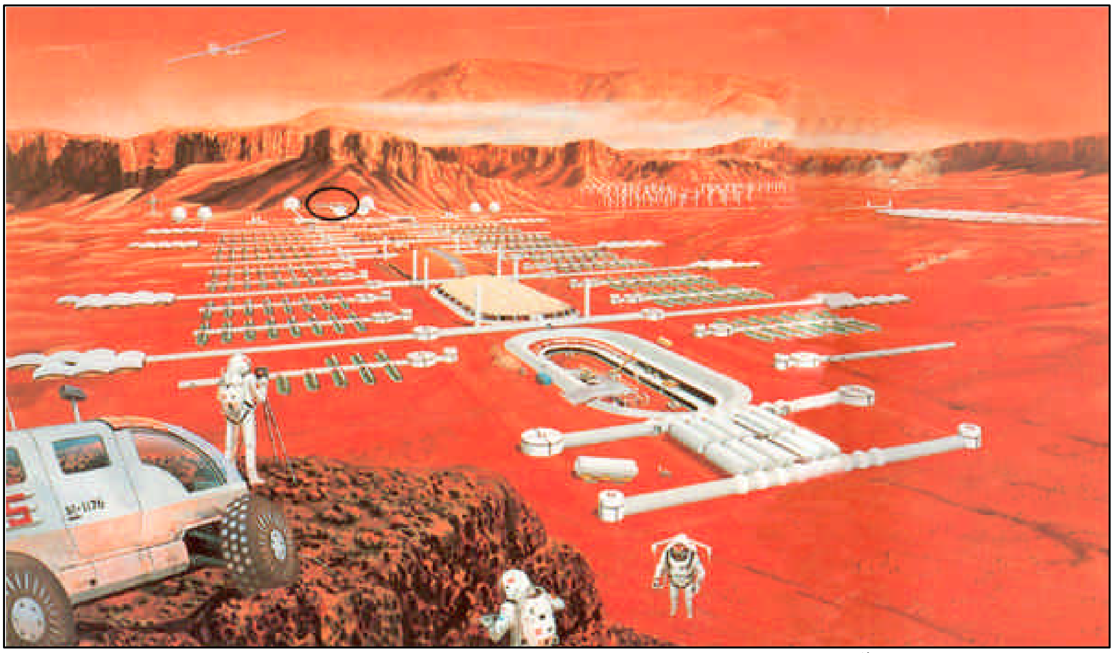
[7.6] Description of three permanent bases: *NASA Concept Base, Mars Habitation 2057* and *PAX*

These bases are examples of permanent Martian bases; all three bases have been designed from different perspectives. The first is a NASA base, the second has been designed by a large Japanese construction corporation and the third is a plan created by a university. The scope of the projects is also very different ranging from only a couple of tens of people to hundreds of people.

[7.7] *NASA Concept Base,* designed 1987 for the first decade of 2000

This base is located South of the large shield volcano *Pavonis Mons* in a gorge on the Martian equator. The base is laid out in a variant of the standard zone division. (See also chapter 5.2) The habitats are located centrally, the nuclear power plants are buried far in the North, the *launch and landing* zone is located in the East, the *industry and use of in-situ resources* zone is located to the North-West and the science area is placed close to the habitat. The base includes:

The NASA Base contains all the necessary elements to permanently support humans on Mars.
[Pat Rawlings]



Obayashi Martian base; *Mars Habitation 2057*, designed for the 100th anniversary of the launch of the Sputnik 1.
[Obayashi Corporation, 1990]

'A Mars explorer, a traverse vehicle, a habitation module, a power module, greenhouses, central base, lightweight crane and trailer, launch and landing facility, water well pumping station, a maintenance garage, tunnelling device, water well drilling rig, large dish antennae, mast antenna, even a Mars airplane[64]
The *NASA Base* is very much a concept study and has not been fully fleshed out. Although all the presumably required elements have been brought together in this base it lacks the permanent feeling of *Mars Habitation 2057*. The scope of the latter project is of course much larger and is set in a more distant future.

The habitats are buried in a similar fashion as is described in other chapters; prefabricated elements are placed and connected and finally covered with Martian soil. The holes in the side of the hill are most probably for resource mining and do not contain habitats (unlike the initial Obayashi base). The familiar greenhouses are placed near the habitat but not connected.

A second smaller scale permanent Mars base developed by NASA is the NASA Outpost[65].

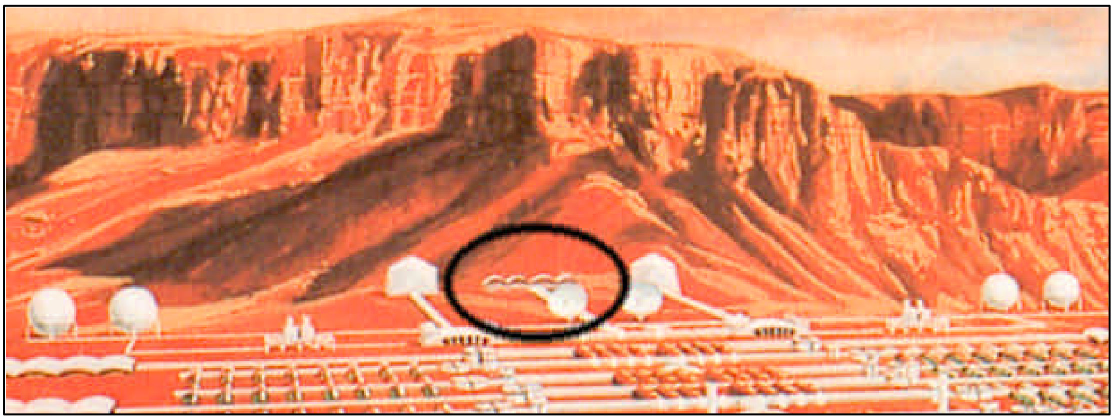
[7.8] *Mars Habitation 2057,* designed 1990 for the year 2057

This base is interesting in the fact that it has been developed by a private company; the Obayashi Corporation of Japan. This is a corporation that has more than 10,000 employees and a capital of €527 million and states: *'It has never been unrealistic to assume that someday humankind would emigrate and homestead the Red Planet and assert that the design of such settlements is the task of the construction industry.'*

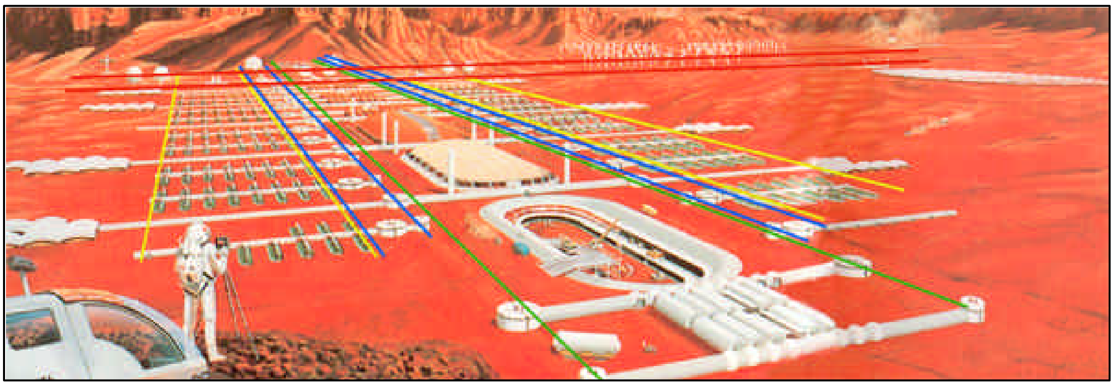
Mars Habitation 2057 concept celebrates the 100th anniversary of the Soviet satellite *'Sputnik*[66] which was launched in 1957 (see also chapter 1.4). The design of this Martian base is intended to house 150 permanent residents and another 150 transients (including a large number of tourists). The permanent crew consists of pilots, engineers, scientists, medical doctors, psychologist, journalists, poets, painters, philosophers, and cooks. A *captain* heads the crew and is the ultimate authority on the base.

The base is located at *Kasei Vallis* (see also chapter 4.1) and is initially placed in the side of a hill. By boring a tunnel into the Southside of a hill the base will be protected from radiation and have the advantage of the weight of the hillside on three sides to counteract the internal pressure of the habitat. The size of the final facility is 500,000m^2 (500m East to West, and 1,000m North to South) The organisation of the base is conceived in *'base lines'* which organise the base in four different zones, the first three run from north to south, while the fourth runs across the northern part of the other three lines:

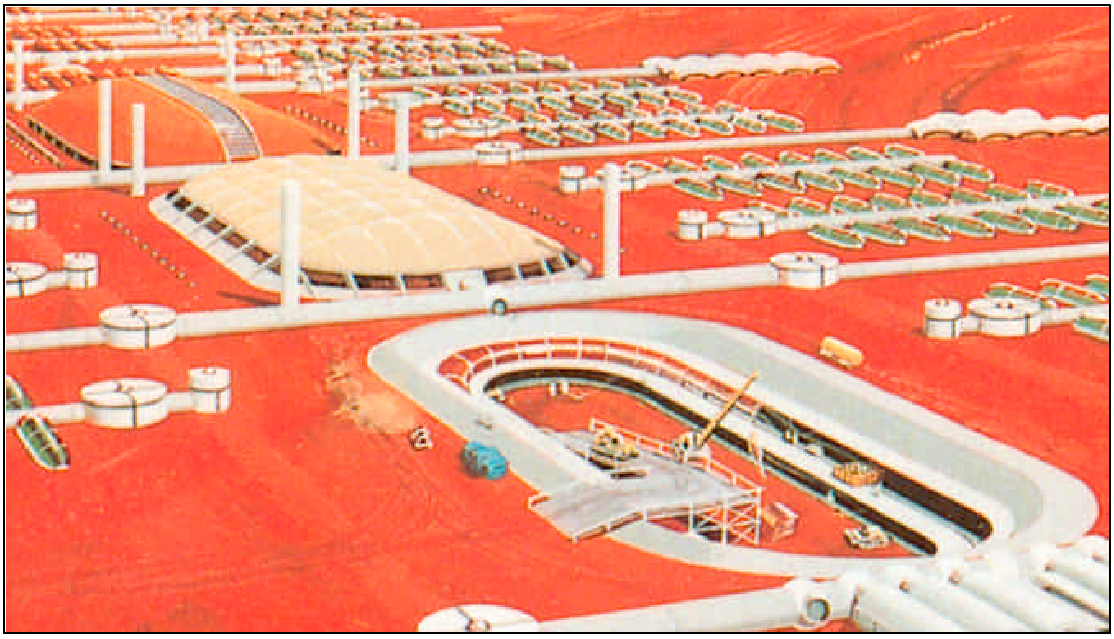
[64] From www.spaceflight.nasa.gov
[65] See supplement [s.4]
[66] The Sputnik was the first manmade object to orbit the Earth.



The initial base is placed in the side of the hill to the north and later extended southward.
[Obayashi Corporation, 1990]



The base is divided in four *base lines*: Habitat line (green), Gas/Water/Pathway line(blue), Food line(yellow) and Auxiliary systems line (red)
[Obayashi Corporation, 1990]



The terrariums seen in three separate fazes; the rear terrarium has been converted into a viable ecosystem, while the second is still transparent, the one on the foreground is under construction.
[Obayashi Corporation, 1990]

- Habitat line - This zone runs south from the initial hillside habitat through an area known as the safe-haven-habitat, the control centre a number of habitats and the terrariums.

- Gas/water/pathway line – Water is extracted from the permafrost in the hills to the North. The water is subsequently collected and pumped via pipes along these zones to the greenhouses that branch of from this zone. Other important resources are also transported along here and distributed to the necessary areas.

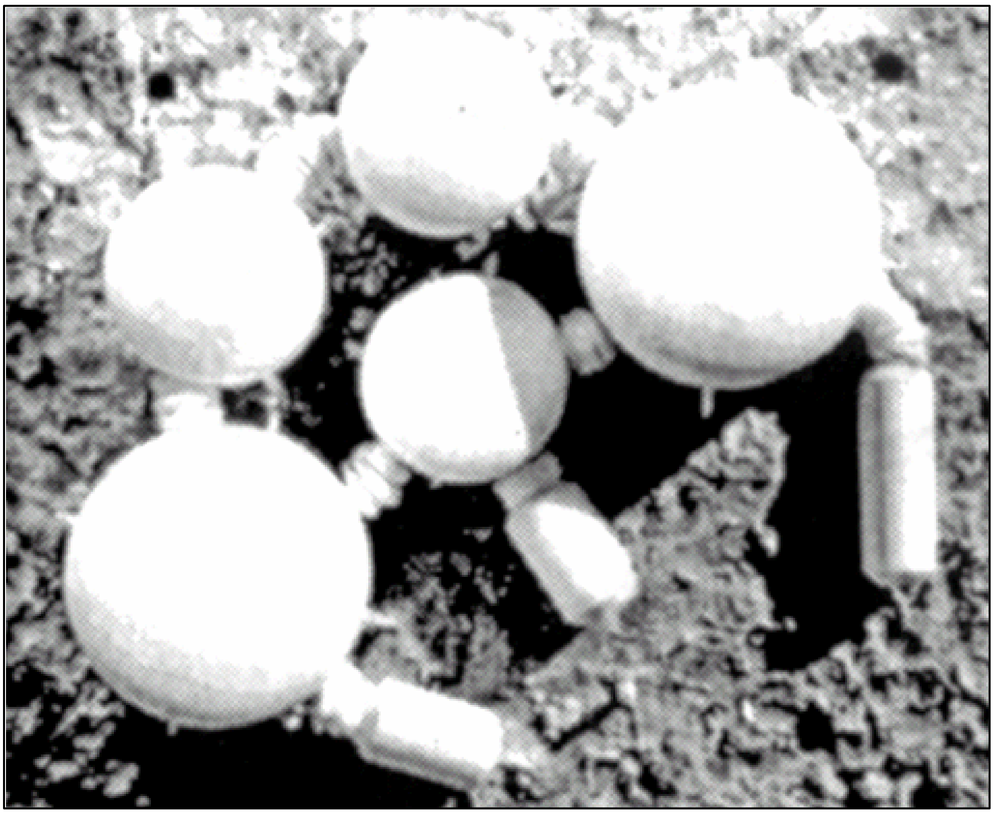
- Food line – The greenhouses are ranked behind each other along the Gas/water/pathway line.

- Auxiliary systems line - This line runs perpendicular to the other three lines and is used to connect the water and oxygen depots (found in the west) with the base. The large microwave-receiving array in the east is also connected via the Auxiliary systems line with the rest of the base.

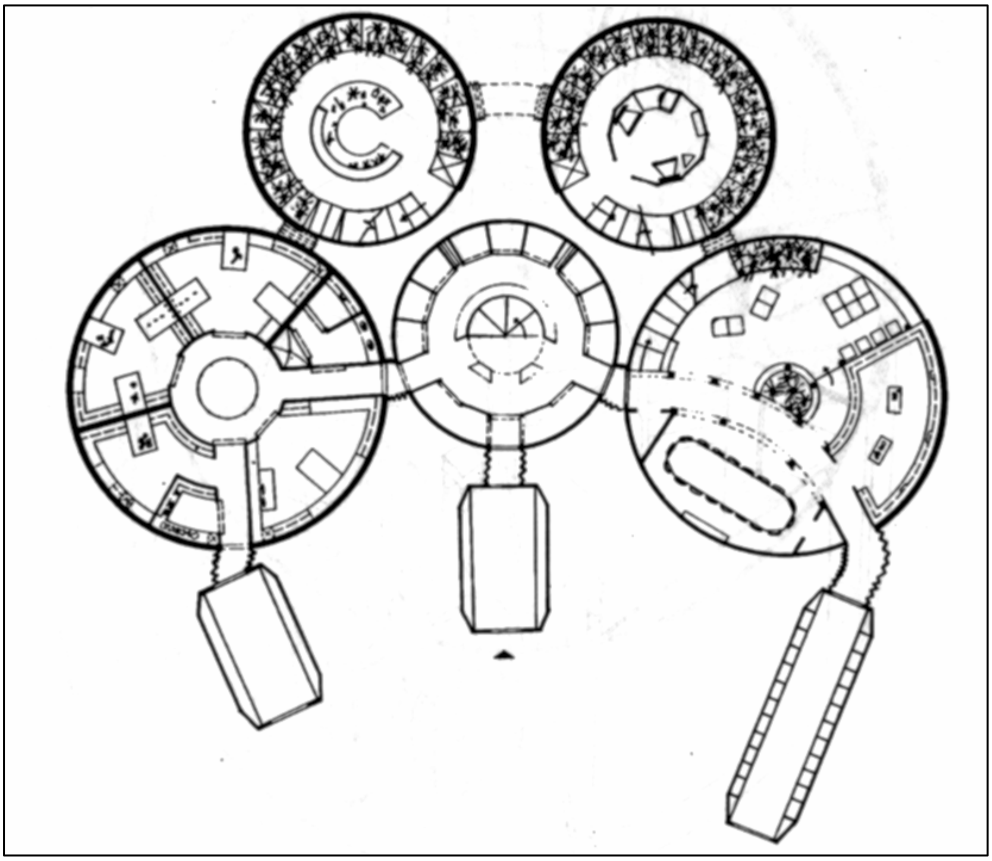
The base is well set up with potential dangerous elements such as the oxygen depots placed away from the base. The landing and launch site is also placed well away from the main area of the base, this eliminates the need of spacecraft having to fly over the habitat and thus risking potential catastrophic crashes. The habitat elements are prefabricated cylinders with a diameter of six meters and a length of sixteen meters and are completely fitted. These habitat modules can be plugged into the habitat line, the only thing that is required is to protect them from radiation by covering them with a three meter layer of soil. The habitats provide a living area for two people. The hundreds of greenhouses are constructed from plastic low-pressure semi-cylinders, fifteen meters long and with a five-meter diameter. The greenhouses have a carbon dioxide rich-atmosphere with only 100mb[67] of pressure; this means that all the work done in here by people must be done with oxygen masks. The total greenhouse area is over 15,400m^2 that doesn't include the terrariums. The terrariums are inflatable domes containing Martian atmosphere and filled with plants and algae, which will turn the carbon dioxide into oxygen over time. Surrounding these terrariums are underground research facilities. Once a terrarium has become oxygen rich it is covered with soil to stop the radiation and sunlight is admitted indirectly into the domes via mirrors. Now the terrarium should be able to sustain an ecosystem including a number of animals and insects, the facilities surrounding the terrarium are converted into living areas.

The Obayashi Corporation uses solar energy collected in space and beamed down via microwaves[68] as a primary source of energy and wind power as a secondary energy source (nuclear energy is seen as unsafe). The entire base is constructed by implementing more than 4,000 tonnes of equipment and construction materials over a 47 year period. A total mass of 24,000 tones

[67] 1/10th the pressure at sea level on Earth
[68] See supplement [s.3]



Model of PAX: Permanent Martian Base, Space Architecture for the First Human Habitation on Mars. A space frame is placed over the entire base and covered in regolith in the final stage.
[University of Wisconsin-Milwaukee]



[University of Wisconsin-Milwaukee]

must be launched from Earth to deliver these 4,000 tonnes to the Martian surface. One of the more extreme viewpoints aired by the authors[69] of this design is that they hope a human is born on Mars in the near future of their base, this is one of the moral and ethical dilemmas concerning space-faring that will have to be dealt with in the next century.

[7.9] *PAX Permanent Martian Base*, designed 1992 for the year 2022

The *Pax* base is to be located at the Viking 2 landing site, 45 degrees North latitude, 251 degrees W longitude on the *Utopia Planitia* (see chapter 4.2). The base is similarly to the *Mars Habitation 2057* set up along a north-south axis, the site is laid out over a large area, with the habitat and solar arrays in the centre, the auxiliary nuclear power plant is located two and a half kilometres to the south, the launch and landing site are located two and a half kilometres to the north. Nuclear contamination will never reach the base due to the wind direction, and the flight trajectories do not cross over the habitat. All other functions are integrated in the central habitat area and do not require the crew to leave the pressurized habitation area.

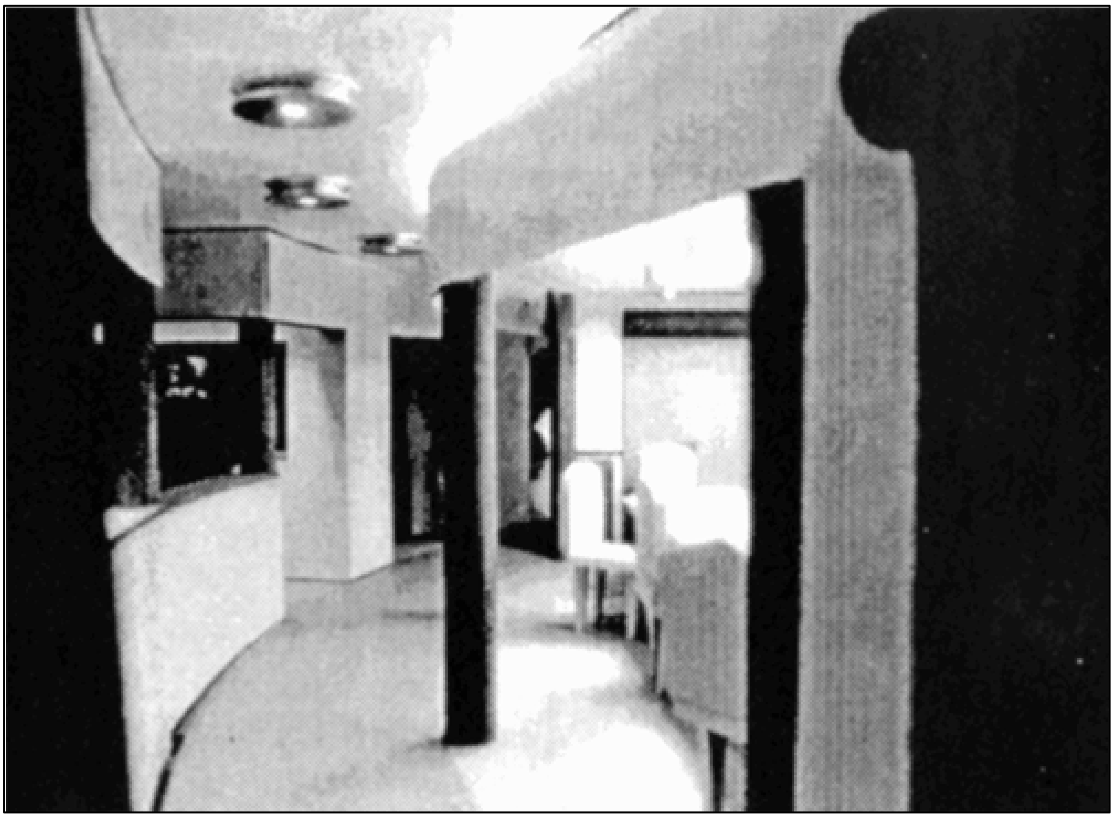
The base is composed of three prefabricated *hard* modules with a nine meter diameter that are covered by a space frame which in turn is covered with regolith to avoid any radiation penetrating the base. Connected to these modules are two twelve meter inflatable *crew support* and *laboratory facility* units. One of the hard modules is joined with both the inflatable modules and serves as an entry to the base. Both the inflatable modules and the entry modules have airlocks that allow access to the outside environment. All modules have two levels; the entry module is located lower then the other units and therefore has one level below the others (see overleaf). The base can support eighteen people comfortably; one of the main ideas behind the PAX base is to make the most expensive and useful components of the base function optimally: the crew.

The steel space frame that covers the base is in place during the building of the base protecting the workers during the construction of the base. The zoning and spatial variety that the base has implemented allows a crewmember to understand where he is and what the function of the unit is while avoiding monotony.

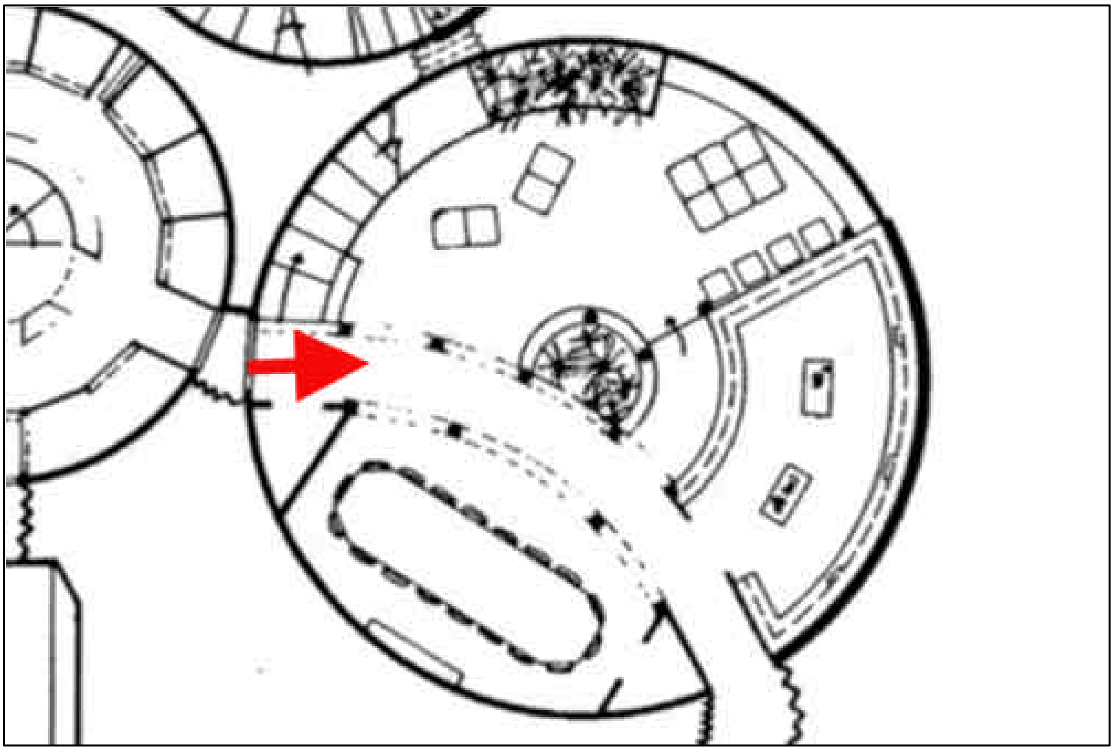
The basic concept for the *Pax* base[70]:

- <u>Embracing entry</u>: the modules are placed in an embracing formation, set slightly back in the centre giving the crewmembers a feeling of moving within. This area also marks a focal point for the base.

[69] Yoji Amemiya, Yoji Ishikawa and Takaya Ohkita
[70] From PAX Permanent Martian Base, Gary T. Moore



The main movement through this space is in an arc; on the right is the wardroom that can seat the entire crew. The two entries on the left respectively contain a group recreational area and the galley.
[University of Wisconsin-Milwaukee]



Floor plan showing the point from which the photograph above was taken.
[University of Wisconsin-Milwaukee]

- Separation of work and play: the laboratory spaces and crew support spaces are physically separated to give the crew a sense of *going to work* and *being home*.

- Circulation efficiency: there are clear circulation paths from module to module as the habitat is organised in an efficient manner. Monotony is avoided by not placing the habitat volumes in a straight line. It is possible for the crew to take different routes when travelling from one place to the other without becoming disorientated. Horizontal transportation is through arcs around the volumes and vertical movement is through the centre of the volumes or along the sides of the volumes.

- Dual egress: as on Earth a person must always be able to flee from a disaster area in two directions (dual egress), so to on Mars. Two opposite exits are possible within any of the modules.

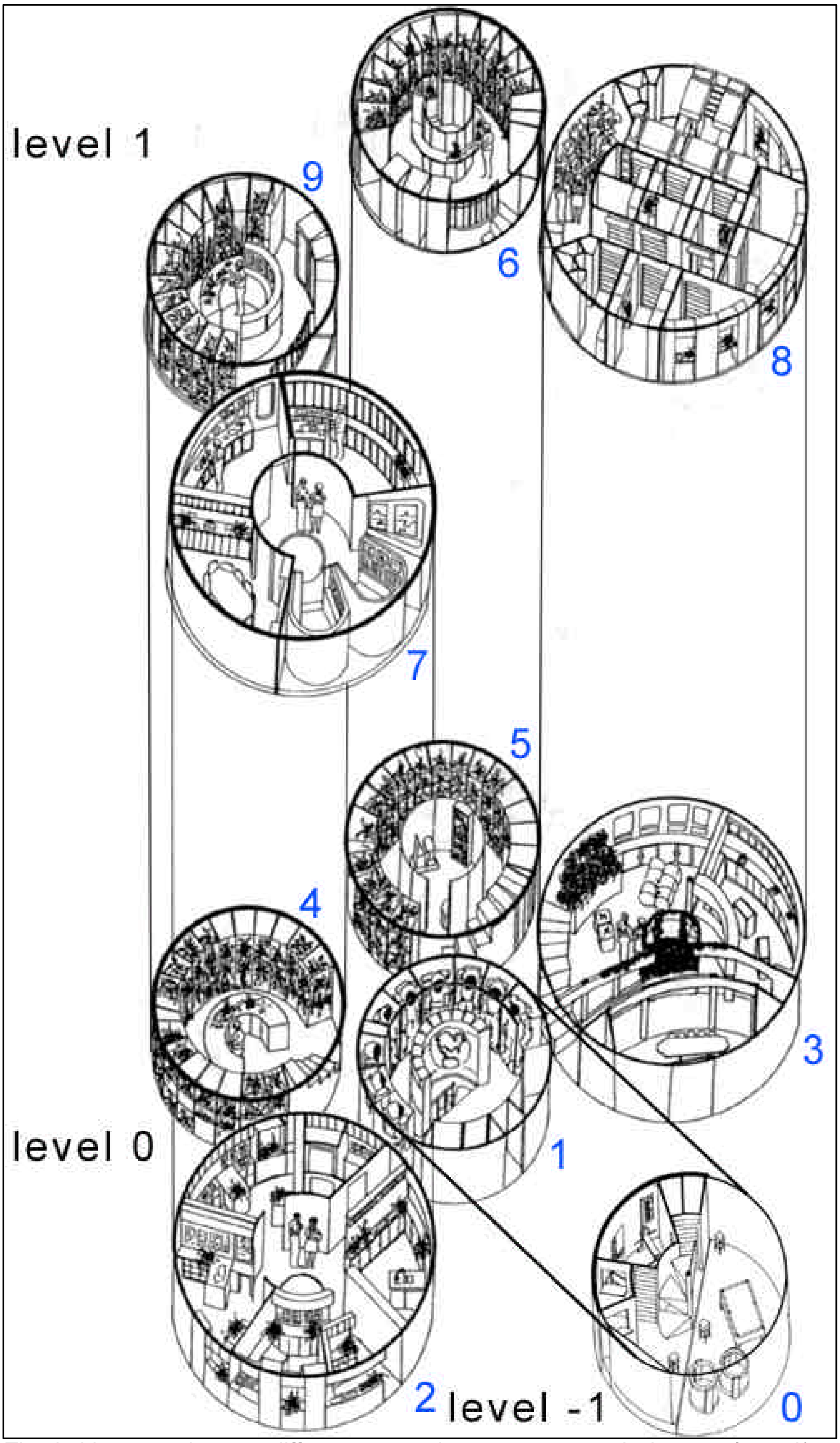
- Central focus in each module: The whole base is centred around the entry module, and each unit has a central focus. The liveability of the base is improved by giving each module a designated focal point where the crew can gather. Personalization is encouraged (within limits)

- Homelike environment: the ability for the crew to personalize their private spaces by bringing things from home that are familiar to them will help keep stress levels down. The crew should live in a comfortable and familiar way.

- Sense of place: it is important for the crew to understand where they are and be able to relate to this. So the private quarters should look totally different to the laboratories. This can be done through decoration but also through layout and lighting.

The Pax design tries to optimise all the requirements that have been set out in the preliminary research (see chapter 5.1). To this end a lot of consideration has been given to technical details, colour, lighting and materials that are based on colour and material design recommendations done by the NASA-Ames Research Centre. The colour scheme has been based on three *activity area definitions*: High activity areas are finished in light, warm and lively earth tones and warm pastels, wall spaces are kept open where possible. The medium activity areas (work areas) are designed with calm, low saturation colours. Light blues and greys represent low activity areas. Contrasting colours are used to break the monotony. Colours are continued from one area into another to avoid the base becoming compartmentalised.

The modules are grouped in such a way that they conform to the PAX zones (no noise pollution in the private areas). Because of this they are not always directly connected to each other; sometimes modules are linked because of convenience or to provide dual egress. The following list provides the functions for all the units in the habitat and how they are connected to other modules:



The habitat contains ten different areas that are connected via tunnels and/or staircases.
[University of Wisconsin-Milwaukee]

1 Entry module, entry level

Dedicated as the main entry to the habitat, it must combine utility with a sense of first impression. Access to the laboratory and crew modules is possible from here through flexible connectors via a central staircase access to the recreation room located below is possible. Entrance to this module is gained through an airlock and *'dusting off'* chamber that connects to the second floor of this unit. This area also contains the racks for suit maintenance and storage. The wall surrounding the stairwell is the focus point of this unit and serves as an eye catcher for people entering the base, because of this function it is given a lot of symbolic importance and attention.

2 Laboratory / Mission Operations module, laboratory level:

The bottom half of this module contains nearly all the laboratories including chemistry, biology and microbiology (the botany laboratories are located in the top half of the module 7). The crew will spend a lot of their time here. The centre of the unit gives access to the Mission Operations area above (7) and a connection to the entry module is situated in the east. The general laboratory has it's own sample airlock allowing robots or crewmembers that are outside the habitat to deliver samples to the laboratory without having to go inside.

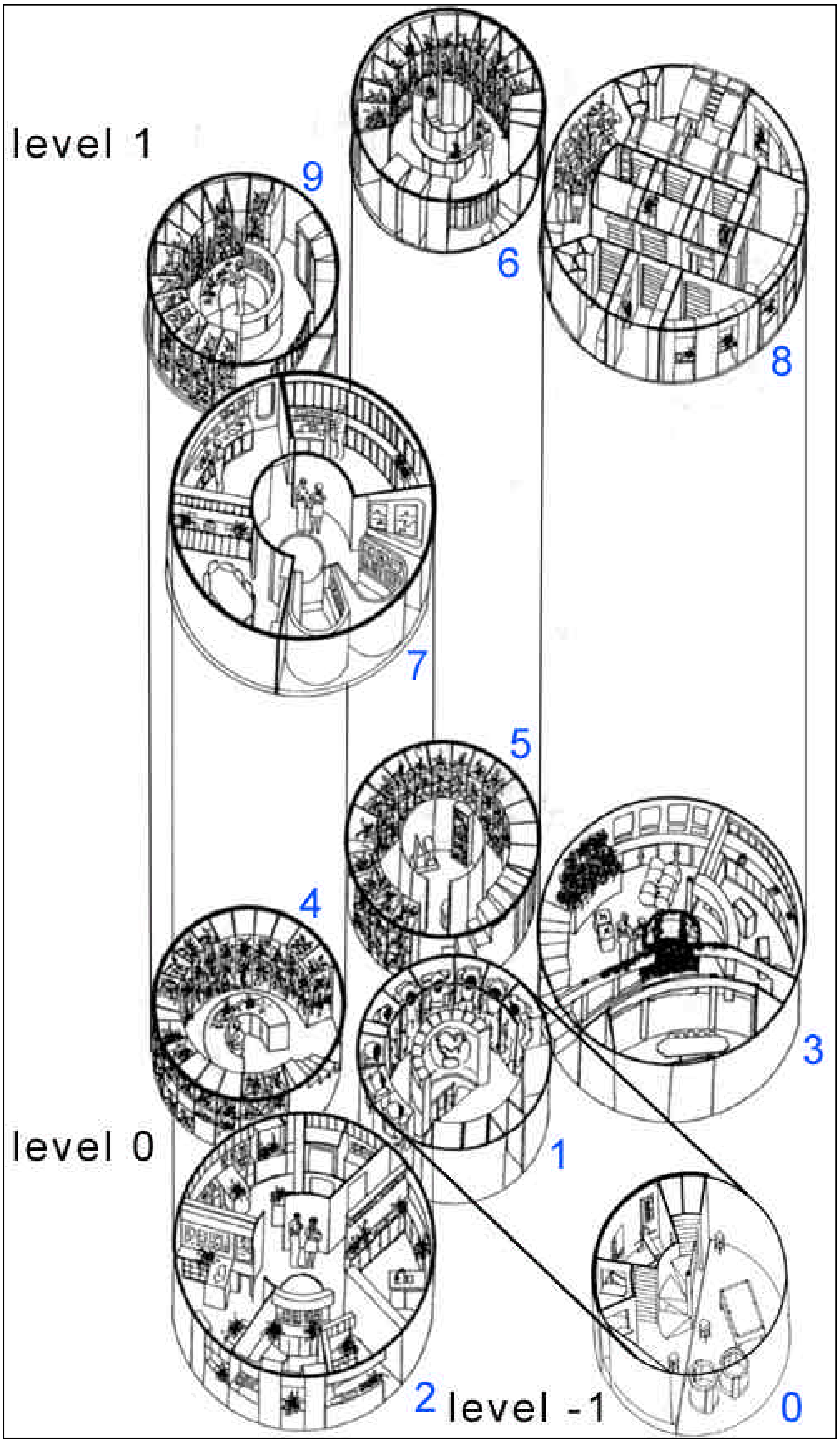
Next to the laboratories there is also a health maintenance facility (HMF) that can deal with most medical problems and can also be used to: '*maintain a deceased crew member's body before transport to Earth.'*

3 Crew Support Module, public level:

The basic needs of the crew are accommodated here; access to this module is through the flexible connections from the entry module or via a staircase that ascends from the crew quarters (8). On this level there is a galley, wardroom, group recreation space and laundry facilities. The wardroom is the only place where the entire crew can gather to this end it has a formal function. The group recreation area that is situated opposite the wardroom across the hall is designed for casual group recreation.

4 Greenhouse (carbon dioxide) module, greenhouse level:

The greenhouse modules are divided in two units with one of the two modules used for intensive high yield crops in a predominant carbon dioxide atmosphere. Crew working in this module will have to wear oxygen masks, passing through is possible but not convenient. Agricultural and biological research will also be an important part of the work done by the crew here. An ingenious rack system along the walls allows maximum light to fall on all the crops. Access to the other modules is possible through the flexible connection tubes and through a staircase to the greenhouse located on top (9). A workstation and research station is located in the centre of this unit.



[University of Wisconsin-Milwaukee]

5 Greenhouse (oxygen) module, library level:

This greenhouse is similar in design to the other greenhouses except that this module is not filled with carbon dioxide allowing the crew to breathe normally here, and smell! This greenhouse also provides food for the crew and a quite place to read. The centre of this level is, but for a small opening, closed of from the rest of the area and contains the library which accommodates three crewmembers at a time. Access to this level is from the greenhouse above via a staircase along the perimeter of the module.

6 Greenhouse (oxygen) module, chapel level:

Identical to the other oxygen greenhouse (which is located below) the only difference is that the library has here been substituted for a chapel. The crew can retreat to this area for a private moment of contemplation; the domed ceiling of the chapel creates a spatial experience. Access to the greenhouse below is via a staircase and via flexible connections to the carbon dioxide greenhouses and the crew quarters.

7 Laboratory / Mission Operations module, M O level:

The top half of this large inflatable module is given over to mission control functions. Backup of those systems that are located here have been placed around the base in case the operations module is lost due to a disaster. Mission control is separated in several areas: conference room, mission control workstations, audio-visual monitor systems and telerobotic systems. From this area the whole base is monitored and inspected including the launch and landing facility, remote robotics can be controlled from here and contact with Earth is also maintained. Two botany laboratories are located on this level besides the mission operations facilities. The botany laboratories are connected to one of the greenhouse modules (9).

8 Crew Support Module, crew quarters level:

This level is designed for crew privacy and retreat and has accommodation for all eighteen crewmembers. The quarters are divided into six single and six double occupancy rooms. The modular furnishing inside the rooms allows the crew to personalize the space. The beds are raised above the room to maximize the floor space and increase privacy, couples can place the beds against each other if they wish. Also located on this level are the two personal hygiene facilities (bathrooms).

9 Greenhouse (carbon dioxide) module, greenhouse level 2:

Identical to the carbon dioxide greenhouse on level 1 except for its connection to the biology laboratory in the Laboratory / Mission Operations module.

0 Entry module, exercise level:

Located directly below the entry level is the exercise area, the crew can use this area to sustain muscle mass (which decreases due to a lesser gravity) and keep themselves healthy. Computers linked to the training machines record information on the crew's health.

Epilogue

The first humans will probably set foot on Mars within the next couple of decades when political will or financial incentive is able to bring the right people together and who are able to fully understand the problems and opportunities that Mars has to offer.

Until that time new ideas, valuable research and hard work will continue on this subject, but only when the first crew successfully returns to Earth will we begin to know what the real possibilities are.

This paper has mainly dealt with introducing the reader to the different bases that have been developed in the last couple of decades. The bases in this paper range from small scale habitats that can support a small crew for a couple of months to bases intended to house hundreds indefinitely. The scope of the missions, the feasibility and the timeframe are nearly all different. Yet all habitats have one function in common and that is to keep the precious human content that they contain alive. To this end all designs have to take into account the Martian environment and all the dangers and opportunities that are involved.

The future of Martian habitats will probably start with an Instant Deployable Habitat and after a couple of successful missions the first domes for agriculture will appear and eventually be converted to allow humans to apply them as habitats. If at any stage large commercial profits are thought to exist from mining on Mars then the bases will most likely grow very fast and very quickly.

When the first permanent habitats start appearing it will be interesting to see if they are designed in the purely functional way that NASA[71] employs or that they strive towards a more humane (but unrealistic?) approach as advocated by PAX. In the end it might be that the financing of a base dictates every aspect.

This planet has - or rather had - a problem, which was this: most of the people living on it were unhappy for pretty much of the time. Many solutions were suggested for this problem, but most of these were largely concerned with the movements of small green pieces of paper, which is odd because on the whole it wasn't the small green pieces of paper that were unhappy.

-Douglas Adams

[71] Who are the world leaders in putting people in space and keeping them alive.

References

Some books are compiled works containing vast amounts of information and have been used extensively throughout this paper, the same holds true for a number of the internet sites that are so vast that only the home page has been recorded here.

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  Mars chronology: Renaissance to the Space Age
  [Compiled by Paul Karol and David Catling 1996]
- www.space.com/scienceastronomy/solarsystem/mars_caves_000321.html
  [space.com]
- dolphin-watch.com/render.html
  [Renderings by by Curt Boyll]
- www.kie.berkeley.edu/mars2012/cohen_habitat.html
  Habitat Distinctions: Planetary versus Interplanetary Architecture
  [By Marc M. Cohen]

[s.0] Supplement

[s.1] Mars/Earth Comparison (by Dr. David R. Williams)

Bulk parameters

Mars/Earth	Mars	Earth	Ratio
Mass (10^{24} kg)	0.64185	5.9736	0.107
Volume (10^{10} km^3)	16.318	108.321	0.151
Equatorial radius (km)	3397	6378.1	0.533
Polar radius (km)	3375	6356.8	0.531
Volumetric mean radius (km)	3390	6371.0	0.532
Core radius (km)	1700	3485	0.488
Ellipticity (Flattening)	0.00648	0.00335	1.93
Mean density (kg/m^3)	3933	5515	0.713
Surface gravity (m/s^2)	3.69	9.78	0.377
Escape velocity (km/s)	5.03	11.19	0.450
GM (x 10^6 km^3/s^2)	0.04283	0.3986	0.107
Bond albedo	0.250	0.306	0.817
Visual geometric albedo	0.150	0.367	0.409
Visual magnitude V(1,0)	-1.52	-3.86	-
Solar irradiance (W/m^2)	589.2	1367.6	0.431
Black-body temperature (K)	210.1	254.3	0.826
Topographic range (km)	30	20	1.500
Moment of inertia (I/MR^2)	0.366	0.3308	1.106
J_2 (x 10^{-6})	1960.45	1082.63	1.811
Number of natural satellites	2	1	
Planetary ring system	No	No	

Orbital parameters

Mars/Earth	Mars	Earth	Ratio
Semimajor axis (10^6 km)	227.92	149.60	1.524
Sidereal orbit period (days)	686.980	365.256	1.881
Tropical orbit period (days)	686.973	365.242	1.881
Perihelion (10^6 km)	206.62	147.09	1.405
Aphelion (10^6 km)	249.23	152.10	1.639
Synodic period (days)	779.94	-	-
Mean orbital velocity (km/s)	24.13	29.78	0.810
Max. orbital velocity (km/s)	26.50	30.29	0.875
Min. orbital velocity (km/s)	21.97	29.29	0.750
Orbit inclination (deg)	1.850	0.000	-
Orbit eccentricity	0.0935	0.0167	5.599
Sidereal rotation period (hrs)	24.6229	23.9345	1.029
Length of day (hrs)	24.6597	24.0000	1.027
Obliquity to orbit (deg)	25.19	23.45	1.074

Mars Observational Parameters

Discoverer: Unknown
Discovery Date: Prehistoric

Distance from Earth	
Minimum (10^6 km)	54.5
Maximum (10^6 km)	401.3
Apparent diameter from Earth	
Maximum (seconds of arc)	25.7
Minimum (seconds of arc)	3.5

Mean values at opposition from Earth	
Distance from Earth (10^6 km)	78.39
Apparent diameter (seconds of arc)	17.9
Apparent visual magnitude	-2.0
Maximum apparent visual magnitude	-2.91

Mars Mean Orbital Elements (J2000)

Semimajor axis (AU)	1.52366231
Orbital eccentricity	0.09341233
Orbital inclination (deg)	1.85061
Longitude of ascending node (deg)	49.57854
Longitude of perihelion (deg)	336.04084
Mean Longitude (deg)	355.45332

Martian Atmosphere

Surface Pressure: ~6.1 mb (variable)
[6.9 mb to 9 mb (Viking 1 Lander site)]

Surface Density: ~0.020 kg/m^3

Scale height: 11.1 km

Average temperature: ~210 K

Diurnal temperature range: 184 K to 242 K
(Viking 1 Lander site)

Wind speeds: 2-7 m/s (summer), 5-10 m/s (fall),
17-30 m/s (dust storm) (Viking Lander sites)

Mean molecular weight: 43.34 g/mole

Atmospheric composition (by volume):
Major : Carbon Dioxide (CO_2) - 95.32% ; Nitrogen (N_2) - 2.7% Argon (Ar) - 1.6%; Oxygen (O_2) - 0.13%; Carbon Monoxide (CO) - 0.08%

Minor (ppm): Water (H_2O) - 210; Nitrogen Oxide (NO) - 100; Neon (Ne) - 2.5; Hydrogen-Deuterium-Oxygen (HDO) - 0.85; Krypton (Kr) - 0.3; Xenon (Xe) - 0.08

Satellites of Mars

	Phobos	**Deimos**
Semi-major axis* (km)	9378	23459
Sidereal orbit period (days)	0.31891	1.26244
Sidereal rotation period (days)	0.31891	1.26244
Orbital inclination (deg)	1.08	1.79
Orbital eccentricity	0.0151	0.0005
Major axis radius (km)	13.4	7.5
Median axis radius (km)	11.2	6.1
Minor axis radius (km)	9.2	5.2
Mass (10^{15} kg)	10.6	2.4
Mean density (kg/m^3)	1900	1750
Geometric albedo	0.07	0.08
Visual magnitude V(1,0)	+11.8	+12.89
Apparent visual magnitude (V_0)	11.3	12.40

*Mean orbital distance from the center of Mars.

[s.2] Mars Reference Mission sequence (from NASA Special publication 6107)

3.5.4 Mission Sequence

Figure 3-7 illustrates the mission sequence analyzed for the Reference Mission. In this sequence, three vehicles will be launched from Earth to Mars in each of four launch opportunities starting in 2007. The first three launches will send infrastructure elements to both Mars orbit and to the surface for later use. Each remaining opportunity analyzed for the Reference Mission will send one crew and two cargo missions to Mars. The cargo missions will consist of an ERV on one flight and a lander carrying a habitat and additional supplies on the second. This sequence will gradually build up assets on the martian surface so that at the end of the third crew's tour of duty, the basic infrastructure could be in place to support a permanent presence on Mars.

3.5.4.1 First Mission: 2007 Opportunity

In the first opportunity, September 2007, three cargo missions will be launched on minimum energy trajectories direct to Mars (without assembly or fueling in LEO). The first launch delivers a fully fueled ERV to Mars orbit. The crew will rendezvous with this stage and return to Earth after completion of their surface exploration in October 2011.

The second launch delivers a vehicle to the Mars surface which is comprised of an unfueled MAV, a propellant production module, a nuclear power plant, liquid hydrogen (to be used as a reactant to produce the ascent vehicle propellant), and approximately 40 tonnes of additional payload to the surface. After this vehicle lands on the surface in late August 2008, the nuclear reactor will be autonomously deployed approximately 1 kilometer from the ascent vehicle, and the propellant production facility (using hydrogen brought from Earth and carbon dioxide from the Mars atmosphere) will begin to produce the nearly 30 tonnes of oxygen and methane that will be required to launch the crew to Mars orbit in October 2011. This production will be completed within approximately 1 year— several months before the first crew's scheduled departure from Earth in mid-November 2009. The third launch in the 2007 opportunity will deliver a second lander to the Mars surface; it will be comprised of a surface habitat/laboratory, non-perishable consumables for a safe haven, and a second nuclear power plant. It will descend to the surface in early September 2008 and land near the first vehicle. The second nuclear power plant will be autonomously deployed near the first plant. Each plant will provide sufficient power (160 kWe) for the entire mature surface outpost, thereby providing complete redundancy within the power function. The outpost laboratory will include tools, spare parts, and teleoperated rovers to support scientific exploration and will provide geological and biological analyses.

3.5.4.2 Second Mission: First Flight Crew, 2009 Opportunity

In the second opportunity, opening in October 2009, two additional cargo missions and the first crew mission will be launched. Before either the crew or additional cargo missions are launched from Earth in 2009, all assets previously delivered to Mars are checked out and the MAV launched in 2007 is verified to be fully fueled. Should any element of the surface system required for crew safety or critical for mission success not check out adequately, the surface systems will be placed in standby mode and the crew mission delayed until the systems can be replaced or their functions restored. Some of the systems can be replaced using hardware originally intended for subsequent missions and which would have otherwise provided system enhancement; others may be functionally replaced by other systems The first cargo launch in October 2009 is a duplicate of the first launch from the 2007 opportunity, delivering a fully fueled Earth-return stage to Mars orbit. The second cargo launch similarly mirrors the second launch of the 2007 opportunity, delivering a second module, a nuclear power plant, liquid hydrogen (to be used as a reactant to produce the ascent vehicle propellant), and approximately 40 tonnes of additional payload to the surface. After this vehicle lands on the surface in late August 2008, the nuclear reactor will be autonomously deployed approximately 1 kilometer from the ascent vehicle, and the propellant production facility (using hydrogen brought from Earth and carbon dioxide from the Mars atmosphere) will begin to produce the nearly 30 tonnes of oxygen and methane that will be required to launch the crew to Mars orbit in October 2011. If the MAV and ERV delivered in 2007 operate as expected, then the systems delivered in 2009 will support the second crew of six that will launch to Mars early in 2012.

The first crew of six will depart for Mars in mid-November 2009. They leave Earth after the two cargo missions launched in October 2009, but because they are sent on a fast transfer trajectory of only 180 days, they will arrive in Mars orbit approximately 2 months prior to the cargo missions. Once the TMI burn has been completed, the crew must reach the surface of Mars. During the outbound portion of this mission, the crew will use their time to monitor and maintain systems on board the transit spacecraft, monitor and maintain their own physical condition, and train for those activities associated with capture and landing at Mars. Additional time will be available during the outbound leg to conduct experiments and continue a dialog with Earth-bound science and exploration teams who may revise or refine the initial set of surface activities conducted by this crew. The crew carries with them sufficient provisions for the entire 600- day surface stay in the unlikely event that they are unable to rendezvous on the surface with the assets previously deployed. The crew will land on Mars in a surface habitat almost identical to the habitat/ laboratory previously deployed to the Mars surface. The transit habitat sits atop a descent stage identical to those used in the 2007 opportunity. After capturing into a highly elliptic Mars orbit (250 by 33793 km), the crew descends in the transit habitat to rendezvous on the surface with the other elements of the surface outpost. There is no required rendezvous in Mars orbit prior to the crew descent. This is consistent with the risk philosophy assumed for the Reference Mission.

Surface exploration activity will consist of diverse observations by robotic vehicles and human explorers, the collection of samples and their examination in the outpost laboratory, and experiments designed to gauge the ability of humans to inhabit Mars.

These payloads are simply examples; the selection of specific experimental capability will depend on the requirements of martian science at the time that the missions are defined in detail. There is also a category listed for “discretionary principal investigator (PI) science.” This category of experimental equipment will be allocated to investigators who have competed through a proposal and peer review process and are selected for one of these flights. This allows a wider range of investigations and participants in the exploration of Mars. Prior to the arrival of the first human crew, teleoperated rovers (TROV) may be delivered to the surface. When the crew arrives, these rovers will be available for teleoperation by the crew. It is also possible for the rovers to be operated in a supervised mode from Earth. If used in this mode, the TROVs may be designed to provide global access and may be able to return samples to the outpost from hundreds of kilometres distance from the site if they are deployed with the first set of cargo missions launched more than 2 years before the crew arrives. As experience grows, the range of human exploration will grow from the local to the regional. Regional expeditions lasting perhaps 2 weeks, using mobile facilities, may be conducted at intervals of a few months. Between these explorations, analysis in the laboratory will continue. Figure 3-10 (Cohen, 1993) provides a possible surface mission timeline for the first 600-day mission. The deployment of a bioregenerative life support capability will be an early activity following crew landing. This bioregenerative system is not required to maintain the health and vitality of the crew; however, it will improve the robustness of the life support system and is important to the early objectives of the outpost. The first crew will stay at the outpost from 16 to 18 months. Part of their duties will be to prepare the outpost site for the receipt of additional elements launched on subsequent mission opportunities. Systems associated with the ascent vehicle, although monitored during the entire stay on the surface, will be checked and, if necessary, tested in detail to ensure that they will operate satisfactorily. The surface crew will also spend increasing amounts of time rehearsing the launch and rendezvous phase of the Mars departure to sharpen necessary skills that have not been used in over 2 years. Because the first crew will have to depart before the second crew arrives, surface systems will have to be in standby mode for approximately 10 months. After their stay on Mars, the crew uses one of the previously landed ascent vehicles to return to orbit, rendezvous with the ERV, and return to Earth. Like the outbound transit leg, the crew rides in a habitat on the inbound transit leg. This habitat is part of the Earth-return stage deployed in a previous opportunity by one of the cargo flights and typically has been in an untended mode for nearly 4 years prior to the crew's arrival. During the return portion of the mission, the crew will again spend a significant portion of their time monitoring and maintaining systems on board the transit spacecraft, monitoring and maintaining their physical condition, and training for the activities associated with Earth return. As mentioned previously, the second crew will be in transit to Mars during a portion of the first crew's return to Earth. This implies that a debriefing of the first crew, to gain insight from lessons learned and suggestions for future surface activities, will begin during this return phase. This debriefing will be relayed to the outbound crew so that they can participate in the interaction with the returning crew and modify their plans to take advantage of the first crew's experience. On landing, the first crew and their returned samples will be placed in quarantine.

As before, the second crew will continue with the general type of activities conducted. By the first crew: diverse observations by

robotic vehicles and human explorers, collection of samples and their examination in the outpost laboratory, and experiments designed to gauge the ability of humans to inhabit Mars. Specific crew activities will build on the lessons learned and questions generated by the first crew. Note in particular that this manifest contains a drill designed to reach depths of 1 kilometer. (The deep drilling operation must be consistent with planetary protection protocols.) This tool will be used to gather subsurface core samples that will help reconstruct the geologic history of Mars, and to try to locate subsurface deposits of water in either liquid or solid form. Such a discovery will substantially enhance the habitability prospects for future crews by possibly upgrading propulsion systems to the use of hydrogen and oxygen and expanding agricultural activities. The second crew will repeat the activities of the first crew in preparing themselves, the ascent vehicle, and the surface habitat for a departure from Mars during December 2013. The third crew will already be in transit to in accordance with the protocols in effect at the time. The crew's re-adaptation to a 1-g environment will be monitored in detail to learn more about how the human body adapts to the varying gravity conditions and to better prepare for the return of subsequent crews.

3.5.4.3 Third Mission: Second Flight Crew, 2011 Opportunity

In the third opportunity opening in December 2011, two additional cargo missions and the second crew mission will be launched. As in the second opportunity, all assets previously delivered to Mars are checked out and the MAV is verified to be fully fueled. Any non-mission-critical maintenance items identified by the first crew or items noted prior to the departure of Flights 7 through 9 are added to the spares manifest and delivered with other surface equipment.

Prior to the arrival of the second crew, the ISRU plants are producing not only the propellants needed for the ascent vehicle, but also water, oxygen, and buffer gases to serve as an emergency cache for the life support system. Teleoperated rovers are deployed on extended traverses, perhaps to distances of more than 100 kilometers, to take measurements, gather samples, and reconnoiter sites for the human crew to investigate in more detail. As before, the second crew will continue with the general type of activities conducted by the first crew: diverse observations by robotic vehicles and human explorers, collection of samples and their examination in the outpost laboratory, and experiments designed to gauge the ability of humans to inhabit Mars. Specific crew activities will build on the lessons learned and questions generated by the first crew. Note in particular that this manifest contains a drill designed to reach depths of 1 kilometer. (The deep drilling operation must be consistent with planetary protection protocols.) This tool will be used to gather subsurface core samples that will help reconstruct the geologic history of Mars, and to try to locate subsurface deposits of water in either liquid or solid form. Such a discovery will substantially enhance the habitability prospects for future crews by possibly upgrading propulsion systems to the use of hydrogen and oxygen and expanding agricultural activities. The second crew will repeat the activities of the first crew in preparing themselves, the ascent vehicle, and the surface habitat for a departure from Mars during December 2013. The third crew will already be in transit to Mars, again necessitating a debriefing of the second crew, with participation by the third crew, during the return to Earth. Once on Earth, the second crew will likely benefit from observations of the first crew, particularly in the areas of modifications to the re-adaptation regime and quarantine protocols.

3.5.4.4 Fourth Mission: Third Flight Crew, 2014 Opportunity

In the fourth opportunity opening in arch 2014, the final two cargo missions and the third crew mission will be launched. As in the second and third opportunities, all assets previously delivered to Mars are checked out and the MAV is verified to be fully fueled. Any non-mission-critical maintenance items identified by the first two crews or items noted prior to the departure of Flights 10 through 12 are added to the spares manifest and delivered with other surface equipment. The experience gained by the first two crews will dictate any additional equipment that can be used to either upgrade existing equipment or add new equipment to enhance the capabilities of this outpost. Prior to the arrival of the third crew, the ISRU plants are again producing not only the propellants needed for the ascent vehicle, but also water, oxygen, and buffer gases to serve as an emergency cache for the life support system. Teleoperated rovers are again deployed on extended traverses to take measurements, gather samples, and reconnoiter sites for the third crew to investigate in greater detail. With the facilities and capabilities available at this stage, the surface outpost will be able to support larger crews for longer periods of time. The potential level of self-sufficiency on Mars should also be evident by this time, and a decision can be made regarding any further use or expansion of the outpost. As before, the third crew will continue with the general type of activities conducted by the first and second crews: diverse observations by robotic vehicles and human explorers, collection of samples and their examination in the outpost laboratory, and experiments designed to gauge the ability of humans to inhabit Mars. Specific crew activities will build on the lessons learned and questions generated by the first two crews and should be focused on providing information needed to determine the future status of the outpost.

Surface Science Payload for Second Flight Crew

Payload Description Payload Mass (kg)
Field Geology Package: geologic hand tools, cameras, 335 sample containers, documentation tools Geoscience lab instruments: microscopes, 125 geochemical analysis equipment, camera Exobiology laboratory: enclosures, microscopes, 50 culture media, Biomedical laboratory 500, Plant and animal lab 500, Traverse geophysics instruments 400, Geophysics/meteorology

instruments (8 sets) 200, 1 kilometer drill 20,000, 10-meter drill 260, Meteorology balloons 200, Discretionary PI science 600
Total 23,000

As with the first two crews, the third crew will repeat those activities necessary to prepare themselves, the ascent vehicle, and the surface habitat for a departure from Mars during January 2016.

3.5.4.5 Mission Summary

This section has illustrated a feasible sequence of missions that can satisfy the Reference Mission goals and objectives. These missions use assumed hardware systems and mission design principles to place the flight crews in the martian environment for the longest period of time at a satisfactory level of risk. The major distinguishing characteristics of the Reference Mission, compared to previous concepts, include:

•No extended LEO operations, assembly, or fueling

•No rendezvous in Mars orbit prior to landing

•Short transit times to and from Mars (180 days or less) and long surface stay-times (500 to 600 days) for the first and all subsequent crews exploring Mars

•A heavy-lift launch vehicle (HLLV), capable of transporting either crew or cargo direct to Mars, and capable of delivering all needed payload with a total of four launches for the first human mission and three launches of cargo and crew for each subsequent opportunity

•Exploitation of indigenous resources from the beginning of the program, with important performance benefits and reduction of mission risk

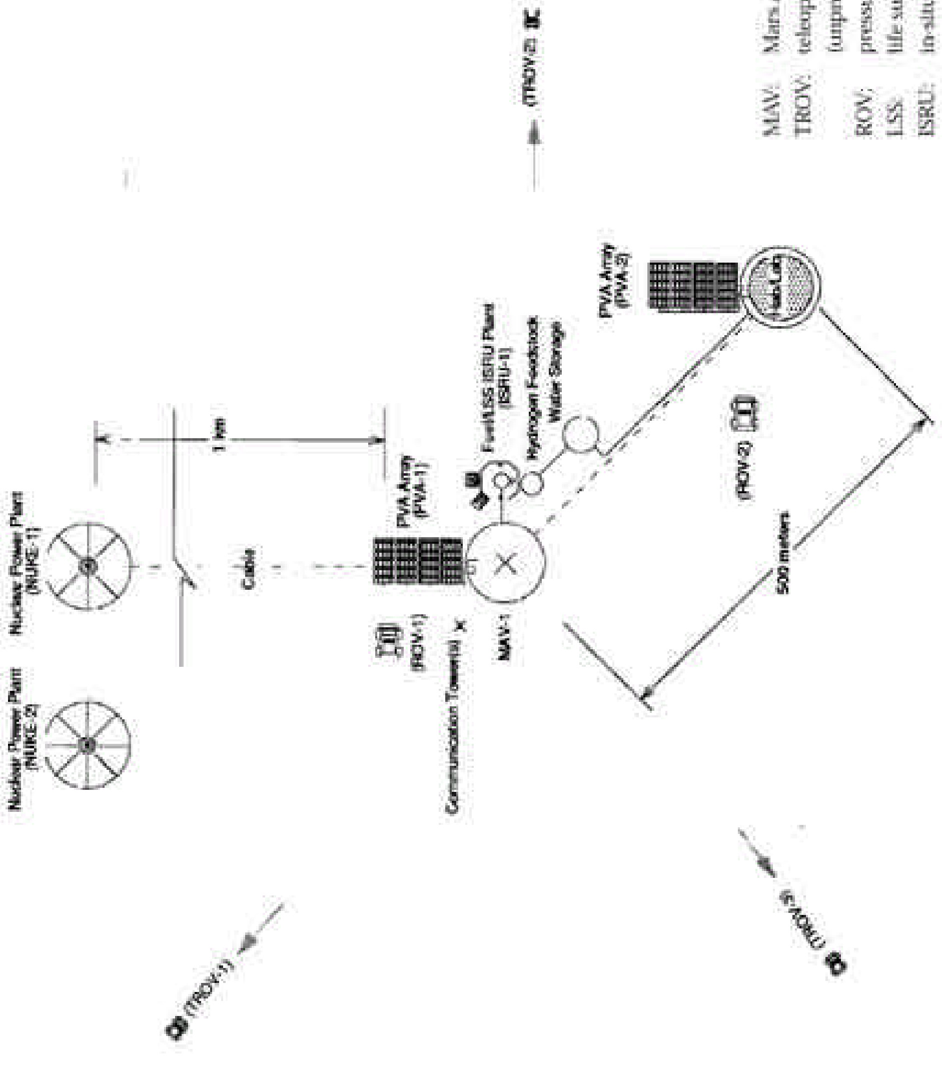
•Availability of abort-to-Mars-surface strategies, based on the robustness of the Mars surface capabilities and the cost of trajectory aborts

3.6 Systems

The following sections discuss the characteristics and performance capabilities of the various hardware elements needed for the Reference Mission. The hardware elements include a launch vehicle large enough to place cargo bound for Mars into a suitable Earth parking orbit, the interplanetary transportation elements necessary to move crew and equipment from Earth to Mars and back, and the systems needed to sustain the crew and perform the proposed exploration activities on the martian surface. Each section describes the principal characteristics of the hardware system as developed by the Mars Study Team.

Payload Description Payload Mass (kg)

Field Geology Package: geologic hand tools, cameras, 335 sample containers, documentation tools Geoscience lab instruments: microscopes, 125 geochemical analysis equipment, camera Exobiology laboratory: enclosures, microscopes, 50 culture media
Plant and animal lab 500 Traverse geophysics instruments 400 Geophysics/meteorology instruments (8 sets) 200 Advanced Meteorology Laboratory 1000 10-meter drill 260 Meteorology balloons 200 Discretionary PI science 1000
Total 4070



MAV: Mars Ascent Vehicle
TROV: teleoperated rover (unpressurized)
ROV: pressurized rover
LSS: life support system
ISRU: in-situ resource utilization
PVA: photo-voltaic array

Figure 3-8 Mars surface outpost after deployment of payloads from first two cargo landers.

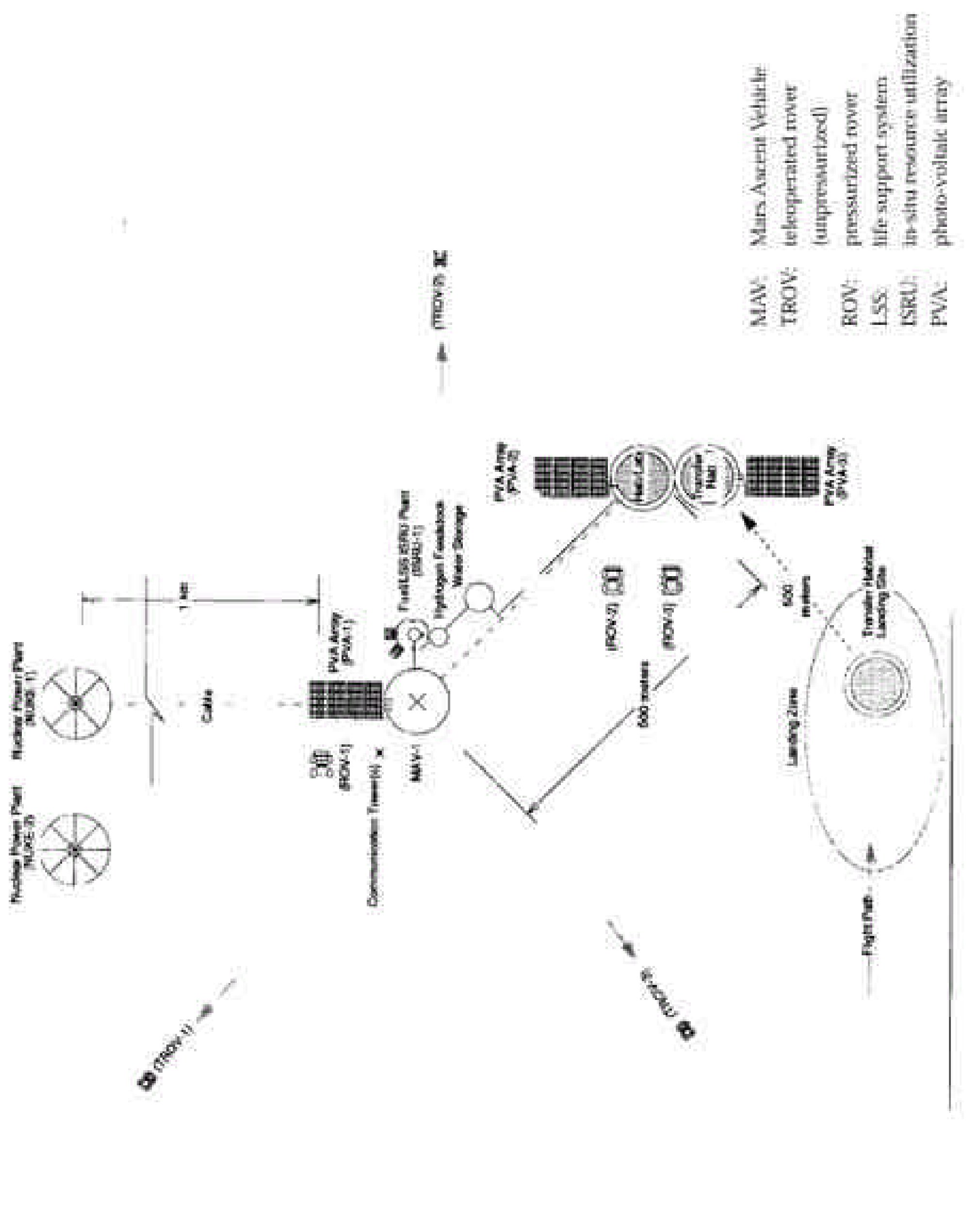


Figure 3-9 Mars surface outpost at the end of first flight crew's stay.

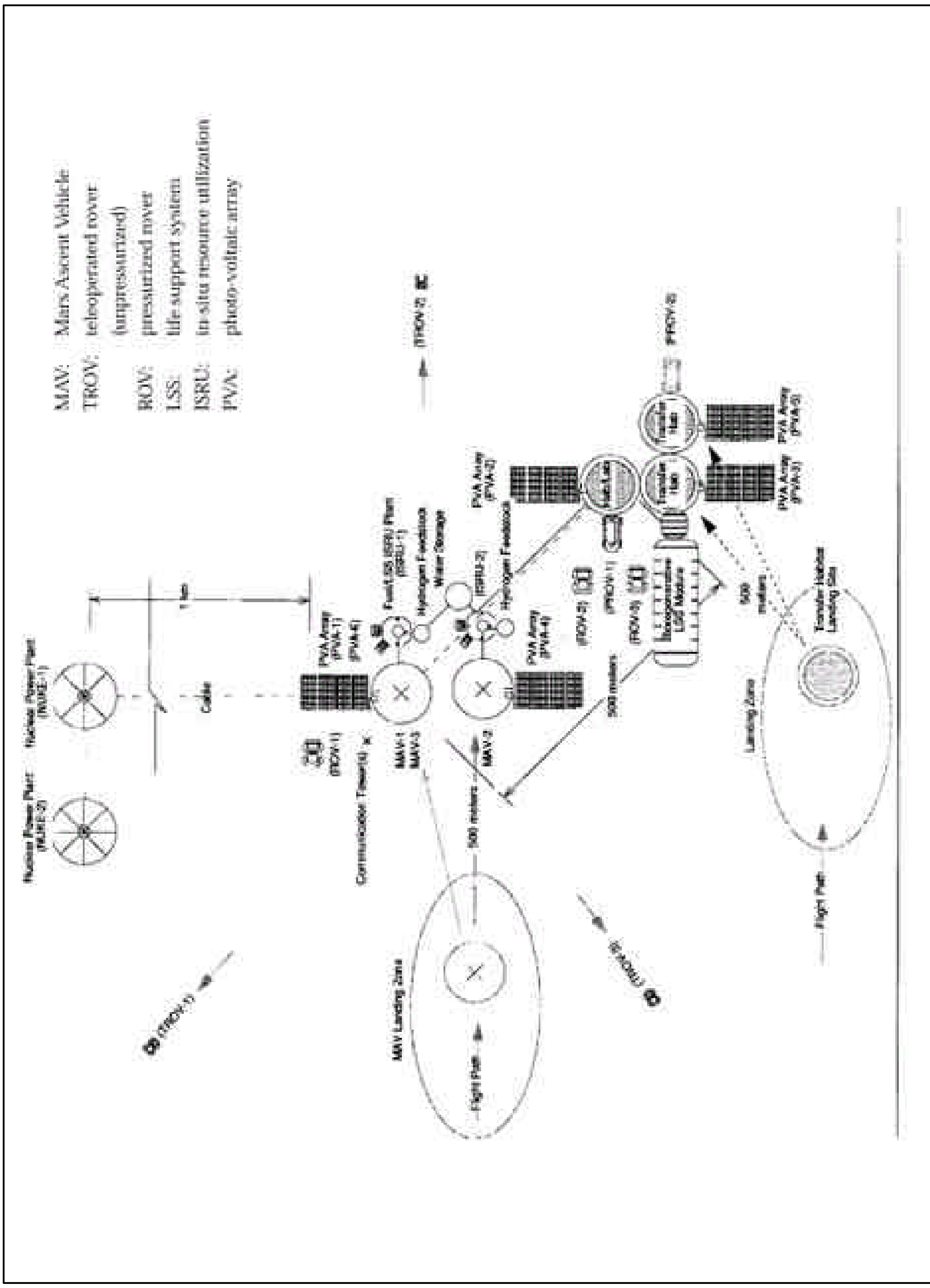


Figure 3-11 Mars surface outpost at the end of second flight crew's stay.

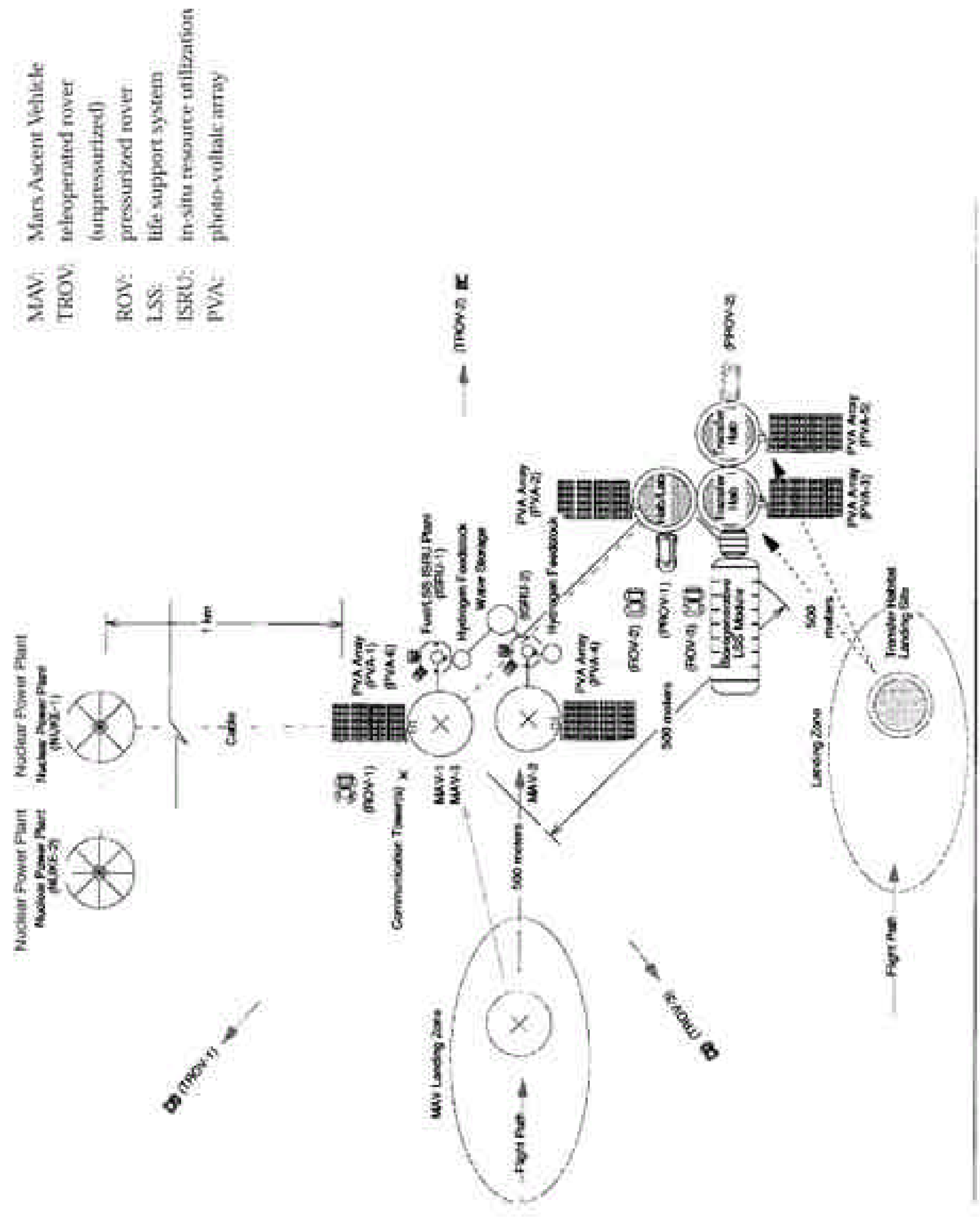
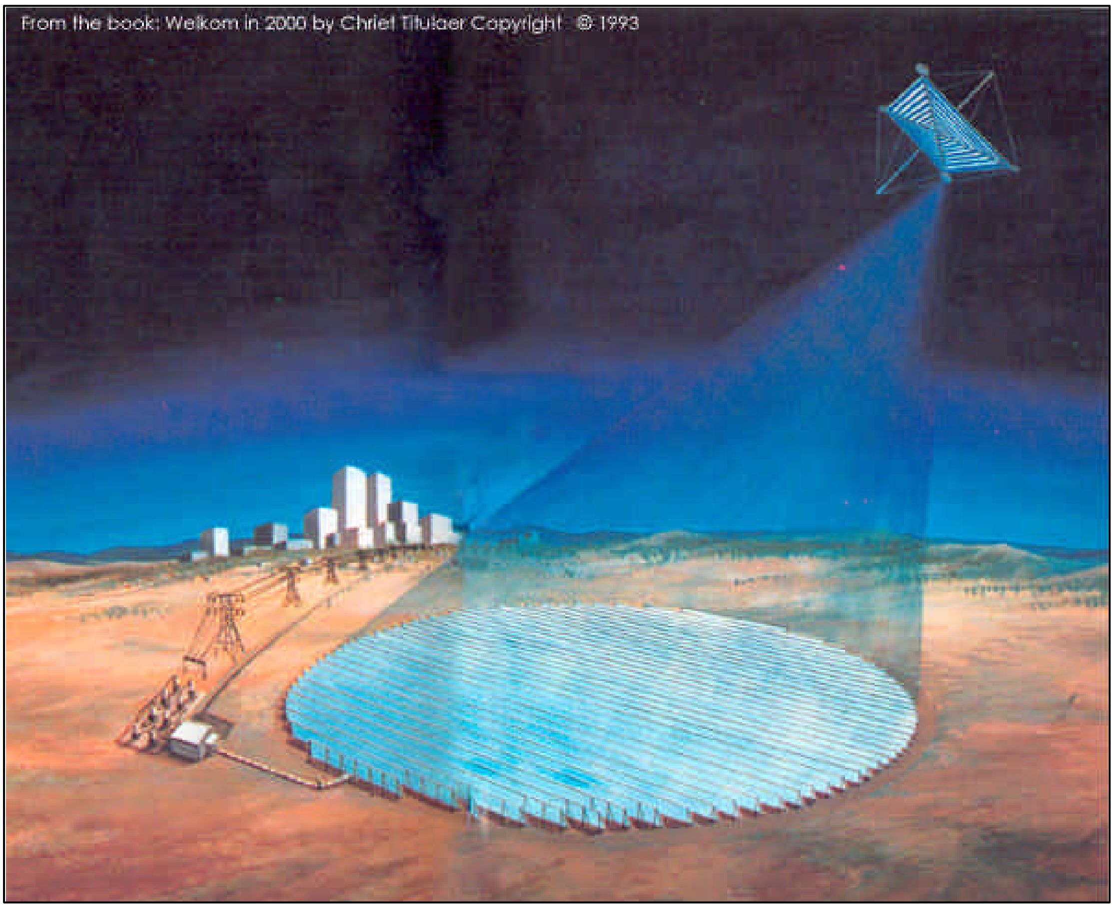


Figure 3-12 Mars surface outpost at the end of third flight crew's stay.

[s.3] Solar energy beamed down by satellite

A satellite measuring 300 by 400 meters, is used as a huge solar panel, it's areosynchronous[72] orbit at 17,000 km from the Martian surface can receive massive amounts of energy and beams it down to the planet via microwaves. On the planet a microwave receiving array converts the microwaves into electricity.



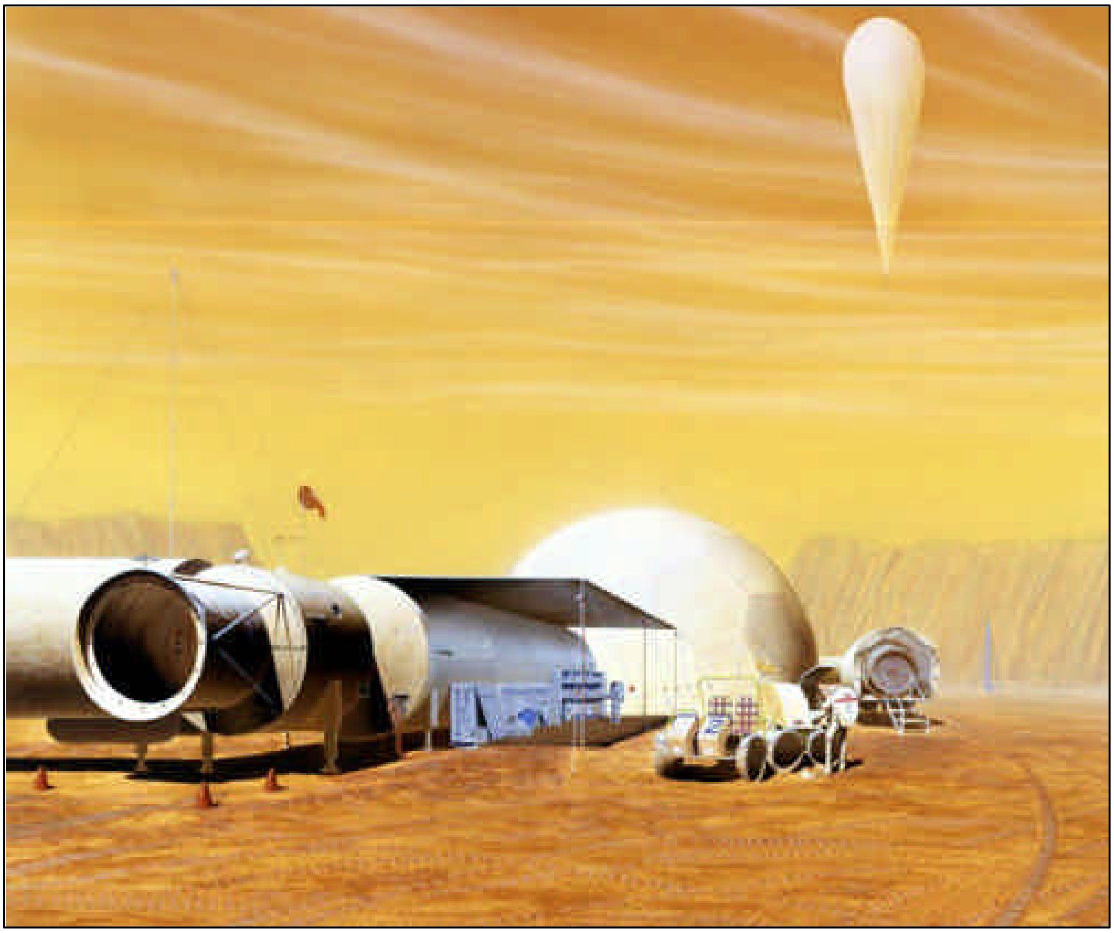
An impression of a microwave array, receiving energy from space.
[unknown, incorrectly credited in the picture]

[72] The Martian variant of geostationary which means at a fixed position above the planet

[s.4] NASA Mars Outpost (from FY-89 Office of Exploration Annual Report)

S89-51054 --- Mars Outpost as outlined in FY-89 Office of Exploration Annual Report, depicted during consolidation Phase. Projected time from start of Emplacement Phase to Consolidation Phase - 4 years with 4 years to complete consolidation and begin full utilization. Main components are a habitat module, pressurized rover dock/equipment lock, airlocks, and a 16 meter constructable (inflatable) habitat. Also visible in this image is a meteorological balloon, an unpressurized rover, a storage work area, a geophysical experiment area and a local area antenna. The Outpost is for 7 astronauts whose mission will focus on research related to Earth sciences such as mining of Mars and Phobos; life science research; advanced technical development; origin of life studies; and further solar system exploration. Mars Outpost elements and procedures are derived from an earlier lunar test bed. This painting was done by Mark Dowman of John Frassanito & Associates For NASA, JSC's of Office of Exploration.

Note: NASA currently has no formal plans for a human expedition to Mars or the Moon. This image and others displayed may not reflect the hardware and overall concept of possible visits to either of those celestial bodies. However, the art work represented here serves as a comprehensive study of various concepts and ideas developed as possibilities over a period of years. The renderings were accomplished by NASA and/or NASA-commissioned artists.



[Pat Rawlings]