A Permanent Settlement on Mars:

The First Cut in the Land of a New Frontier
Master of Architecture Thesis
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A Permanent Settlement on Mars: The First Cut in the Land of a New Frontier

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ABSTRACT

Humans have been fascinated with the planet Mars for thousands of years. Only in the last half a century has it been possible to contemplate sending people to our celestial neighbor. Since then, a rich discourse has evolved concerning how to achieve this goal. The discussion, thus far, has been dominated by mechanical and aerospace engineers with marginal participation from architects. This thesis explores the issues involved in conceiving and constructing habitats on the surface of Mars that can be addressed through architecture.

The goal is to design sustainable and pleasant spaces for humans living in extreme conditions, in order to facilitate the development of a viable community by a small group of people living in isolation, within the realistic engineering constraints of safety, efficiency, and expandability.

The first permanent settlement on Mars is considered at architectural and planning scales. A detailed architectural design is developed for the first phase of construction to house 24 people, situated at the base of a set of mesas in Candor Chasma, using in-situ derived masonry construction and inflatable technology imported from Earth. A primary consideration in the design is the expectation that the first step will provide the vision for an expanding community. A dual band linear growth pattern along which spaces are arranged through a conceptualization of the relationship between humans, plants, and machines is envisioned and a possible configuration of the settlement when it reaches a population of 100 is presented.

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01 - Introduction

'The future of mankind will be decided by the race between two competing human drives, one unleashing military power to compete for Planet Earth's finite resources, the other organizing international cooperation to provide access to unlimited extraterrestrial resources.'
Thomas Paine, NASA Administrator 1968-70

New Frontiers

The dream of human exploration beyond the surface of the earth is tied to the belief that new lands create new opportunities and prosperity. Now, at the beginning of the 21^{st} century, humans live on every continent and every environment on Earth - we live in an age without a frontier. In the past, societies that have achieved unchallenged domination of their environments have ceased to develop and become stagnant. A new frontier is necessary if humanity is to continue its exponential progress. Fortunately a new frontier exists and awaits our arrival.

The first serious study that moved the idea of settling Mars from the realm of fantasy into the realm of the possible was Wernher von Braun's 'The Mars Project' [von Braun 1952]. Since then a rich discourse has evolved concerning how to achieve this dream. Traditionally this discussion has been the monopoly of mechanical and aerospace engineers with marginal participation from architects. However, if the commitment to establish a permanent presence on Mars is made, many of the challenges will need to be addressed through architectural design working in combination with engineering. The first structures built on Mars will play a critical role in the formation of a new Martian society. It is therefore imperative that architects contribute constructively to the design in order to insure that the first cuts made in the ground of the new frontier will create a viable prototype for the future growth of the new community. This thesis explores the issues involved in planning habitats for Mars that can be addressed through architectural design.

Thesis Goals

This thesis will strive to address three parallel challenges.

Social and Design Challenge:
How can a small group of people create a viable community in isolation? How can the habitable spaces be made sustainable and pleasant for humans living in extreme conditions?

Engineering and Scientific Challenge:
What are the engineering and structural imperatives, constraints, and opportunities in constructing habitats on Mars?

Architecture and Engineering Synergy
The final challenge explores the relationship of the first two, by asking to what extent can architectural considerations have an impact on a construction with tight engineering constraints?

Approach

This thesis explores the design of the first permanent settlement on Mars at an architectural and a planning scales. A detailed design was developed for the first phase of construction to house 24 people. At all stages of the design process a primary driver for making decisions was the expectation that this was in deed a first step in a growing community and therefore each choice has a planning implication as the settlement grows. The expectation is that the settlement will grow to accommodate about 100 people, at which point it will be a mature base, which can serve as a support for starting other settlements. The final design presents a possible configuration of the complete settlement that is based on the logic set up by the first phase of construction.

Settlement purpose

The goal of the settlement will be to establish a permanent base on Mars from which high-value scientific and engineering research can be performed in three main areas:

1- Search for past and present life on Mars.
2- Basic science research to gain new knowledge about the solar system's origin and history
3- Applied science research on how to use Mars resources to augment life-sustaining systems and how to live on other planets.

02 - 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 Astronautics, 1896

''When we explore the Moon or Mars, we really explore ourselves and learn more accurately how we fit in.'
Michael Collins, Apollo 11 Command Module Pilot [Collins 1990]

Why Mars?

With the end of the Cold War, political and ideological rivalry is no longer a compelling motive for space exploration. The new motives for reaching out will be scientific curiosity in combination with economic benefit in an environment of international cooperation. Besides the idealistic goal to start a new branch of human civilization and help to guarantee humanity's continual success, a view most vocally expressed by Robert Zubrin [Zubrin 1996], there are several more specific reasons for establishing a human presence on Mars. The search for life on other worlds is perhaps the most widely accepted one. Additionally, humans are needed to conduct basic science research in order to gain new knowledge about the solar system's origin and history, and applied research on how to use Martian resources to augment life-sustaining systems. To these I would like to add the possibility that Mars will become the ultimate 'urban laboratory' where the extreme conditions will force a questioning of the basic assumptions of how to structure a viable community. Finally, Mars can provide a worth-while project accomplished by many nations working together. With time, space travel will become routine and commercial enterprises will become possible, but the original missions can only be carried out by collaboration between governments.

Mars is the most Earthlike planet in the solar system (see fig 01). It is the only planet where we can reasonably imagine sending humans in the near future. It has seasonal changes and almost exactly the same length day. All of the resources necessary to sustain life are readily available on or near Mars's surface [Meyer 1996], [James 1998], [Zubrin 1996]. In contrast, the Moon lacks many vital elements that will need to be imported from Earth. A commonly sited statistic is that if concrete is discovered on the Moon it would make sense to mine it in order to extract its water. Additionally, the Moon has a 27 day and night cycle, making it almost impossible to grow food. Thus, Mars is the only world in the solar system that has the potential of becoming a new home to humans.

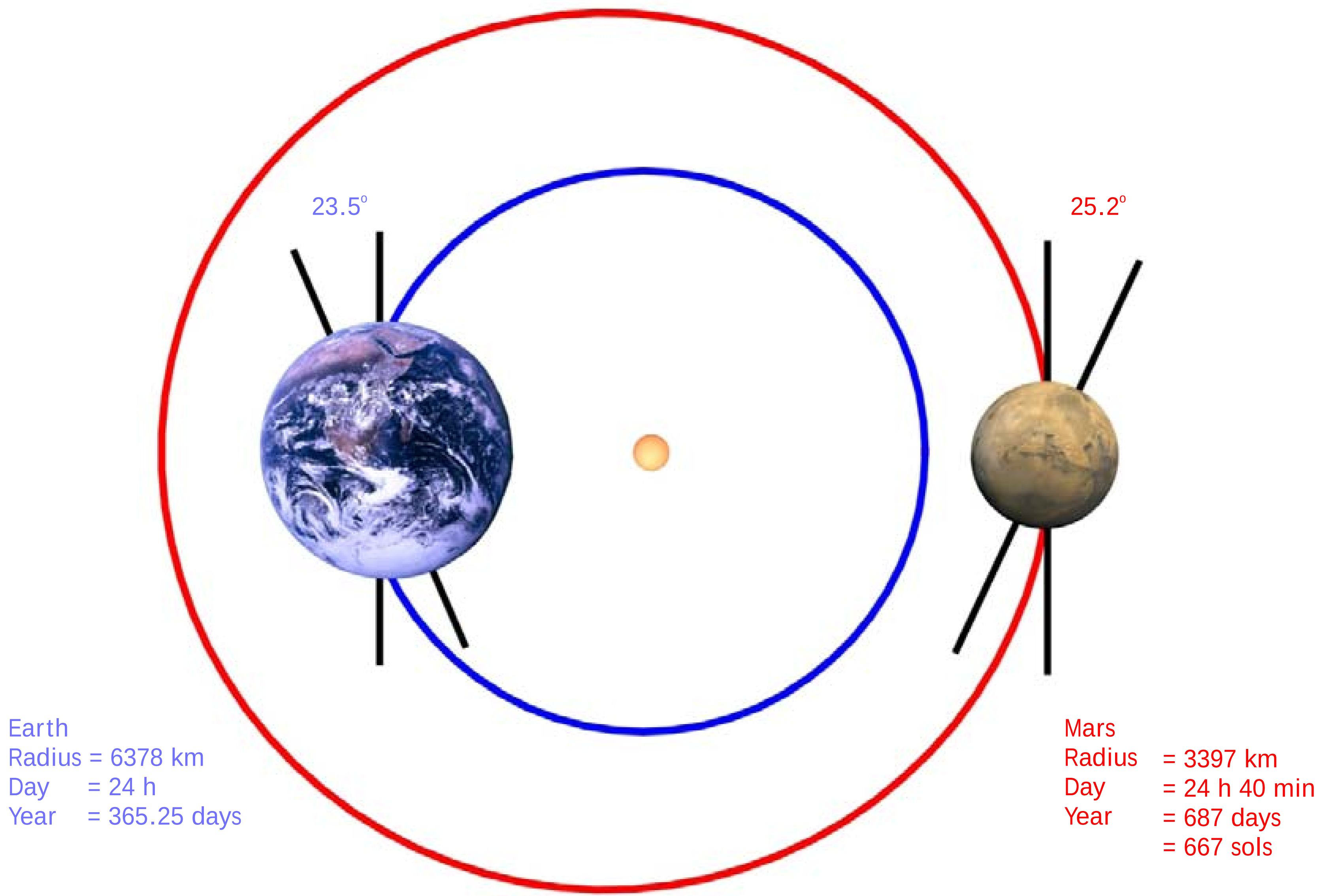


fig. 01 Comparison of size, orbit, and rotation properties

Atmospheric pressure

Mars has a very tenuous atmosphere. Even at the lowest point on the planet, the floor of the impact basin Hellas Planitia, the atmospheric pressure is about 100 times lower than the 1013 millibars found at sea level on Earth. This means that the main structural challenge on Mars is to hold down the interior pressure of all habitats. The severity of the problem can be reduced if the interior pressure is lower than sea level pressure. The highest sizable city on Earth is Potosi, Bolivia. At an elevation of 4000m the atmospheric pressure there is only 620 millibars or about 60% of the sea level pressure. Since humans have lived for generations at Potosi without detriment to their well being, the habitats on Mars can also be pressurized at 620 millibars without increasing the risk to the settlers.

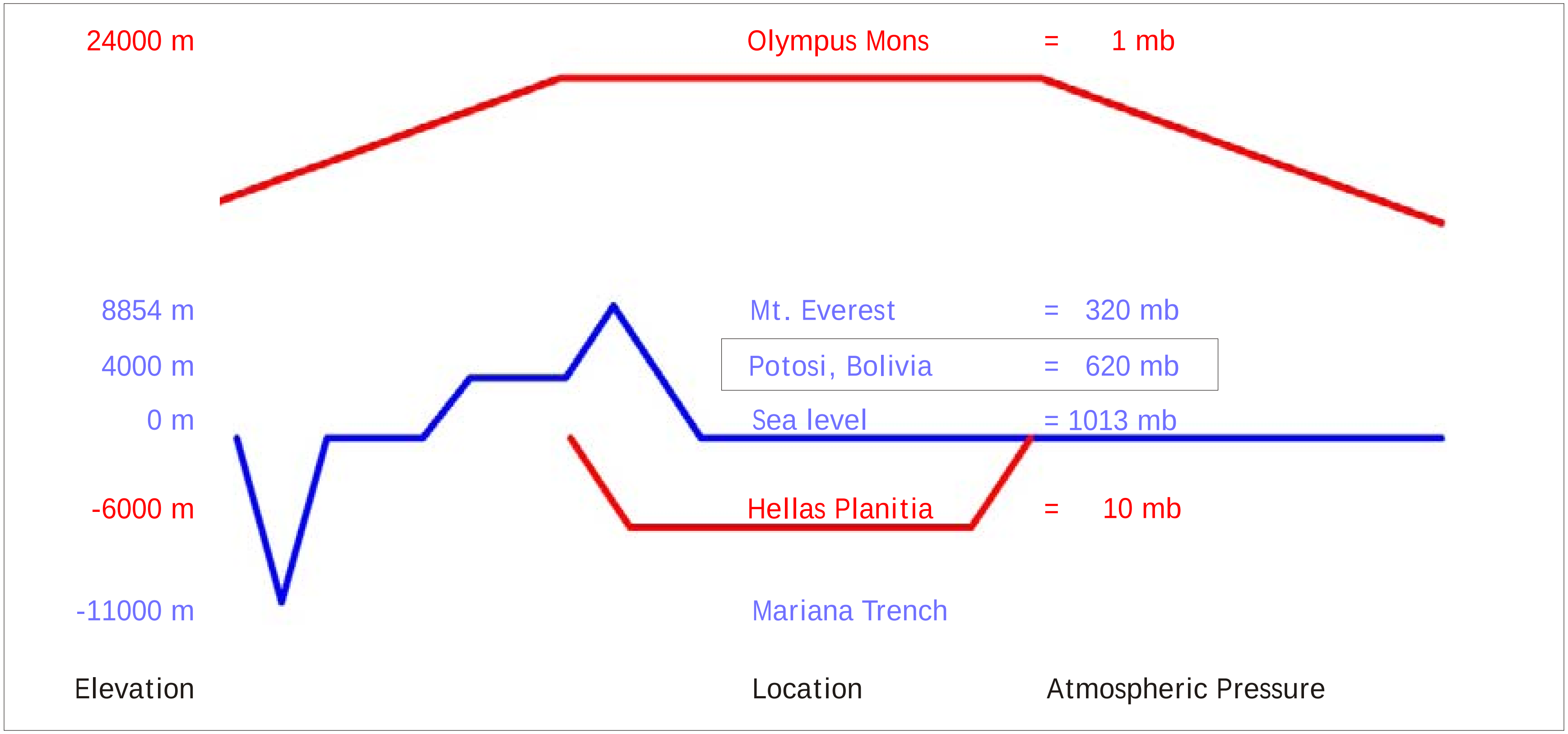


fig. 02 Comparison of elevation and atmospheric pressure of Mars and the Earth.
vertical elevation diagrams are to scale. red = Mars, blue = Earth

Temperature

On average, Mars is about 1.5 times further away from the Sun than the Earth, which makes it a much colder place. The average temperature is -60°C. Without a thick atmosphere to insulate the surface the diurnal temperature variation is much larger. However, temperatures as high as 20°C have been recorded near the equator.

Gravity

Mars is smaller and has a lower overall density than the Earth, resulting in a surface gravity that has only 38% the strength of the Earth's. Ironically this does not make construction easier. The loads on any human-rated habitat generated from the difference of pressure between the interior and exterior are about an order of magnitude greater than the weight of the materials necessary to enclose the space. Thus the major structural problem on Mars is holding the buildings down and not holding them up against gravity like on Earth.

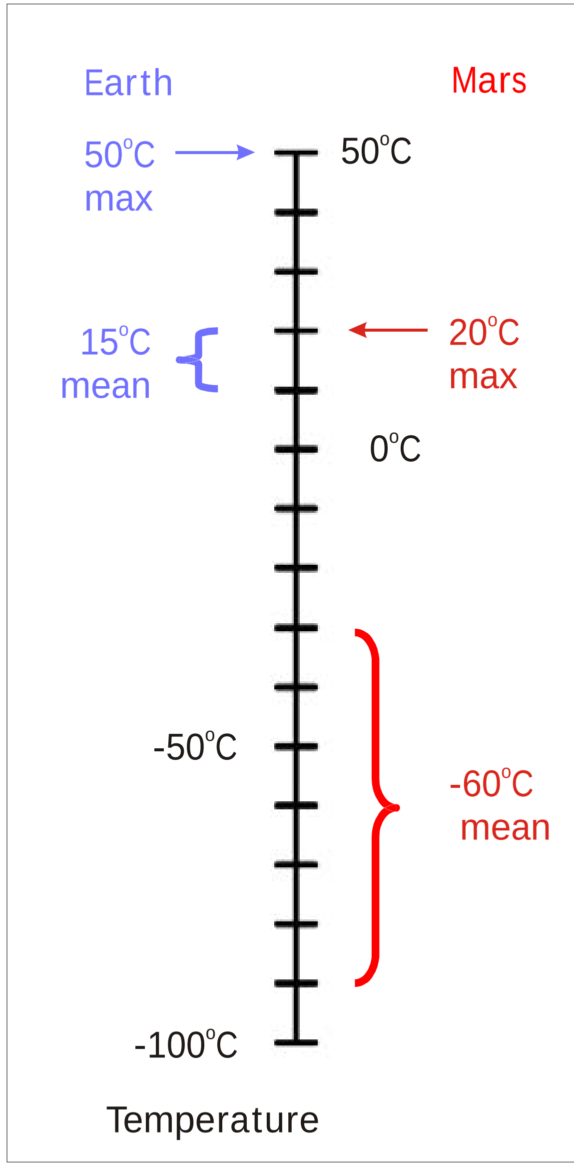


fig. 03 comparison of temperature

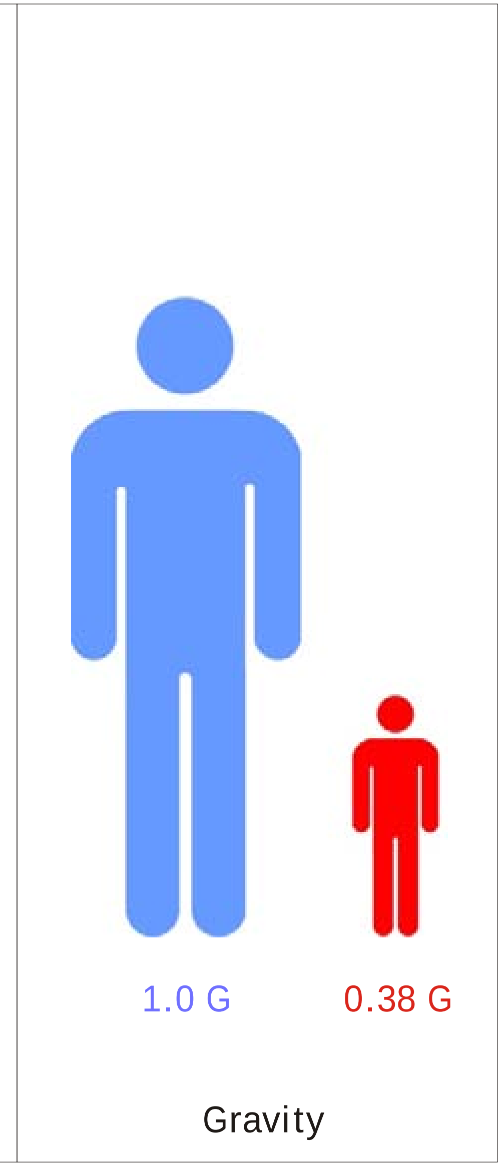


fig. 04 comparison of gravity

Radiation

The final important feature of the Martian environment is radiation. Mars has a very weak magnetic field and an atmosphere that is only one percent as thick as the Earth's. Thus the surface is not protected from radiation like it is on Earth. There are three different types of radiation to worry about. First there is the solar wind, a stream of charged particles that is emitted constantly from our star (fig. 05). The second is cosmic rays (fig. 06). Cosmic rays are produced by exploding stars in our galaxy and bombard the solar system from all directions. The final source is solar flares (fig. 07). Periodically the sun expels large clouds of charged particles that race out through the solar system. Settlers on Mars can be protected from the first two types of radiation by covering all habitable spaces with about one meter of regolith [Zubrin 1996]. The radiation form solar flares, however, is more difficult to stop. Fortunately they are predictable and relatively slow moving. With good observations of the Sun, the settlers can have more than an hour warning before a solar event is about to hit Mars. Thus not all spaces need to be protected against solar flares, just enough to accommodate everyone for a day.

fig. 05 solar wind

fig. 06 galactic cosmic rays

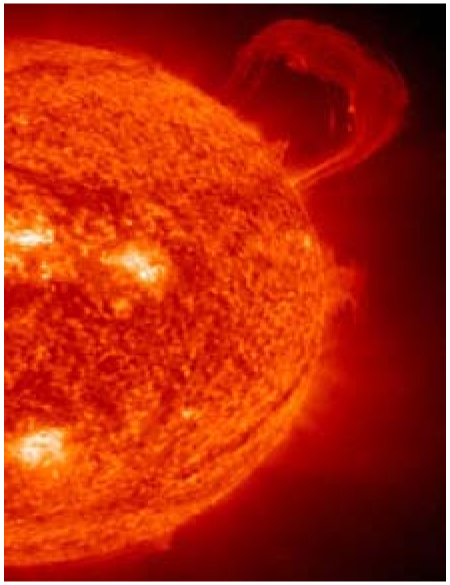


fig. 07 solar flares

Parameter	Mars	Earth	Ratio
			Mars/Earth
Bulk			
Mass (10^24 kg)	0.64	5.97	0.11
Equatorial radius (km)	3397	6378	0.53
Mean density (kg/m3)	3933	5515	0.71
Surface gravity (m/s2)	3.71	9.78	0.38
Escape velocity (km/s)	5.03	11.19	0.45
Solar irradiance (W/m2)	589	1368	0.43
Topographic range (km)	30	20	1.5
Orbital			
Semimajor axis (10^6 km)	227.9	149.6	1.52
Sidereal orbit period (days)	686.98	365.25	1.88
Orbit eccentricity	0.093	0.017	5.6
Length of day (hrs)	24.66	24	1.03
Obliquity to orbit (deg)	25.19	23.45	1.07
Seasons			
Northern Hemisphere	earth days	days	
Spring	171	93	1.84
Summer	199	94	2.12
Fall	171	89	1.92
Winter	146	89	1.64
Mean Temprature (deg C)	-60	15	
Diurnal Range (deg C)	-90 to -30	+10 to +20	
Max Temperature (deg C)	+20	+50	

fig. 08 Summary of all relevant parameters of Mars compared with the Earth

03 - Social Structure and Psychological Issues

'...space settlements [have] the potential to become truly humane communities, as expressed in their design characteristics. Sponsorship and political/philosophical orientation of space settlements will provide for international participation under high-density living and working conditions. A newly found sense of ecology, a nonexploitative utilization of resources, is envisioned. ... in the long run space settlements could become model communities for those of us remaining on 'Spaceship Earth.'
[Preiser 1991]

03-1 Social Structure

Prior to beginning design, the social structure and purpose of the settlement must be specified. Due to its extreme isolation the Mars settlement cannot function like a normal part of established terrestrial society. One must therefore look for precedents in the rich history of thought on how to structure an isolated human society that stretches as far back as the age of colonization in Ancient Greece, and as recently as Paolo Soleri's Arcosanti project, which is still being built [Soleri 1984]. Besides the numerous theoretical works on the subject, there have been a number of utopian experiments carried out, most notably on the American frontier during the 19^{th} century [Tod 1978], [Holloway 1996].

Some of the most important stands that people have taken focus on the tension between individual and communal needs, the attitude towards human sexual and family life, and on the government structure of the group. Without trying to be social engineers the designers of the first base must imagine a viable social structure that is reflected in the spatial organization of the habitat.

For example, the organization of the outpost must take into account the variability of human character. A balance must be reached between the need for individual freedom with the need for communal life. Many failed utopias have tried to sway its members too far in one direction or the other [Tod 1978]. It is unrealistic to try to reform human nature or to shape it to fit the most efficient engineering solution. Rather, its many aspects should be acknowledged and accommodated. Thus instead of only one type of space, the design must incorporate variations within a set of main principles. Existence of both a public and a private sphere, and their relationship, is critical. Public areas must be shared by all and governed by rules that are decided democratically. On the other hand, individuals must have control over private areas, unless private activities threaten the life of the community.

Family and interpersonal relationships

Many utopian and isolated groups have attempted to restrict personal and family love out of the fear that they create a conflict of interest with loyalty to the group. This approach has always failed because love for the group is far less satisfying. Humans are far too individualistic and different from one another to love equally everyone in the group. Cases where the abolition of the family and eugenics seem to have led to stable societies, like Sparta where the society was in a constant state of war, or fervent religious communities where puritanical morals placed severe restrictions on personal relationships, are not acceptable precedents. Moreover, writers like Fourier and Freud show the importance of sexuality in normal human behavior and discuss the problems that can arise in repressing it. Therefore, personal and family love must be allowed to flourish. The Mars station design must provide quarters of various sizes for both single residents and married couples, and eventually children.

Command Structure

Traditionally, space activities have had a quasi-military command structure that has worked well for short duration missions with narrowly defined objectives. This model, however, is unacceptable as a system of government for a civilian community.
A mixture of authority and democracy will be more appropriate. There should be a commander, who will make autocratic decisions when instantaneous action is required. When there is no strong time pressure, the commander should solicit opinions and reach a consultative decision. Democratic voting or consensus-seeking should be used on issues revolving around life within the habitat [Connors 1996]. The habitat design should reflect this arrangement in the spatial relations between the command room and the general meeting space.

International make up of the Martian community

A long term project like the construction of a habitat on Mars will be an endeavor of an international stature. The main practical reason is the prohibitive cost of sending humans on such a long voyage. Currently only the richest governments contemplate such an endeavor. With time space travel will become routine and commercial enterprises will become possible, but the original missions will be carried out in the name of all humanity by international collaboration between governments.

03-2 Psychological Issues

Psychological issues have also been identified in isolated and crowded environments. The best-documented cases are the scientific research stations in Antarctica and nuclear submarines [Harrison 1991]. Experimental manned ecosystems such as Biosphere II, NASA's Lunar-Mars Life Support Test Project (LMLSTP) [Lane 2002], and the USSR's Bios 3 project [Boston 1996] provide further evidence. Finally there are lessons from off-shore oil rigs, remote manufacturing and military sites, undersea research vessels, and manned balloons [Connors 1996].

Several potential problems have been recognized. Crewmembers develop odd sleeping hours that may not problematic to them, but can be disturbing to others. Mood disorders like anxiety and depression also occur, but usually are not severe and can be accommodated. Slowing down of work and cognitive functions due to the illusion that one has 'all the time in the world' has also been observed. Crewmembers become very sensitive to changes in air quality and odors. Close viewing distances cause temporary loss of the ability to focus beyond several meters [Weybrew 1991]. On Earth, many of these problems are dealt with by organizational means such as self-selection and screening of personnel. Communal rituals that build social cohesiveness, such as sharing of food, are also very important. Another way that the stresses of overcrowding might be alleviated is through meditation. Practice of meditation is a valuable tool in relieving stress that is common in many eastern cultures.

The need for privacy and the ability to view outside the habitat are the two major psychological issues that can be addressed architecturally.

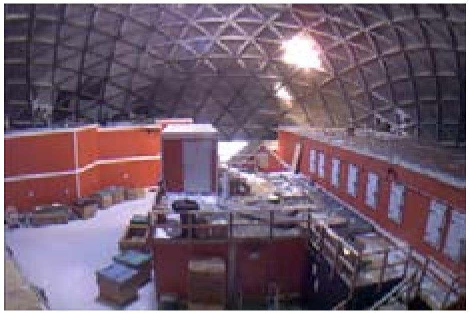


fig. 09 Interior of Amundsen-Scott South Pole Station, operated by NSF

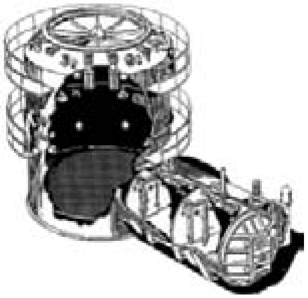


fig. 10 NASA's Lunar-Mars Life Support Test Project

fig. 11 Biosphere II

Privacy

The most important issue, that can be dealt with architecturally, is the need for privacy and the proper relationship between work, social and private spaces. One important aspect of privacy is the extent to which people are able to exert control over the amount and nature of the contact they have with others. This type of control serves four main functions: it provides opportunity to concentrate undisturbed; being 'away' provides necessary down time for rest; it helps people manage the image that they project to others; and allows for private interactions. There is a danger that too much privacy will create subgroups and cliques. However, a lack of privacy creates greater risks and therefore a balance must be sought. There may also be tensions due to the international makeup of the crew. Different cultures have various standards on privacy and its spatial characteristics. In many non-western cultures privacy is almost nonexistent and often people who seek to be alone are regarded with suspicion.

Windows

The need for windows and surface habitation is another important design issue. Mars has a very thin atmosphere and no magnetic field to protect its surface. Therefore any structure that will be inhabited by humans will have to be shielded by several meters of regolith. However, turning the settlers into troglodytes should be avoided. Living on the surface and having a view outside will have considerable psychological advantage. If one undertakes the long journey and intends to settle on Mars one should be able to see Mars from the comfort of their home. This view was advocated by the early cosmonauts' and astronauts' who insisted that windows should be an integral part of any spaceship design. Submarine sailors also echo the need to look outside - a privilege that is called ‘periscope liberty’ [Haines 1991]. Finally windows were a high priority in the new building for the Amundsen-Scott South Pole Station, which will have a big advantage over the original windowless dome [Blakeslee 2003].

03-3 The Future of Martian society

Once the Martian population grows, other settlements will be formed, and commercial activity will develop. This larger society will stop being a utopian community. A completely new social organization will be invented, which is impossible to predict now. However by setting up the first steps we can hope to have a positive effect on the shape of this new branch of human civilization.

04 - Engineering Challenges and Construction Methods

04-1 Engineering Challenges

If the decision to establish a permanent presence on Mars is made and the construction of a large, permanent habitat begins, then the construction methods must be carefully considered. Relying on habitats brought entirely form Earth is an unsustainable strategy unless truly revolutionary advances in transportation technology are made. A more realistic approach would be to maximize the use of Martian materials and to implement simple, well understood, and tested building techniques. Before describing the choices of materials and construction methods, it is useful to review the engineering challenges to be overcome.

1- Low atmospheric pressure

As examined in chapter 02, Mars' tenuous atmosphere that is about 100 times less dense than the Earth's at sea level. Even if the habitats are pressurized at the low pressure that is experienced at the elevation of the highest cities on Earth, the structure of the habitat will still have to resist the enormous outward force of 60 kPa (8.7 psi).

2- Safety

For safety the settlement must be composed of several interconnected segments. In case of an accidental loss of pressure or a fire, the settlers must be able to evacuate and seal any segment, thus localizing the emergency.

3- Radiation

All habitable spaces must be protected from the ionizing radiation that reaches the surface of Mars. The easiest way to accomplish this is to cover all structures with about one meter of regolith.

4- Enormous distance from Earth

The extreme cost of importing materials and equipment from Earth emphasizes the need for locally available materials. Furthermore, the use of simple construction is important because the replacement of broken parts will take years.

5- Dust storms

Despite its thin atmosphere Mars has dynamic weather. The most important phenomenon are the seasonal dust storms that can grow to envelop the whole planet. The storms occur when winds pickup extremely fine dust particles from the surface and carry them at speeds up to 100 km/hr [Zubrin 1996]. The low atomospheric pressure makes the power of the winds relatively insignificant, however the dust will abrade and degrade any unprotected materials.

04-2 Construction Methods

Masonry

Masonry is chosen, because it is the only readily available resource on the Martian surface, it is simple to produce, and is extremely durable. The most abundant material on the surface of Mars is regolith and rocks. In fact the whole planet, except for the polar caps, is covered with nothing but regolith and rocks. Bruce Mackenzie, has proposed that it the first settlers can manufacture bricks using the regolith [Mackenzie 1987]. Using pitched-brick vaults and self-supporting domes (see pages 30 - 32) one can construct a wide range of spaces using no centering, thus greatly simplifying construction [Richards 1985], [Robinson 1993].

Masonry is very strong in resisting compression. However, it has low tensile strength. In order to balance the interior pressure, the only option is to cover the masonry structures with as much as 10 m of regolith. However, as discussed in chapter 03, turning the settlers into cave dwellers is highly undesirable. Therefore, in order to give the settlers the ability to view outside the habitat and to facilitate access to the surface, it is necessary to use masonry in combination with another system that can resist the pressure through tension. The best technology that meets these criteria is inflatable modules.

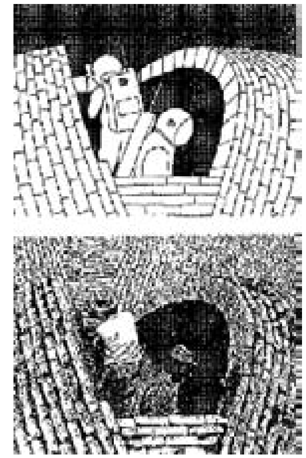


fig. 12 masonry

Inflatables

Inflatable modules brought from Earth will comprise the second construction system. The benefits of using inflatable structures are that they can be made very light and they offer a big advantage in weight to volume ratio compared to a rigid shell habitat. Finally, these structures have relatively small deployment operations and can be pretested on Earth.

The benefits and challenges of the two systems are summarized in figure 14.

fig. 13 space inflatable

Rigid interior structure from which a bladder is inflated to resist the internal pressure. allows windows and views outside compartmentalized space - optimize the bladder as a pressure membrane - low mass - advantage in weight to volume ratio compared to rigid shell structures - relatively small deployment operations - can be tested on Earth	Masonry covered with regolith to balance the internal pressure. allows larger open spaces no view - manufacture bricks using regolith reinforced with fibers from used parachutes - utilizes most widely available Martian resource - using pitched-brick vaults and self supporting domes, construct a wide range of spaces using no scaffolding
Use inflatables for spaces that require access to the exterior – airlocks, greenhouse support, and private quarters. Use regolith covered vaults for larger spaces with no view – public areas, kitchen/dinning, labs, and baths.	

fig. 14 Summary of benefits and challenges of masonry and inflatables

04-3 Masonry

Ancient vaulting techniques

The history of masonry arches and vaults can be traced back to about 3000 b.c. in Lower Egypt and Mesopotamia [van Beek 1987]. One of the oldest brick vaults covers the storehouses at the Ramesseum, the tomb complex of Ramses II who reigned to about 1224 b.c. The largest unsupported brick vault in the world also dates from ancient times. It spans the great hall of the palace at Ctesiphon. There are three distinct methods for constructing vaults that were developed in antiquity.

Radial Vaults

The most common is the radial vault, where the space between the side walls is filled with loose bricks that serve as temporary support (or centering) for the vault. Then, bricks are laid in successive courses, with mud and small stones placed at the outer edges to cant the bricks in until the vault closes at the crown. After the mud dries the centering is removed.

Ribbed Vaults

The most rare method involves leaning two long, slightly curved bricks against one another over the center of the space. Though they are the simplest to construct, ribbed vaults are the least strong of the three methods (fig. 17).

Pitched-Brick Vaults

Also know as leaning arches, this technique is the most useful for work on Mars, because it requires no centering (fig. 18). The first bricks on each side are laid at an angle against a side wall, the second set of bricks is placed on top of the first, also leaning against the wall and so on until the arc of the vault closes at the top (fig. 20). Successive arcs are leaned on the first one until the end of the vault is reached (fig. 21). The remaining triangular space is filled in with smaller arcs (fig. 22). Often, more courses are laid on top of the first one leaning in opposite directions.

fig. 15 Vault over the great hall at the palace at Ctesiphon. Built between 3rd and 6th cen a.d. 25.5 m span, 28.4 m high. Made of lightly fired brick using leaning arches method. Largest unreinforced brick vault in the world [van Beek 1987]

fig. 16 Vaults at Ramesseum, 13th century b.c. storehouses in Egypt. Each vault consists of four courses of mud brick. Successive courses lean in opposite directions. about 4 m span.

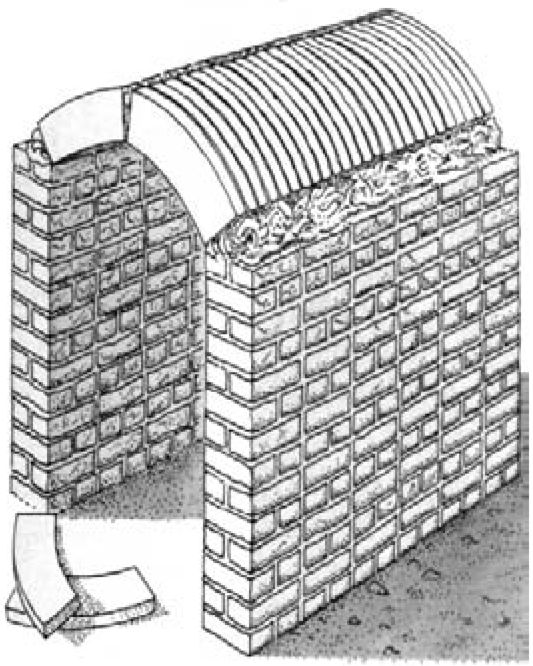


fig. 17 ribbed vault

fig. 18 construction of a vault without centering

fig. 19 vault built using leaning arches

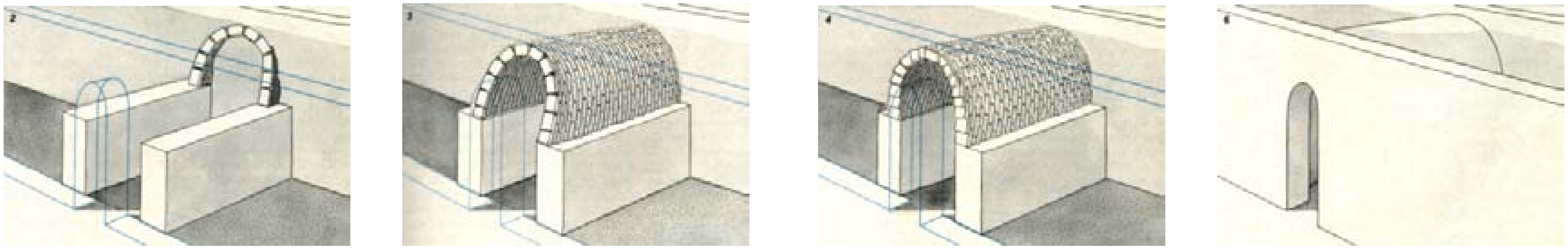


fig. 20, 21, 22, 23 basic steps in constructing a vault using the leaning arches method

Domes

One major advantage that domes possess is that they only need support at four points, unlike vaults that require continuous support along two walls. Domes can also be constructed without centering using a similar idea to the pitched-brick vaults. First four piers are erected and connected with four arches. The first set of arches will require some centering, however subsequent domes can be built by leaning the arches on the previous domes. Next the spaces between the arches are filled in concentric courses (fig. 27). The construction can be stopped after the completion of any course and the structure will remain stable. This principle was most famously and spectacularly applied by Brunelleschi at the dome of the Duomo in Florence.

The only instruments that are required to built a dome in this way is a hammer to help in positioning the bricks, and a rope or a stick attached to the center to guide the geometry.

It is also possible to shape the bricks so that successive courses interlock, making the use of mortar as a glue unnecessary.

figs. 24, 25, 26
Steps in the construction of a masonry dome notice the measuring stick that is used to guide the geometry of the dome

fig. 27 Constructing a brick dome using concentric brick courses in contemporary Egypt.

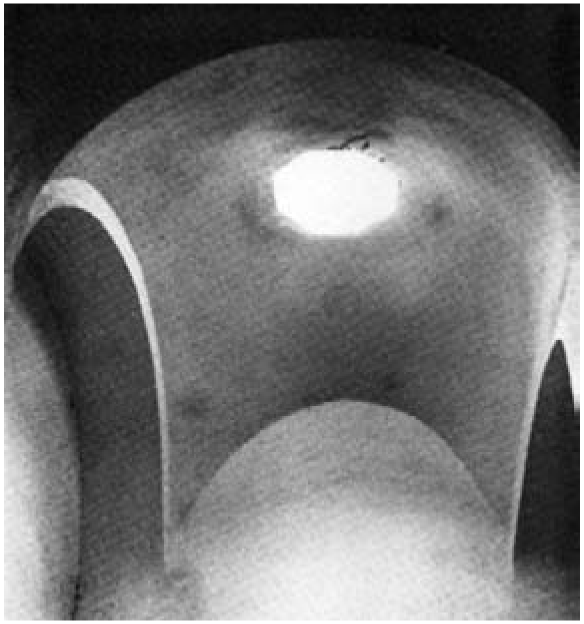


fig. 28 A completed masonry dome that has been finished with plaster. Notice that top of the dome can be left open without losing stability.

Contemporary Masonry

In more resent times, Egyptian architect Hassan Fathy has been an avid advocate for low-tech masonry construction for much the same reasons that it will be used on Mars - its wide availability, its simplicity, durability and elegance. Using the simple forms of pendentive domes and barrel vaults in many imaginative combinations and with modern planing and space making ideas, Fathy has shown that the ancient techniques are still appropriate in the contemporary world and might be the first choice for the future [Richards 1985].

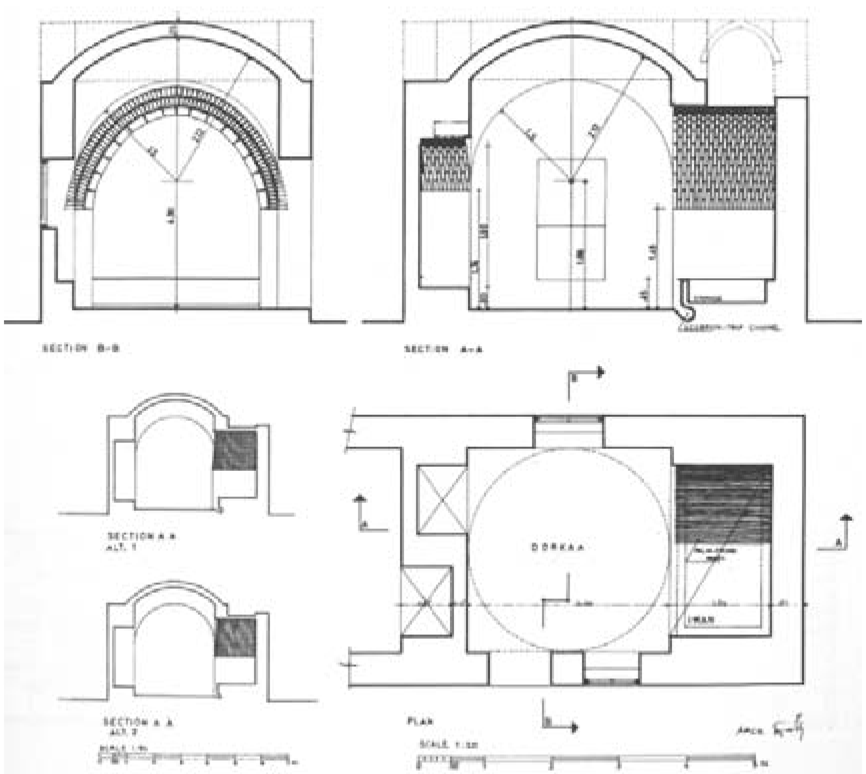


fig. 29 Using the two simple elements of a dome and a vault in imaginative combinations Hasan Fathy has designed many intricate structures.

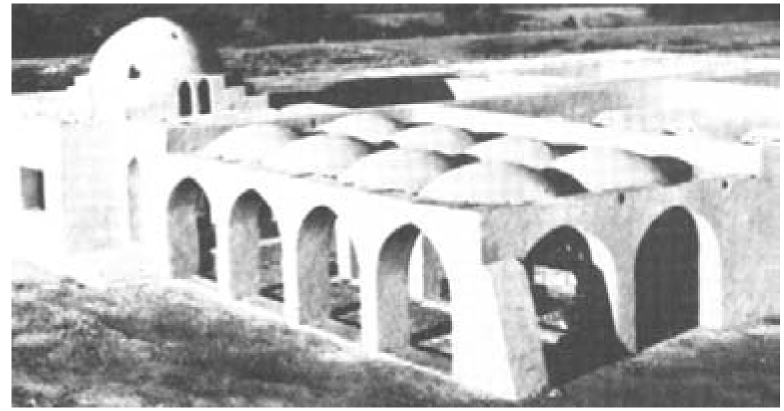


fig. 30 Mosque in Gourna, Egypt, architect Hassan Fathy

fig. 31 Dar al Islam mosque in New Mexico, architect Hassan Fathy

Masonry on Mars

Five challenges to constructing masonry structures on Mars should be considered.

Making brick

There are a number of ways to manufacture bricks. The one that will be chosen depends of the type of soil and the amount of water that is available at the landing site. On Earth, bricks are either sun-dried or fired in a kiln. On Mars the kiln can be made by insulating a propellant tank that is recovered from a landing craft. Power could be provided by waste heat from the nuclear reactors and by solar reflectors. The strength of the bricks can also be increased by compressing them using a simple mechanical press before firing (fig. 33). Fibers, from shredding the parachutes of incoming capsules, can be used to further reinforce the units. Most of the water that is mixed into the bricks can be recovered during the drying or firing process and reused [Mackenzie 1997].

Cut stone

An alternative to fired brick might be cut stone. If a soft enough rock is found at the landing site it might be possible to make large masonry units by shaping boulders. Although this approach, requires more tools that are likely to break down often, it is worth exploring.

Mortar

Mortar is used to fill in the irregularities between bricks and even out stress concentrations, as well as to hold the individual bricks in place until the vault or dome is complete. Originally, mortar will be made by mixing dust and water. If more strength is needed, some additives might be acquired from plant products or will have to be imported from Earth. Eventually, the mortar may be entirely from plant derived polymer extracts. The second function of mortar can be obviated by shaping the brick so they can interlock.

Seal

Once the enclosures are completed they can be glazed on the inside to make them air tight. Any remaining cracks can be patched up with plant products. A series of plastic sheets can be laid inside the cover material to trap air that might still escape and recover it using small tubes. If further leaks occur, the moisture in the air will quickly freeze thus sealing the crack.

fig. 32 The tools required to make mud brick: fine soil, water, a container to mix in, a form, and hands. on Mars all of the step will be performed by robots.

fig. 33 Using a hand-operated press can considerably increase the strength of the brick [Mackenzie 1987]

fig. 34 Clay model of a concept for a Mars base using masonry vaults by Bruce Mackenzie

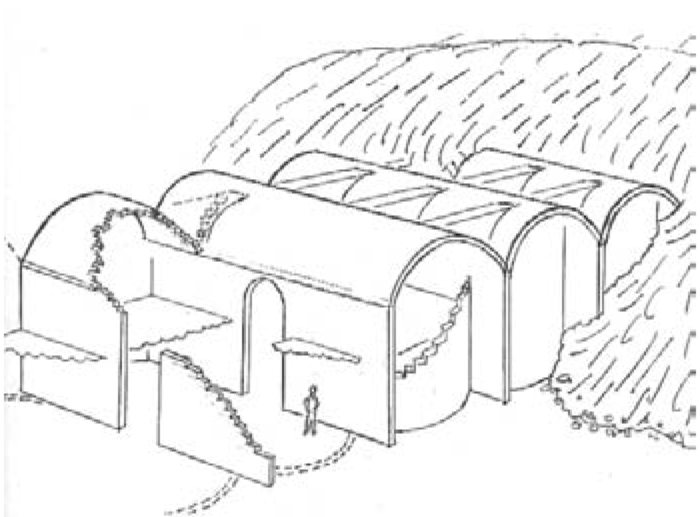


fig. 35 Drawing of a concept for a Mars base using masonry vaults buried by regolith [Bruce Mackenzie 1987]

Cover

The primary function of the masonry is to hold the shape of the habitat, both in the pressurized and depressurized state. When fully pressurized the forces on the masonry will be roughly balanced. When fully depressurized the masonry will be required to hold the full force of the cover. The structure must be designed so that the masonry never goes into tension, in other words, the load lines for both cases must fit inside the masonry.

The amount of cover that is needed to balance the internal pressure depends on the density of the material used. For example, if only the fine Martian regolith is used then the habitats need to be buried by 10 m. Assuming the average density of the fine regolith at the Viking and Pathfinder sites of 1500 kg/m^3 [Cattermole 2001] and the Martian acceleration fo gravity of 3.71 m/s^2, then one cubic meter of regolith exerts a pressure of,

$$(1500\ kg/m^3)\ (3.69\ m/s^2)(1\ m^3) = 5565\ kg{*}m/s^2 \text{ or } 5.57\ kPa$$

Therefore to balance 60kPa of internal pressure, the required cover is,

$$60\ /\ 5.57 = 10.8\ m$$

If, however, igneous rocks with an average density of 2500 kg/m^3 are used, then only 6.5 m of cover are needed. The safety factor that has to be applied does not need to be large, because the internal pressure can be accurately controlled using pressure valves. For the purpose of this thesis, a combination of regolith and rocks, and a safety factor of 1.25 are assumed, which translates into a cover of 10 meters.

Masonry details

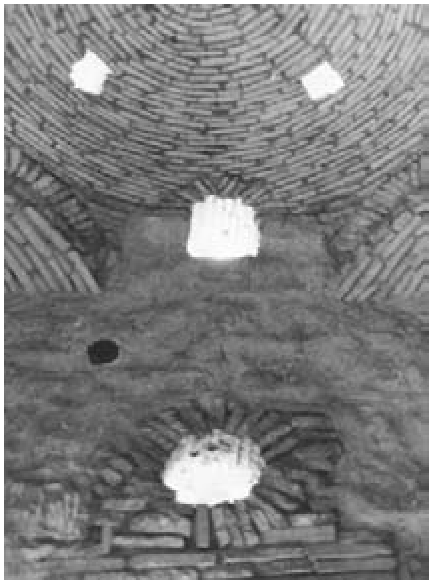


fig. 37   openings in a dome

fig. 38   free end of a pitched-brick vault

fig. 36   pitched-brick vault with opening

fig. 39   Detail of the vaults at the Ramesseum,
notice the opposite pitch of bricks on alternating courses

Alternative techniques

There are three alternative building techniques that may prove useful upon further study of Mars: concrete, Catalan vaulting, and ceramic construction.

The constituents of cement are available in some locations [Collins 1990], [Clifton 2000]. Combined with a plentiful supply of water it may be possible to make concrete. Concrete however has serious problems, because it requires scaffolding and special conditions under which it has to cure.

Another possibility is thin tiled construction, also known as Catalan vaulting. This method has been used in the Mediteranian for hundreds of years and was made famous in America by Rafael Guastavino in the late 19th century. The main drawback of this system is that it requires fast-setting mortar, which might be more difficult to make.

Finally, California architect Nader Khalili has developed a structural system using ceramics. He constructs the shape of the building using bags of clay and then fires the assembly from the inside, effectively making one giant piece of ceramic.

All three of these methods might prove to be viable alternatives to the brick construction that I have outlined. Deciding which is the optimal for construction on Mars will be part of the applied research that will be conducted by the first settlers.

figs. 40, 41, 42
Catalan vaulting: thin tiles are arranged one course at a time to complete a large number of compression forms. Fast-setting mortar is required to hold the tiles in place until each course is completed.

figs. 43, 44, 45
Steps in the construction of a ceramic house by architects Nader Khalili.

04-4 Inflatables

The idea of using tensile fabric structures for space applications has been around since the 1960's. The first in-depth design for such a structure was carried out by NASA in the late 1990's. The project was originally focused on creating a transit vehicle to take six people to Mars, hence the nickname 'TransHab' for Transit Habitat. The final design was adapted to serve as the main crew quarters of the International Space Station (ISS). TransHab has a revolutionary hybrid design that consists of a central hard structural core from which a tensile shell is inflated. The design of the shell itself is also innovative. It is composed of four functional layers: an internal bladder, a structural restraint layer, a micrometeoroid debris shield, and an external thermal protection blanket. The project concluded with the construction of a full scale prototype of the system that was subjected to a deployment test in a vacuum chamber, thus proving that inflatable structures technology is ready to be applied to the design of habitats for space applications [Kennedy 2002].

TransHab was design for the zero-gravity environment of outer space. The central idea of using an inflatable bladder that is deployed from a rigid frame has been adapted in this thesis for use in the 0.38 G gravity on the Martian surface. Such inflatable modules will be used to house activities that require access to the surface of Mars.

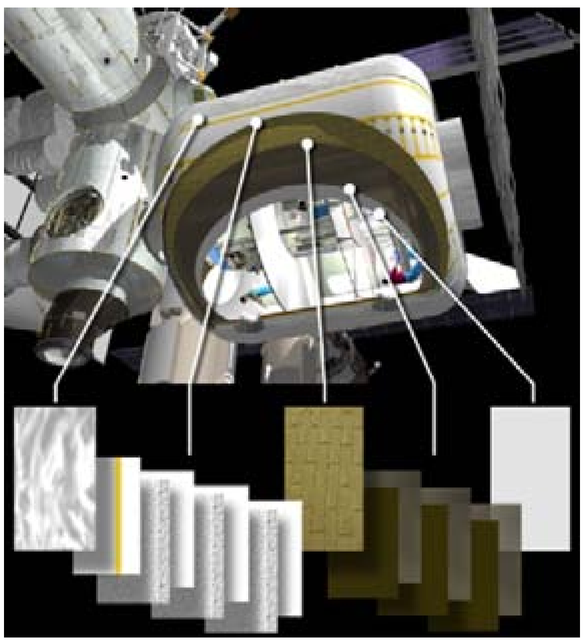


fig. 46 Rendering of TransHab attached to the ISS

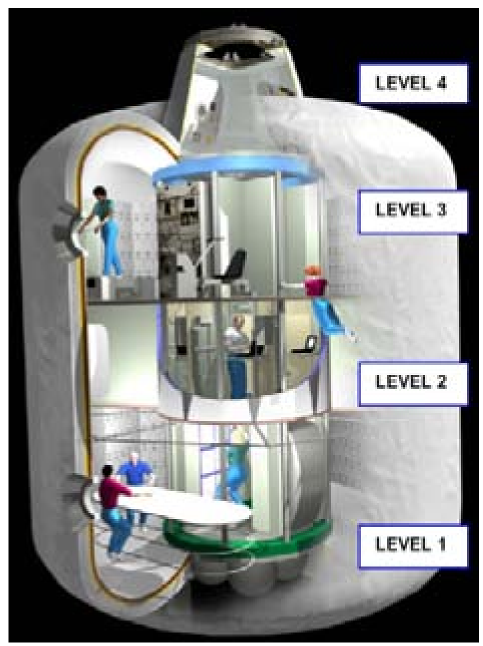


fig. 47 TransHab cut-away

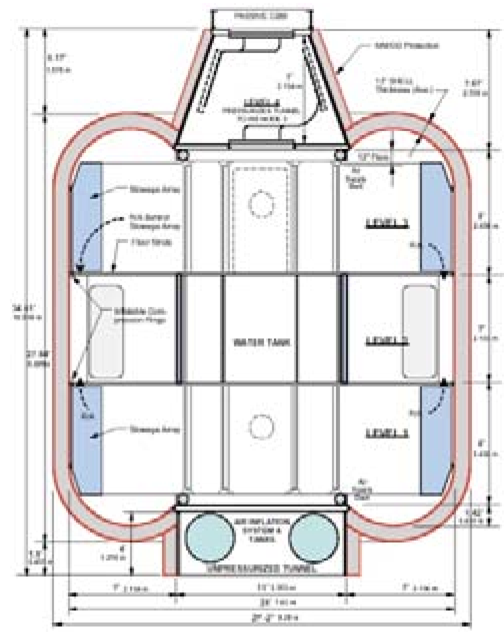


fig. 48 TransHab section

04-5 Additional Components

Airlocks

Sophisticated items like airlocks, and pressure doors would have to be imported from Earth until Mars develops a mature manufacturing capability. By coordinating with the design of the interplanetary capsules most of the necessary items can be salvaged from the landing craft, with the exclusion of the initial landing base, which should be preserved as part of history.

Plant-rated greenhouses

Greenhouses are also imported from Earth. Plants and humans require different living standards. Thus the greenhouses can be optimized for plant growth if humans do not have to enter them on a regular basis [Mackenzie 1997]. Plants require lower pressure, higher CO_2 content, and lower radiation protection than people. Additionally, such 'plant-rated' greenhouses can be designed with lower safety margins, and thus can be made lighter and cheaper than human-rated habitats. The plants will be grown on movable beds and transported robotically through an airlock to a human-rated shelter where they can be tended, harvested and replanted.

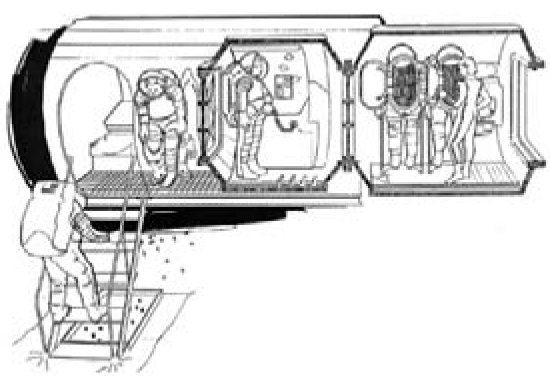


fig. 49 Human and vehicle airlocks are imported from Earth

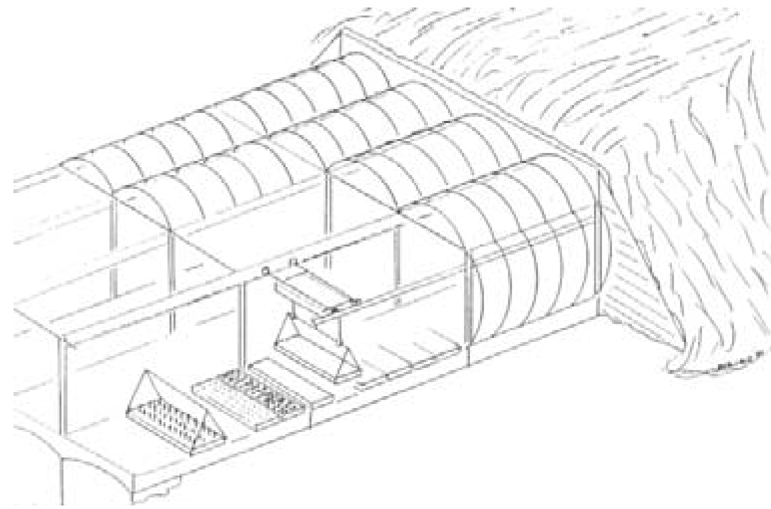


fig. 50 Plant-rated greenhouse design for Mars [Mackenzie 1987]

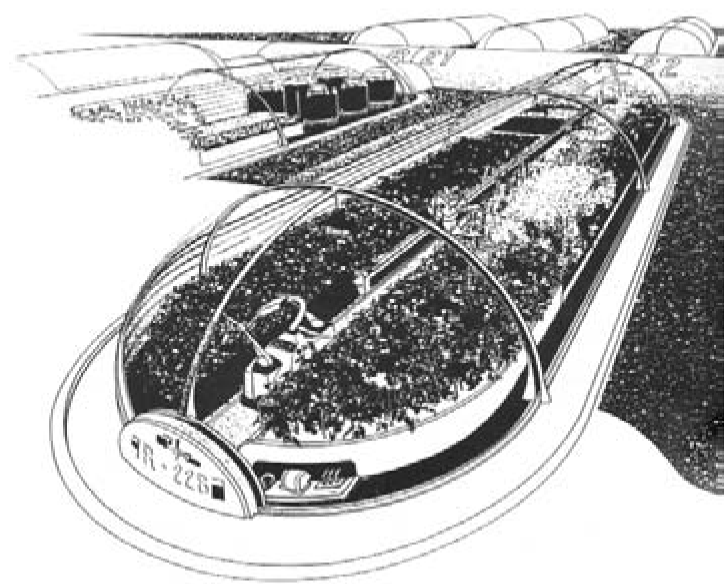


fig. 51 Plant-rated greenhouse design for Mars [Ishikawa 1997]

05 - Development Scenario

The first missions to Mars will be making a giant leap that will far surpass our voyages to the Moon. The first humans to set foot on Mars will have traveled orders of magnitude farther and longer than the nine deep space missions that were carried out during Apollo. The space ship that will carry them to Mars will be designed with the highest constraints for safety and reliability. Every component will be tested numerous times before being incorporated into the vehicles. For this reason, the first explorers will travel to Mars and live on its surface in habitats brought entirely from Earth. They might carry out experiments on how to use the in-situ resources to help future generations build habitats, but they themselves will have to rely on what can be brought from Earth. It has been suggested that we should establish a permanent presence on Mars with the very first mission. As much as I would like to see that happen, I believe that such a step is beyond out technical and political capabilities. Therefore an incremental approach to the settlement of Mars is a more realistic assumption.

Mars Reference Mission

The Mars Reference Mission [NASA 1992] is a well developed plan for the first four missions to Mars that serves as a standard against which future proposals can be compared. It is a good starting strategy to develop an initial habitat for 12 humans that can be used as a base for future development.   Inspired by Robert Zubrin's Mars Direct plan, the Mars Reference Mission incorporates the ideas of using in-situ resources to supply fuel and oxygen for the return journey. It stipulates that the first three missions land at the same site in instantly deployable spacecraft type modules, also inspired by Zubrin's 'tuna can' habitat idea. By connecting the modules, the infrastructure to support a semi-permanent surface habitat with 12 crew members is accumulated. There will also be greenhouses, life support machinery and in-situ recourse utilization machinery. Pressurized and teleoperated rovers that can be outfitted with attachments to aid in construction work will also be available. Power will be provided by two nuclear power plants (160 kW each) and supplemented by several photovoltaic arrays.

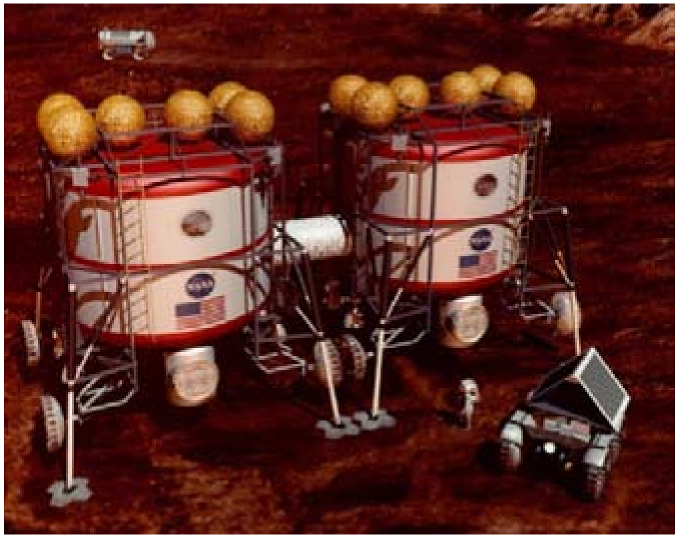


fig. 52   NASA Mars Reference Mission

The goal of this initial habitat will be to demonstrate two capabilities. First, that Martian habitability has no fundamental limitations due to uniquely Martian characteristics such as low gravity, absence of a magnetic field, soil toxicity, or the radiation environment. Second, that self-sufficiency can be achieved on the local scale of a Mars base. This includes providing a reasonable quality of life at a reasonably low risk for the crews, and operating a bioregenerative life support system capable of producing food and recycled air and water.

Once this infrastructure is available, and the above questions have been answered in the positive, the construction of a larger permanent habitat using Martian resources and building materials can commence.

fig. 53 NASA Mars Reference Mission
A newly arrived habitat is towed into position next to a habitat form a previous mission by an unpressurized rover.

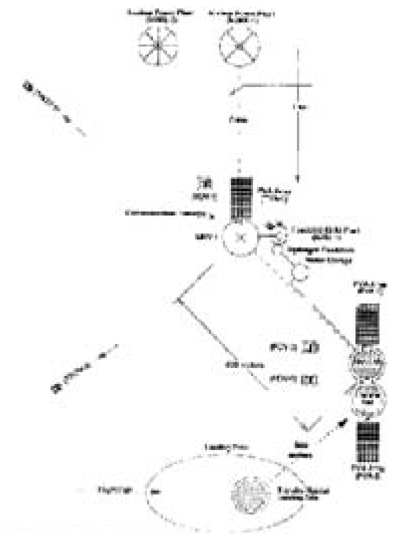


fig. 54 Mars surface outpost at the end of the first crew's stay

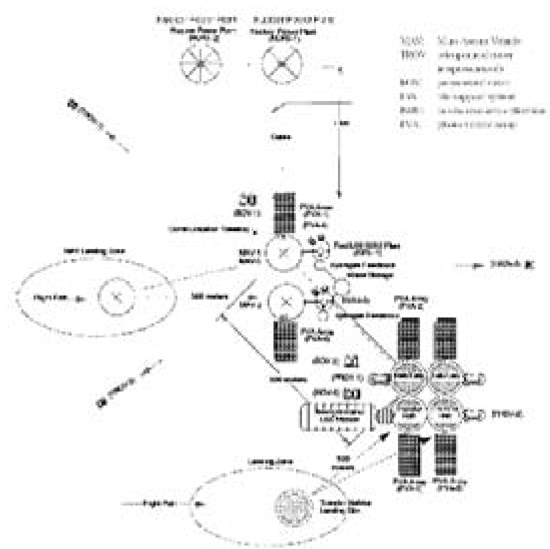


fig. 55 Mars surface outpost at the arrival of the fourth crew

At the end of the Mars Reference Mission there will be a crew of 12 on the surface of Mars with the potential to survive there for several years. If subsequently the decision is made to begin the construction of a permanent settlement, the following strategy can be adopted. At every launch opportunity 12 more settlers arrive at the site. Energy efficient launch opportunities occur between Earth and Mars approximately every 2.5 years. Thus the first crew on the surface or Mars will have 2.5 years to construct the first phase of the permanent settlement which will house 24 people - themselves and the 12 new arrivals. At every subsequent launch opportunity 12 more arrive and have to be accommodated. This thesis develops the detailed design for the first phase of construction, while considering the continual expansion of the settlement.

Crew

Much has been written about possible selection process and the make up of the first crews that will go to Mars. While more work needs to be done in this area, it is safe to assume that each crew member will have a primary specialty plus cross training in one or two other fields. The primary specialties required will be builders, engineers, farmers, and scientists. The builders will primarily work on expanding the habitat. Their work will mainly take them outside the habitat constructing the new segments or planning at a small indoor studio. The engineers will be responsible for the establishment and maintenance of the life support system. They will develop new in-situ resources in the vicinity of base. More than anyone else the engineers will work throughout the whole settlement, as well as perform extensive extra vehicular activity (EVA). They will have a garage and maintenance shop where rovers and external chemical plants can be brought in for repair in a pressurized environment. In general they will be much like the ‘alchemists’ in Stanley Robinson’s ***Red Mars*** [Robinson 1993]. The farmers will work mainly in plant preparation area that will support the plant-rated greenhouses. They will share some of the research space with the scientists. The scientists will perform the basic science alternating between long roving trips and work in laboratories at the settlement. At any time there will be at least one long duration roving mission. In between trips time will be devoted to examining specimens at a open laboratory space and synthesizing results in more private area or at the private quarters. Finally, there will be a commander who leads and coordinates work at base. Common tasks such as cooking and cleaning the common spaces will be shared equally by all, or rotated. Initially, most of the settlers will be builders, engineers and farmers, with only a few scientists, in order to establish an initial functioning habitat. As the settlement matures and a steady growth is achieved the population will include more scientists.

Future of the Settlement

As the settlement evolves and experience of living on Mars is acquired the settlers will develop new and better designs and methods of construction. It can therefore be expected that once a mature station of about 100 people is completed new settlements will be started. Thus there is an expected maximum size of the first settlement, beyond which it is impossible to plan for at this time.

The break down of the various specialties for both the first phase of 24 people and the mature settlement of 96 people are presented in figure 56. Figure 57 shows the space estimates for the first phase.

Summary of settlement population for first phase

total population = 24 (12 on Mars and 12 more arriving after 2.5 years)
6 builders + 6 'alchemists'/engineers + 4 farmers + 7 scientists + 1 commander/administrator

Builders – work on expanding the habitat. Mainly on EVA + some studio planning work
Engineers – establish and maintain life support. Repair the exterior chemical plant modules in garage. Develop new resources.
Farmers – work mainly in plant preparation area. Occasionally go inside plant rated greenhouses.
Scientists – rotate on roving trips. Analyze samples in open lab space. Synthesize results in more private area or at private quarters.
Commander – leads and coordinates work at base.

Arriving	Total
1st Landing - 12	
4 builders	4 builders
2 engineers	2 engineers
4 farmers	4 farmers
2 scientists	2 scientists
	12 total
2nd Landing -12	
2 builders	6 builders
4 engineers	6 engineers
	4 farmers
6 scientists	7 scientists
	1 commander
	24 total

Completed base

1 commander
4 communication specialists
- command and communications room

5 doctors/psychologists
- labs

40 basic science
- 2 three-person expeditions at all times
- 34 work in labs at base

10 builders
- work outside and indoor studio

24 farmers
- greenhouses and supporting areas

12 engineers
- fix machinery, monitor systems

96 total

fig. 56 settlement growth

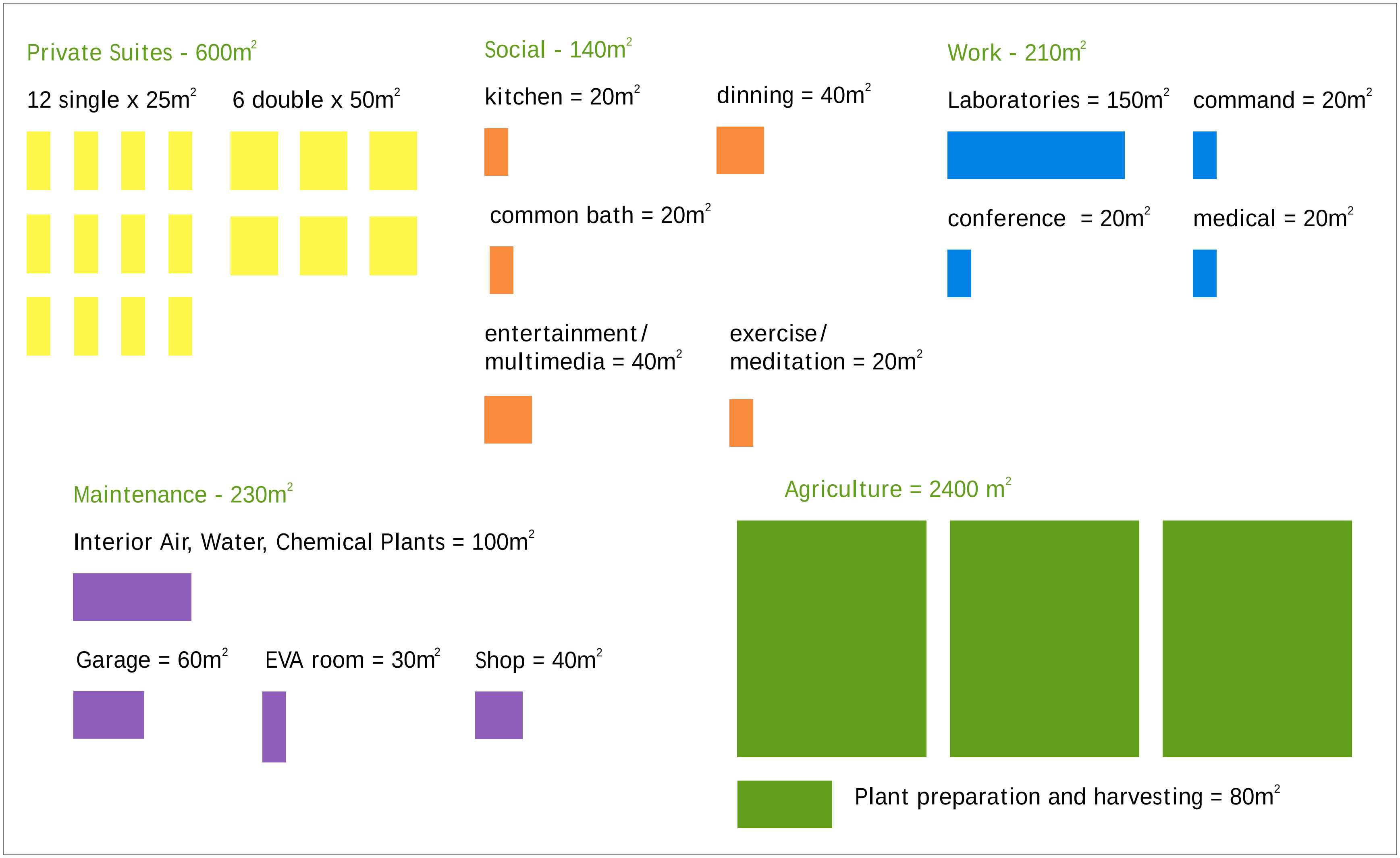


fig. 57 Space estimates for first phase of construction

06 - Site: Base of a mesa in Candor Chasma

Site selection and response to the site are key design problems for the first settlement.

There are a large number of engineering and logistical issues to be considered. The settlement must be located in proximity to geologically varied region of scientific interest. There must be easily accessible in-situ resources, most important of which is water. Low elevation is important in order to take advantage of higher atmospheric pressure, which aids both in harvesting gases from the atmosphere and landing using parachutes. The location must also have convenient access to and from orbit and a clear communication system view of orbit and the Earth. A number of sources also suggest that a location in the northern hemisphere might be advantageous due to the longer summer [Dubbink 2001], [Robinson 1993]. The site should also allow for expansion by a modular growth pattern.

There are many architectural and urbanistic issues as well. The first permanent habitat will be our first cut in the new frontier. It is therefore a very important step that will have an effect on the future development of the planet. A transplant of a pattern from the homeland in a model such as the 'Law of the Indies' will not work. There simply won't be the resources available to impose a predetermined plan that doesn't account for local conditions. The other extreme of a completely unplanned and pragmatic approach like the one taken by North American settlers is also unrealistic. The base must react to the site within a set of guiding rules. The site must also provide real and perceived sense of protection. On Earth, the location of a new settlement has traditionally been dominated by considerations for defense. On Mars there are no natives to defend against, thus the need for real and psychological sense of protection against the hostile environment will become more dominant. Finally any settlement needs a symbol that the residents can identify with, a landmark that identifies the structure as home, or a sacred place that will symbolize the founding of the community. It should be recognized that eventually the site of the first settlement will become a place of veneration and pilgrimage.

In the years to come we will continue to gather more accurate and detailed information about potential sites, and almost certainly a much more informed decision will be reached about the final site. For the purpose of this thesis, however, I have chosen a site based on the best available information as of the fall of 2003.

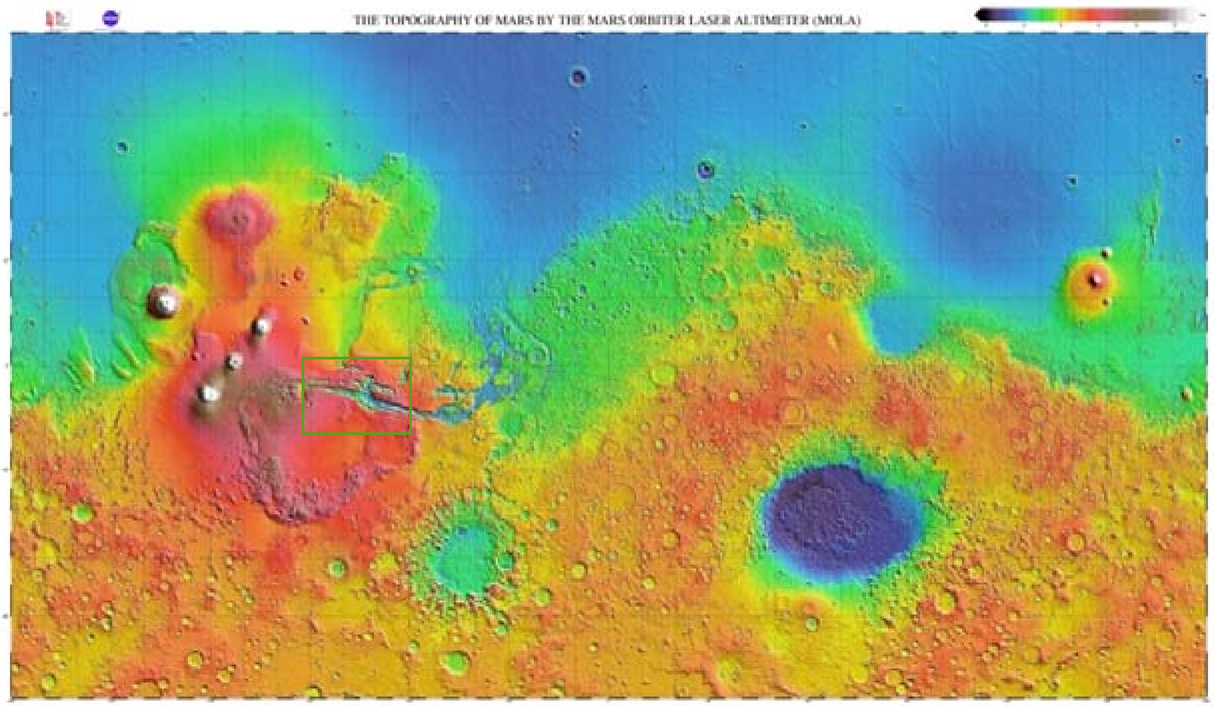
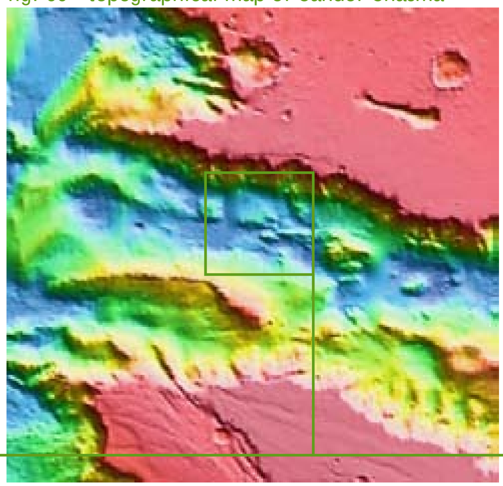


fig. 58 topographical map of Mars

fig. 59 computer rendering of Candor Chasma

fig. 60 topographical map of Candor Chasma



Candor Chasma

Candor Chasma is one of the northern branches of Valles Marineris, which is the deepest, and the largest canyon on Mars. It is located just south of the equator and thus has relatively high average temperatures. The elevation of the floor of the canyon is almost 4800 meters, below the planetary mean offering relatively high atmospheric pressure.

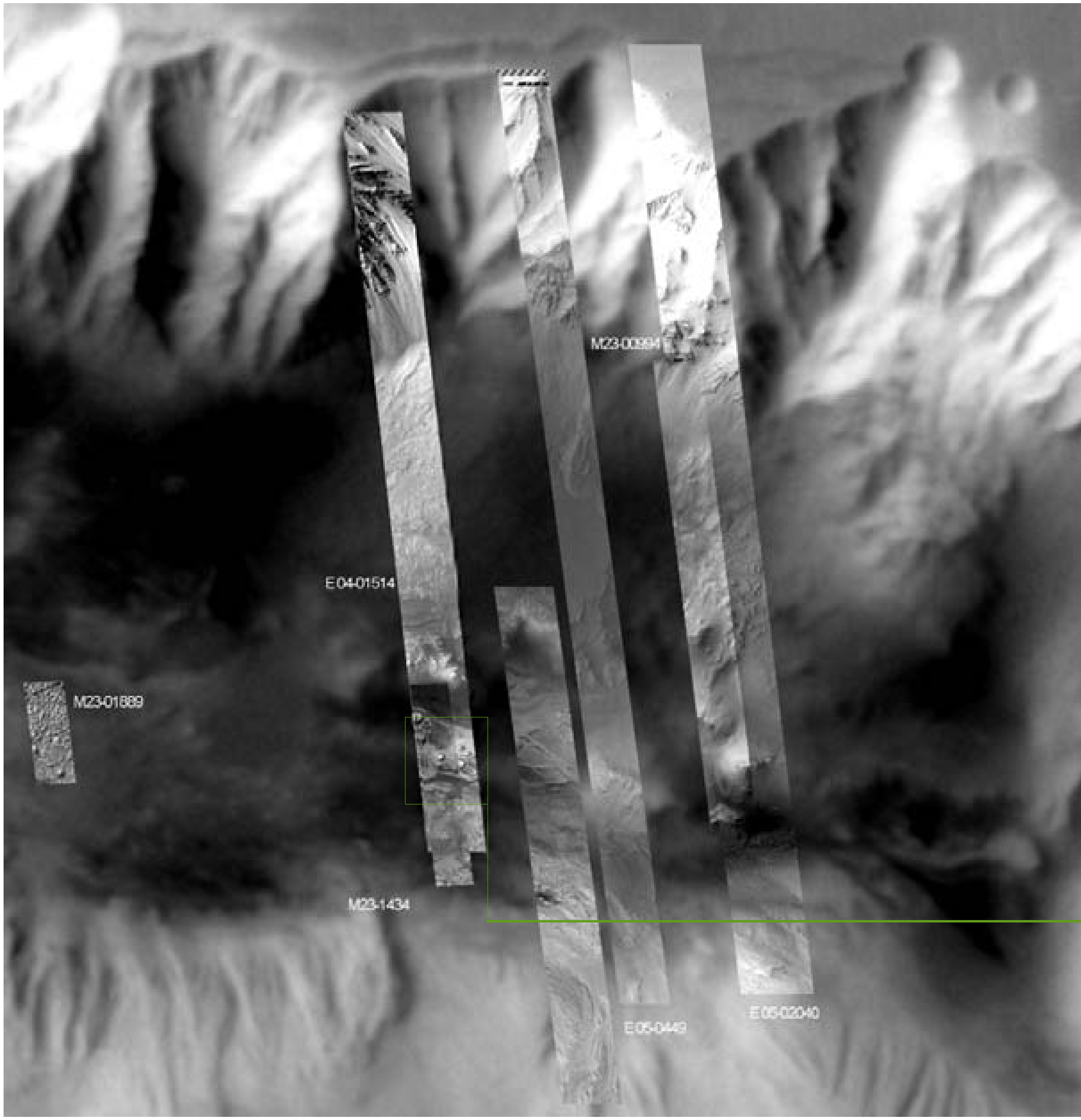
NASA also sees the Candor Chasma region of the Valles Marineris as a possible landing site for the Mars Reference Mission:
“It offers a unique opportunity to sample rock layers and their interbedded soils that would reveal the petrochemical history, age dates, and the environmental changes that may correlate 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.” [NASA 1992]

project site

The group of mesas in the middle of Candor Chasma fulfil many of the requirements for a successful site.

The walls of the canyon are about eight kilometers above the base. The panorama of the cliffs and valleys will present a beautiful view for the first settlement. Additionally the mesas themselves present a interesting sight giving the settlement a view in the close range as well.

There are relatively flat areas to the north and south of the mesas, that can serve as landing areas, where the flightpaths to and from orbit will not overfly the settlement.



project site

fig. 61 All of the available high-resolution images from the Mars Global Surveyor superimposed on lower resolution context image.

fig. 62 MGS image E04-01514

Acquisition parameters

Image ID (picno): E04-01514
Image width: 672 pixels
Image height: 8064 pixels
Pixel aspect ratio: 1.29

Derived values

Longitude of image center: 70.10°W
Latitude of image center: 6.00°S
Scaled pixel width 4.32 m
Scaled image width: 2.90 km
Scaled image height 44.96 km
Solar longitude (Ls): 164.22°
Local True Solar Time: 14.65 hours
Emission angle: 0.00°
Incidence angle: 41.78°
Phase angle: 41.77°
North azimuth: 93.02°
Sun azimuth: 20.00°
Spacecraft altitude: 382.83 km

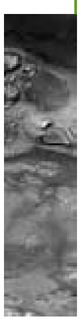


fig. 63 MGS image M23-01434

Acquisition parameters

Image ID (picno): M23-01434
Image width: 768 pixels
Image height: 3200 pixels
Pixel aspect ratio: 1.3

Derived values

Longitude of image center: 70.05°W
Latitude of image center: 6.29°S
Scaled pixel width: 2.87 m
Scaled image width: 2.20 km
Scaled image height: 11.90 km
Solar longitude (Ls): 106.37°
Local True Solar Time: 14.37 hours
Emission angle: 0.06°
Incidence angle: 46.16°
Phase angle: 46.20°
North azimuth: 93.01°
Sun azimuth: 45.51°
Spacecraft altitude: 381.13 km

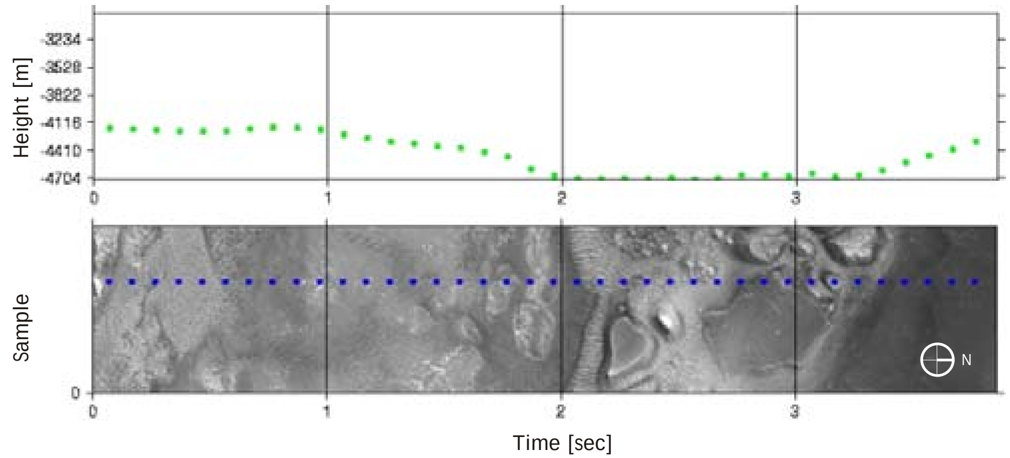


fig. 64 MOLA track data super imposed on image M23-01434

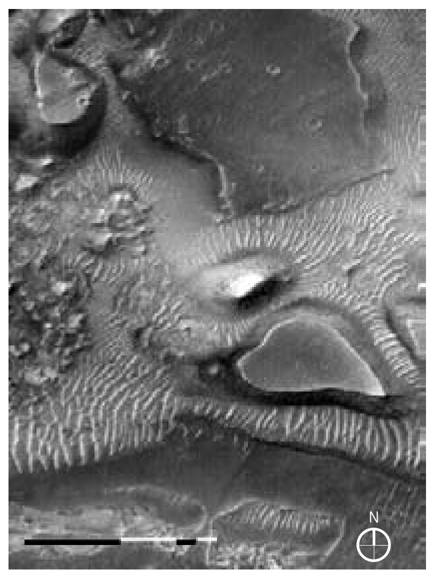


fig. 65 detail of MGS image M23-01434

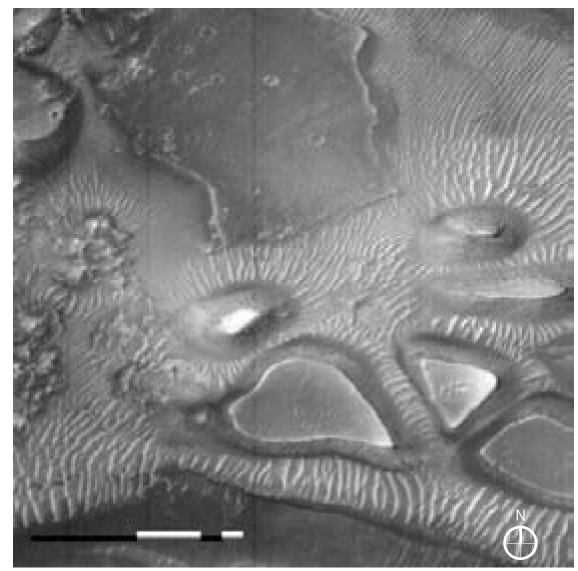


fig. 66 detail of MGS image E04-01514

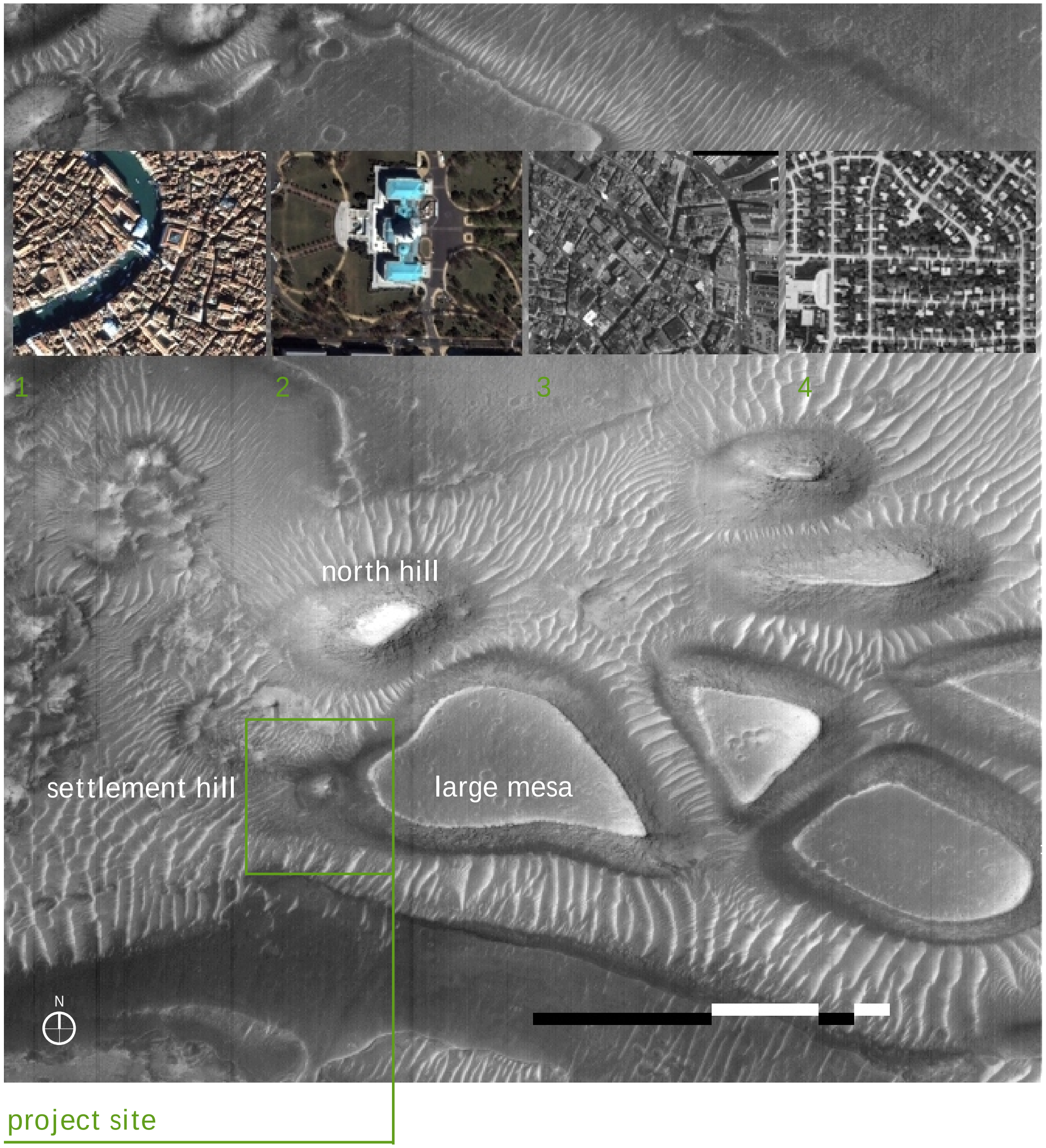


fig. 67 detail of MGS image E04-01514

Horizontal Scale

To better understand the scale of the site on an untouched alien landscape it is useful to compare the available images with some scaled Earth city textures.

1. A medieval town - the area around the Rialto Bridge in Venice, Italy.
2. A large monumental building - the United States capitol building in Washington D.C.
3. New England colonial town - The North End neighborhood in Boston, MA
4. A typical American suburb - in this case Champaign, IL

Vertical Scale

It was assumed that bases of the Mesas were covered with debris aprons, sloping at an angle of repose of 30°. Using the solar angle at the time the images were acquired it was estimated that the upper portions of the mesas are sloped at and angle of 45°. Combining these two estimates with the horizontal dimensions from the images, the following heights of the mesas were derived:

settlemtn hill - 40 m
large mesa - 70 m
north hill - 100 m

fig. 68 Digital model of the site
view from the north-west

The settlement will grow at the base of the small hill at the western edge of the large mesa. The first phase of construction will begin at the north facing slope (towards the left on fig. 68). The hill will thus become the identifying piece of landscape for the settlement.

07 - Organization Diagrams

In developing the design for the first permanent settlement on Mars a number of different issues were considered, each with a distinct set of precedents. Positive aspects were derived from each precedent and the results were synthesized into a new logic.

Vision for the settlement

Every settlement needs a vision and a plan for its future. There are numerous precedents throughout history. One example that has been particularly influential to this thesis is the 'Law of the Indies' - the set of rules that were established in Spain for the design of all colonial cities built in South America (fig. 69). Every colonial city was laid out on a square grid that was offset by 45° from north. The public buildings, like the church and the governor's mansion, faced the plaza, which occupied the central plot. The distinguished citizens lived on the plots immediately adjacent to the center and the rest occupied the outlaying squares. This vision was so successful that it was widely applied as recently as the 20th century when company towns housing mining operations were set up in the deserts of northern Chile. The largest of these is Chacabuco (fig 70). The particularities and the rigidity of the Law of the Indies are not applicable to the Martian settlement. I have attempted to achieve, however, a vision for the future of the new settlement that incorporates the same rigor of the logic governing the relationships between the various elements.

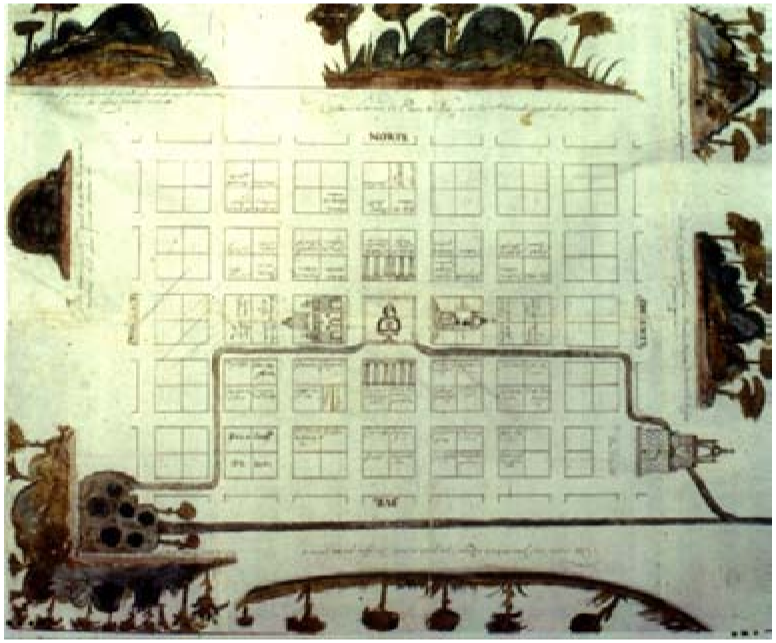


fig. 69 The Law of the Indies

Engineering requirements

The primary engineering requirements for the design of the settlement on Mars are safety, efficiency and expandability. Safety, as discussed in chapter 04, requires that there be a number of interconnected and individually pressurizable segments. In case of an accidental loss of pressure, a fire, or other failure, there must be at least two means of egress from every space. Furthermore, the loss of one space must not cut off functioning portions of the settlement from each other. Efficiency is dictated by the large distance from Earth and the shortage of labor and energy on Mars. Expandability requires that the pattern of development be easily repeatable and expandable without compromising the qualities of the structures that have already been completed.

Linear City

A similar set of demands was addressed when architects and planners were attempting to accommodate the changes brought about by the industrial revolution. The most appropriate model to use on Mars is the Linear City, first proposed by the Spanish planner Arturo Soria. His plan was 'designed on the basis of an expandable spine of transport … to ameliorate the crush of population on large urban centers, to integrate the inevitable facts of roads and railways and to allow a continuous growth pattern' [Curtis 1996].

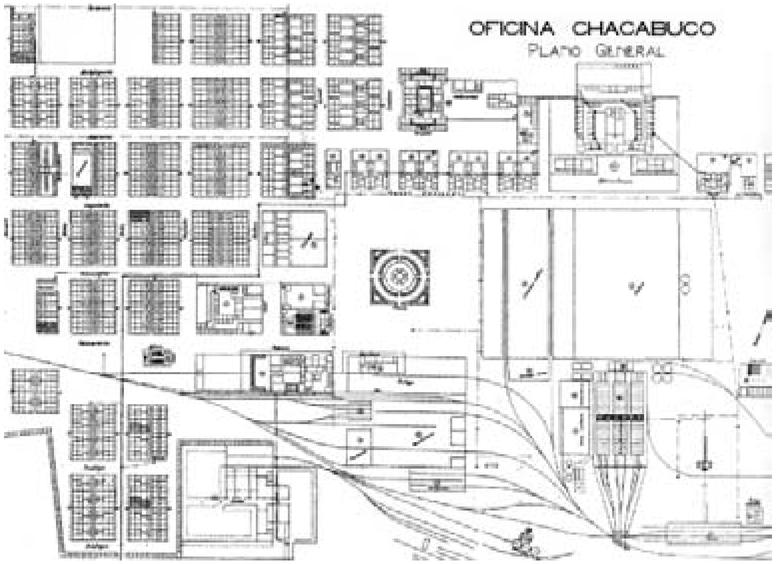


fig. 70 Plan of Chacabuco, Chile

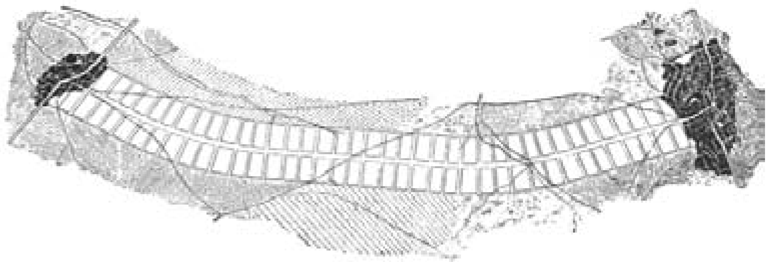


fig. 71 Linear City by Arturo Soria

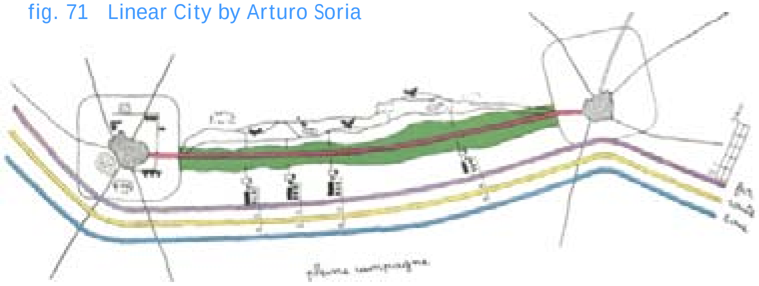


fig. 72 Linear City by Le Corbusier

Linear City

The settlement will grow in two parallel, linear bands of development, along the base of the small hill (fig. 68). Each band will carry circulation paths (fig. 73) and utility chases (fig. 74). The two bands will be linked periodically by transverse connections.

Because the settlement runs at the base of a hill, one of the bands will be buried deeper than the other. Thus the functions that require access to the surface will be housed in inflatable modules along the outer trunk, while the other will be buried deeper allowing the use of masonry construction. However, the bands do not have to always run at the same level. As long as there are two redundant paths, the bands can merge, diverge or run above each other. For example, the back band can come out of the ground and allow for two levels of housing.

Utilities

The infrastructure that is needed to operate the bio-regenerative life support system will follow the same logic. The necessary greenhouses and chemical plants are built in a series of nodes. Each node will have the complete capability of cycling water, air, and nutrients. Thus the distance of any space to the nearest unit will be minimized. The dual band of the distribution system will provide redundancy. If one unit fails, demand can be covered by transferring resources from adjacent units.

The logic of the Linear City governs the essentials needed to keep the settlers alive.

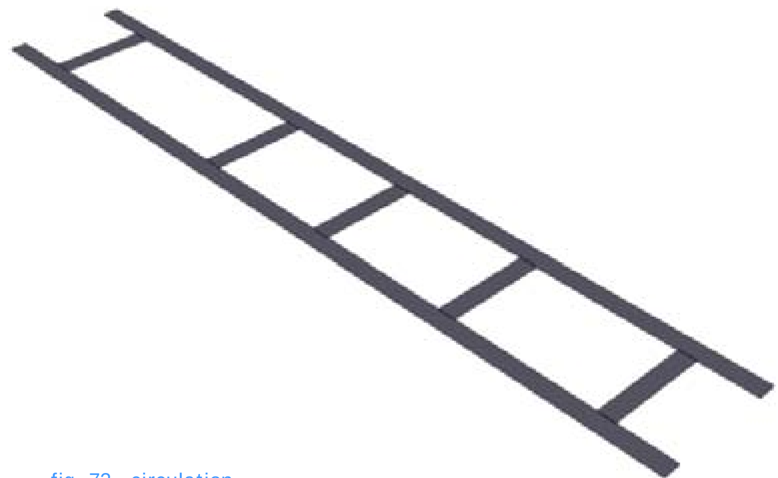


fig. 73 circulation
linear development in two parallel bands

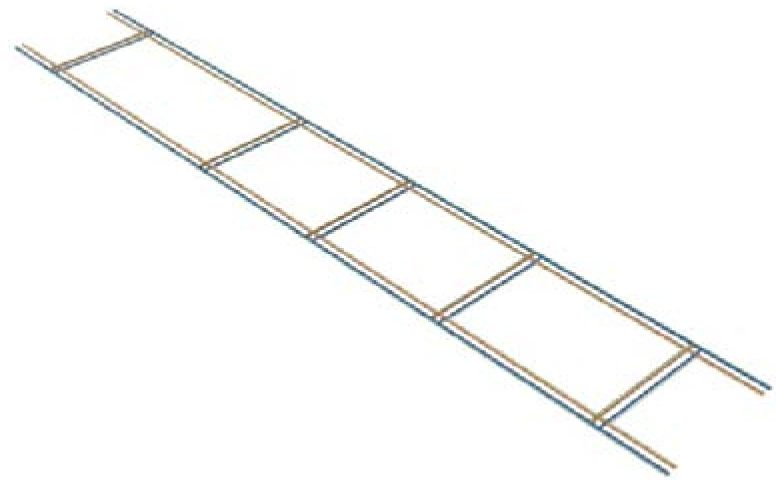


fig. 74 utilities

Vegetation

Keeping the settlers alive however is not enough. Therefore a second logic system is overlaid over the linear development to help shape the architecture in a way that will keep the settlers sane.

The habitable spaces are arranged along the linear bands through a conceptualization the relationship between the infrastructure, the humans, and the vegetation that will accompany them on Mars. The system was born from the realization that we have a "cultural and daily reliance on higher plants" [Boston 1996]. Unlike the image presented by most works of science fiction, where humans and their machines go out to explore the universe, in reality humans will have to rely on plants together with machines to sustain them. This thesis attempts to elevate the interdependence between humans, plants and machines to the status of a guiding concept for the design.

Air circulation

A final system of relationships governs how air is circulated throughout each space. The supply air always comes from between the vegetation and is returned on opposite sites of the spaces, thus adding auditory, visual and olfactory stimulation that is much needed in the enclosed environment.

Figures 75 and 76 diagram the relationship of the major components of the first phase of construction that will house 24 people to the infrastructure and circulation bands. The following pages describe how each system applies to the various spaces in more detail.

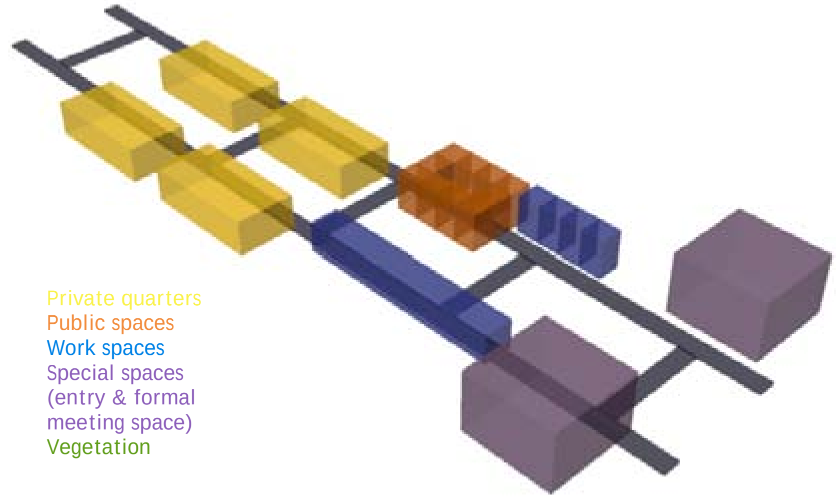


fig. 75 segments

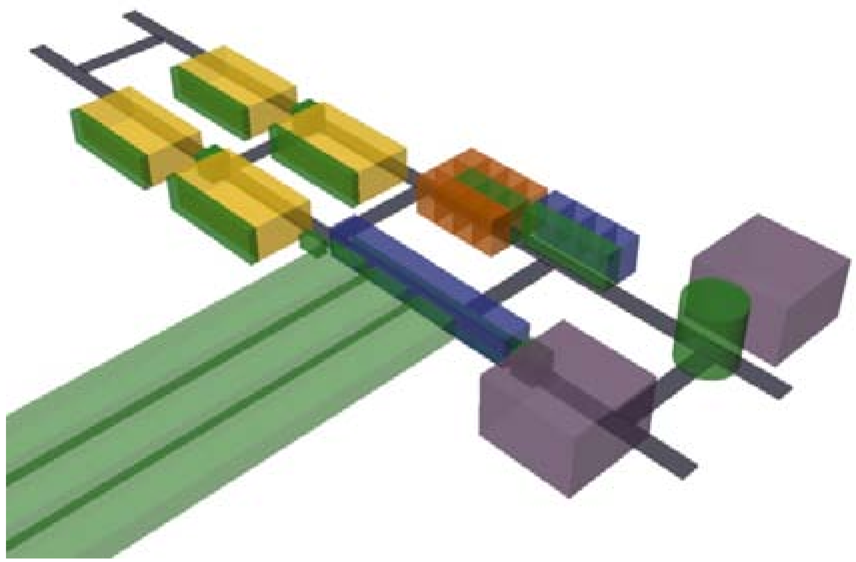


fig. 76 vegetation

Vegetation as symbol

Immediately between the main entrance and the formal meeting space there will be a space where a special tree will be planted at a ceremony to mark the beginning of the settlement. The event will be celebrated both on Mars and on Earth. The tree will symbolize hope in the future of the settlement, it will grow as the settlement expands. When new people arrive from Earth the first object they'll see as they enter is the First Tree. As new segments of the base are built seedlings from the first tree will be transplanted there. The exact species of the tree should be chosen by the settlers themselves who will be responsible for its care.

Vegetation as life support

The relationship between the vegetation in the plant-rated green houses and the humans will be different. These will be specially designed plants, like miniature wheat and high protein soy that refresh the air and water and provide most of the food. They will be genetically engineered to withstand the harsher environment of Mars. Their existence will be closely tied to the infrastructure and the spaces from where the farmers will tend the plants.

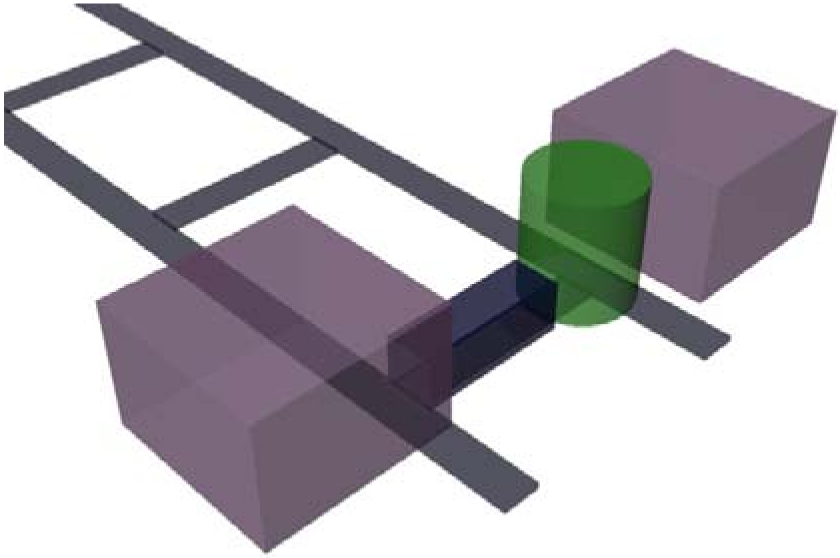


fig. 77 vegetation as symbol

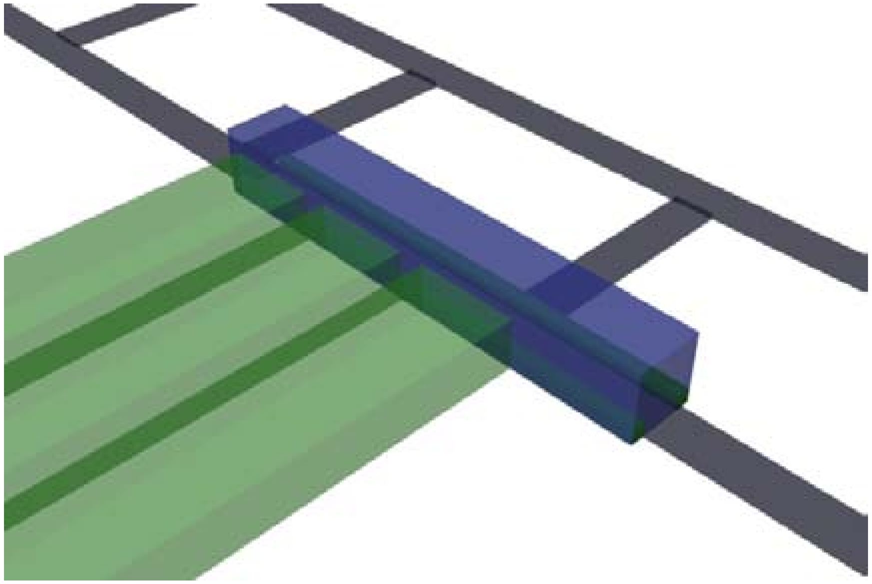


fig. 78 vegetation as life support

Vegetation as mediator of view

Views of Mars will be mediated by vegetation. One will look at the red through the green. Every private suite will have a small garden area in front of its window. This will be a personal, even sentimental relationship. Not everyone will want to or have time for taking care of plants, but the opportunity will be there.

Similarly connector segments will terminate with small gardens and a windows to the outside.

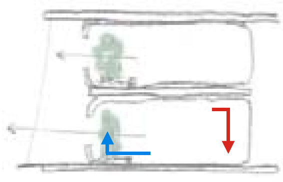


fig. 79 air circulation

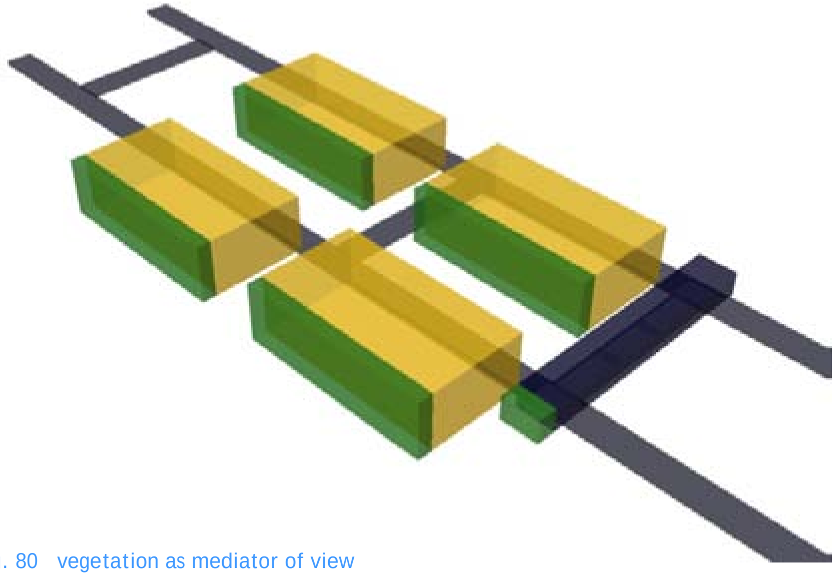


fig. 80 vegetation as mediator of view

Vegetation as mediator of activities

The scientific work areas will require some degree of privacy and will thus stand off the main circulation. Here the trees will act much like a green belt, giving some separation of activities the need to coexist. The resulting form acts like a 'building thoroughfare' [Alexander 1977].

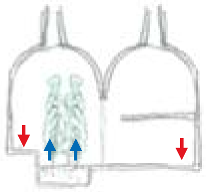


fig. 81 air circulation

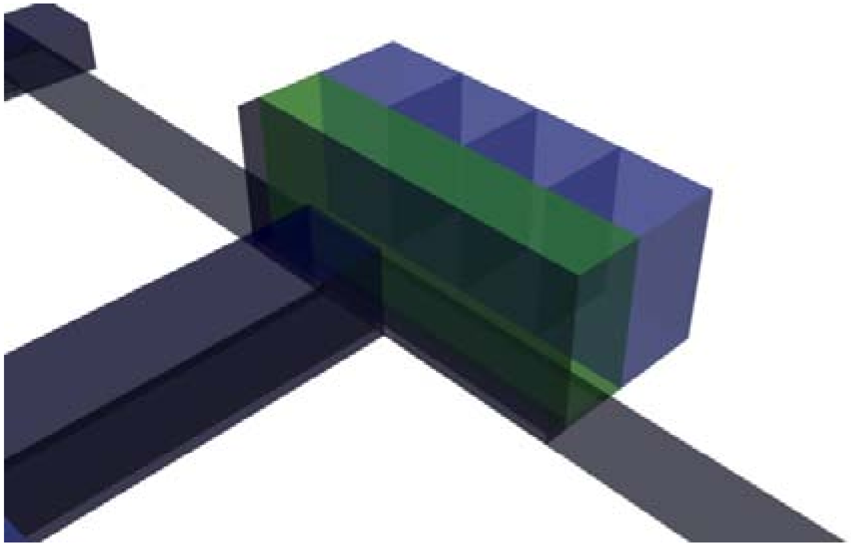


fig. 82 vegetation as green belt

Vegetation as mediator of social life – version 1

The trees are at the center of the social life, like the Common of New England colonial towns (fig. 84). The various social spaces are arranged around the periphery. There are numerous views at and through the vegetation. The trees provide much needed change in the underground space [Carmody 1993]. The trees, which can not be genetically engineered as easily as smaller plant species, will need the same protection as the humans. Both will share the safest segments under the hill. Bamboo will be for used for building material and fruit trees will enrich the diet.

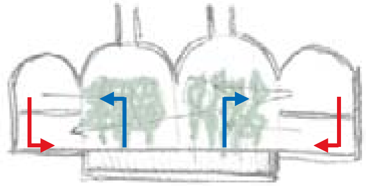


fig. 83 air circulation

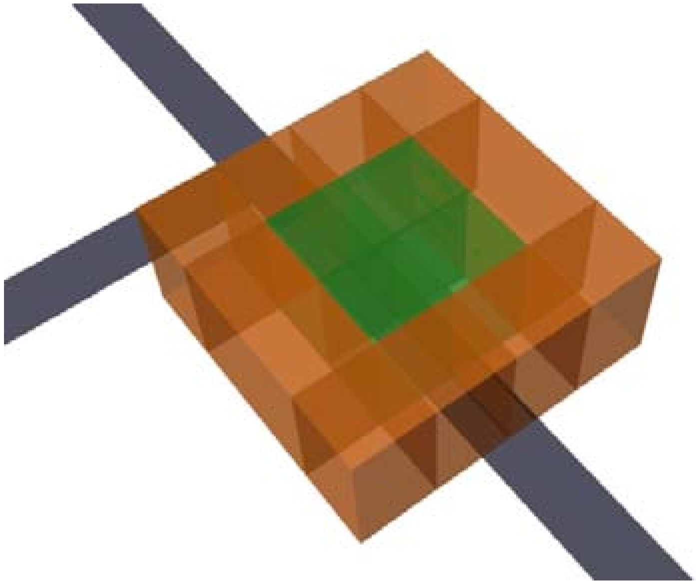


fig. 84 vegetation as symbol

Vegetation as mediator of social life – version 2

The reverse possibility can also be used. Much like a clearing in the woods or a Chinese garden, the social space can be surrounded by the vegetation. The edges of the space are hidden thus the limited size of the space is obscured (fig. 86).

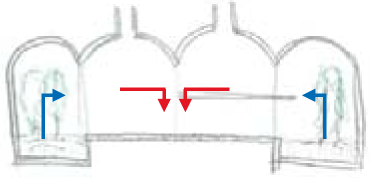


fig. 85 air circulation

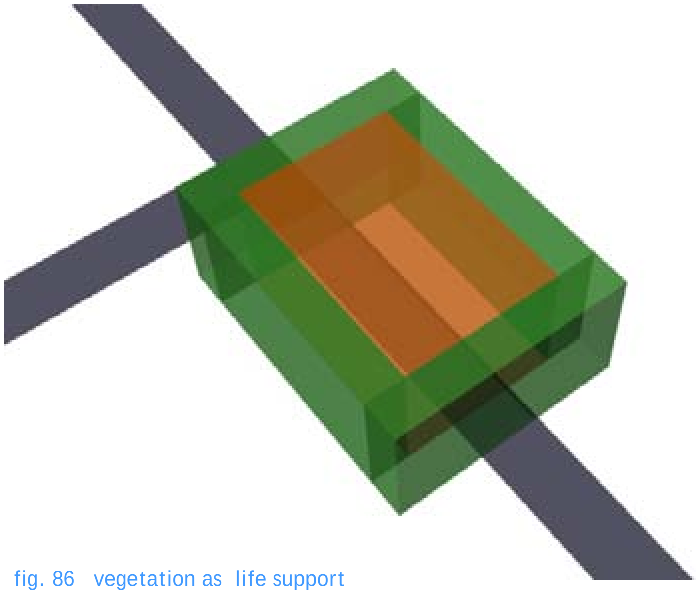


fig. 86 vegetation as life support

Vegetation as mediator of social life – version 3

A third possibility is to distribute the vegetation in pocket gardens providing focused diagonal views between and through the social spaces (fig. 87).

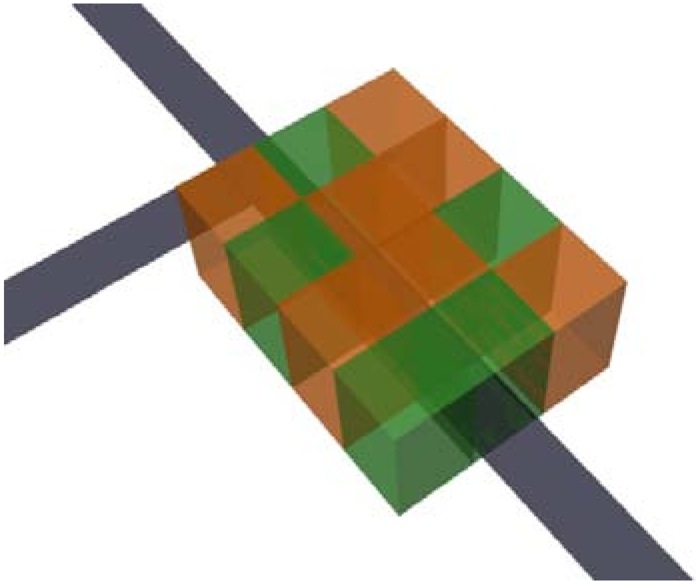


fig. 87 pocket gardens

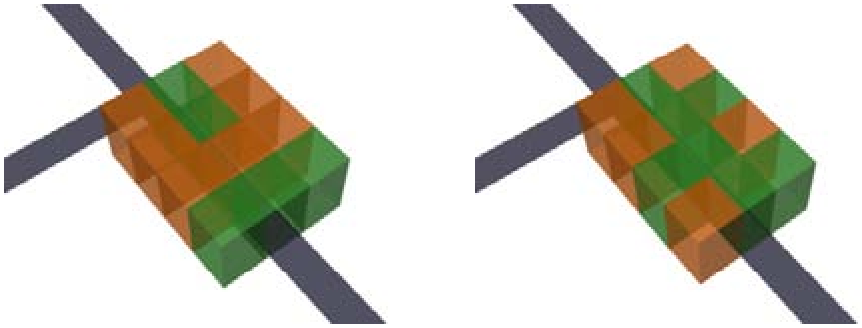


fig. 89 hybrid relationships

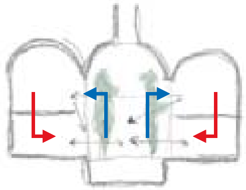


fig. 88 air circulation

08-1 Design of Phase I

The first phase of construction for 24 inhabitants was designed in detail by balancing the social and psychological needs with the engineering challenges.

An attempt was made to include the richness of spaces and relationships that can be found in terrestrial cities, within the given spatial limitations. In some areas it was possible to overlap many activities in one space. Other functions, however, could not be mixed in, due to their specific nature. Finally, some spaces were purposefully left unique, like the formal gathering space and the dome with the First Tree.

The initial base for 12 people will be assembled just north of the settlement hill (fig. 67). The first phase of the permanent habitat will be constructed along the north edge of the hill, starting with the entrance airlocks, which will also be connected to the initial base. Subsequently the settlement will be expanded in both directions, following the principles demonstrated by Phase I.

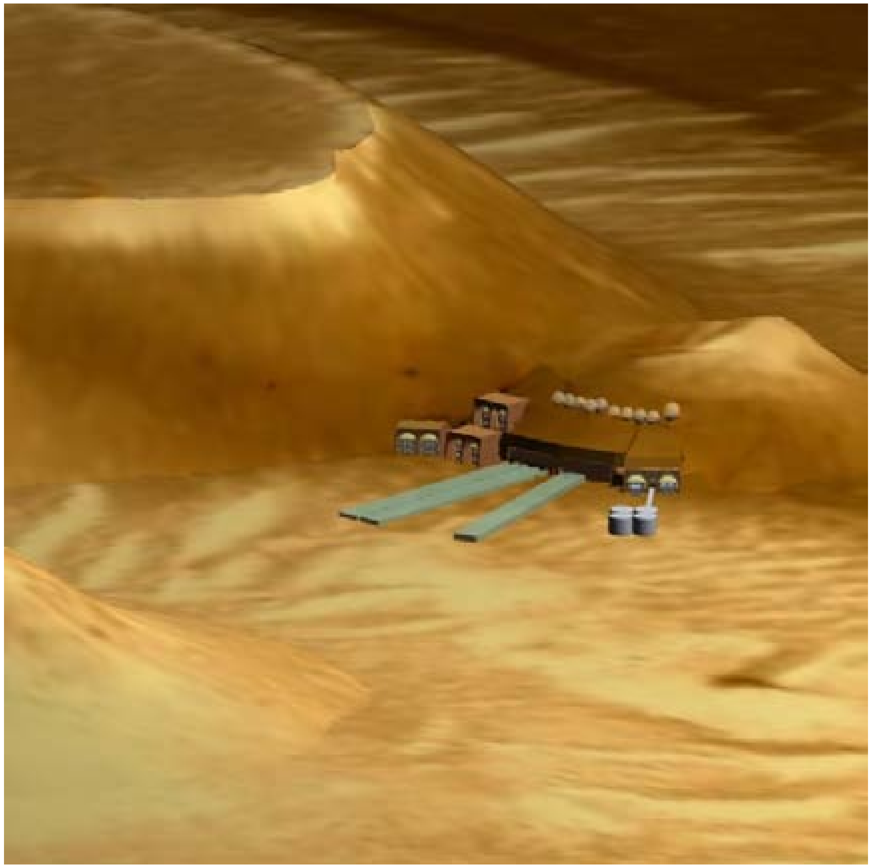


fig. 90 Completed Phase I, housing 24 people

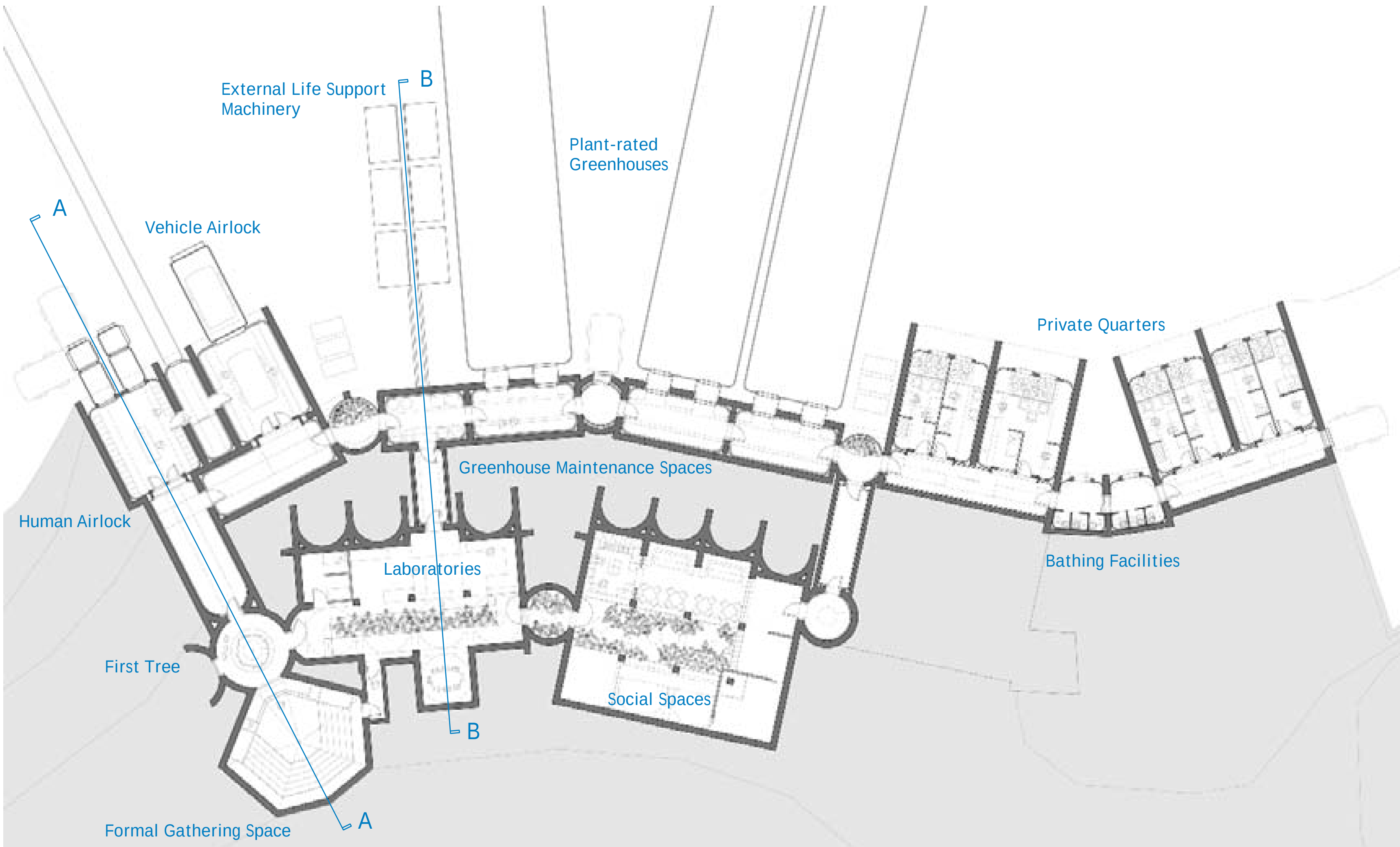


fig. 91 main level plan, scale = 1 : 500

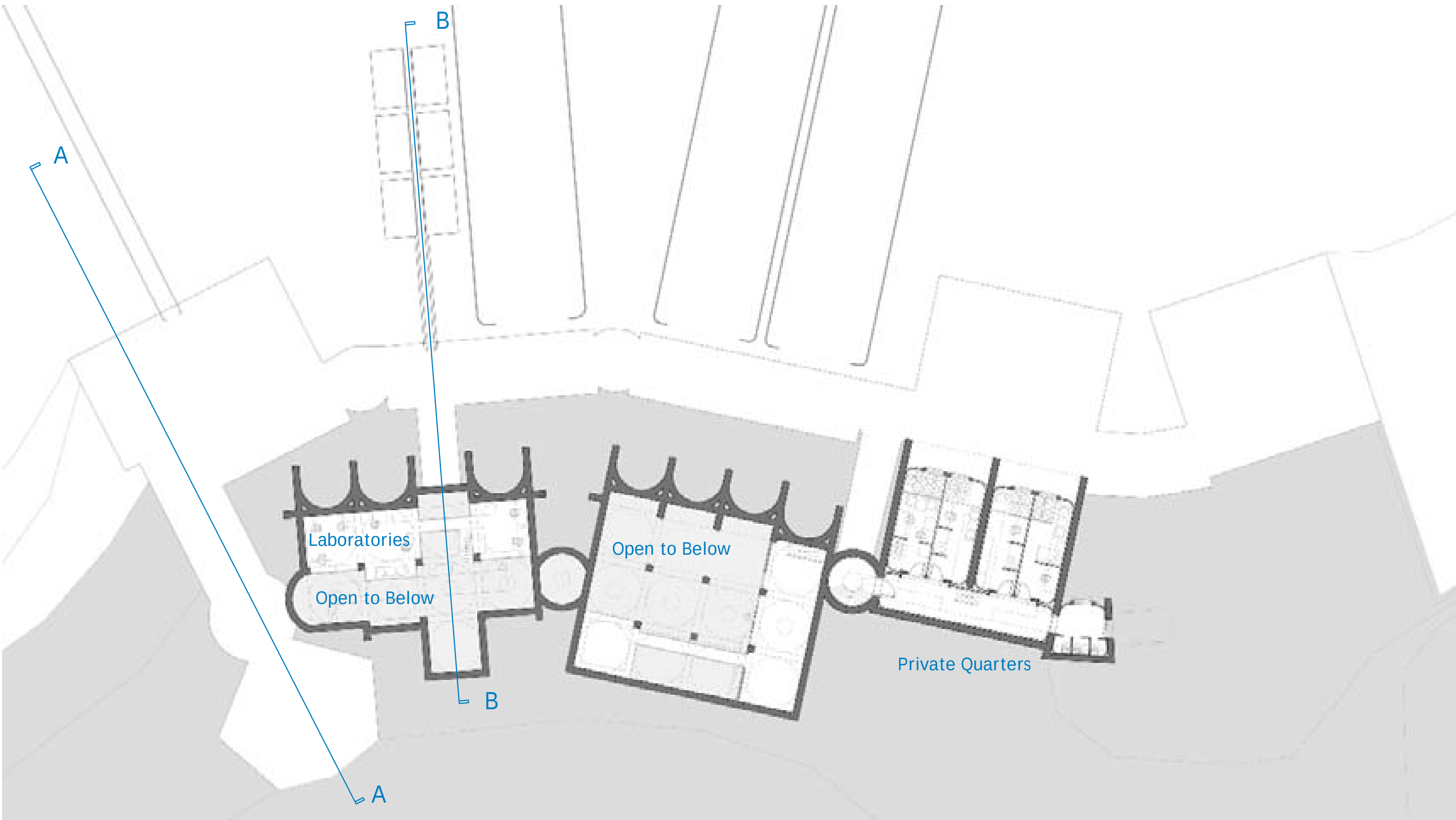


fig. 92 mezzanine level plan, scale 1 : 500

Entrance

The main entrance is composed of three pressurized modules: main entry, a connection to the initial Mars Reference Mission (MRM) base and a garage.

Main entry
This module consist of two airlocks with multiple egress options. One of the airlocks will be used for direct access to the Martian surface. This path will be used for daily exterior activity, such as construction and repair work. The other airlock will be a docking port for rovers where rovers from the landing area will arrive with new settlers. Long distance roving expeditions will also depart and arrive here. Directly on the interior of the module will be the preparation area for suiting up.

Connection to MRM base
The new settlement will be permanently connected to the original landed base via a pressurized tunnel.

Garage
The garage will be equipped with a vehicle-sized airlock, and a repair shop for rovers and machinery. The majority of the in-situ resources utilization machinery will be located outside the base on movable platforms. They will only be brought into a pressurized environment for major repairs.

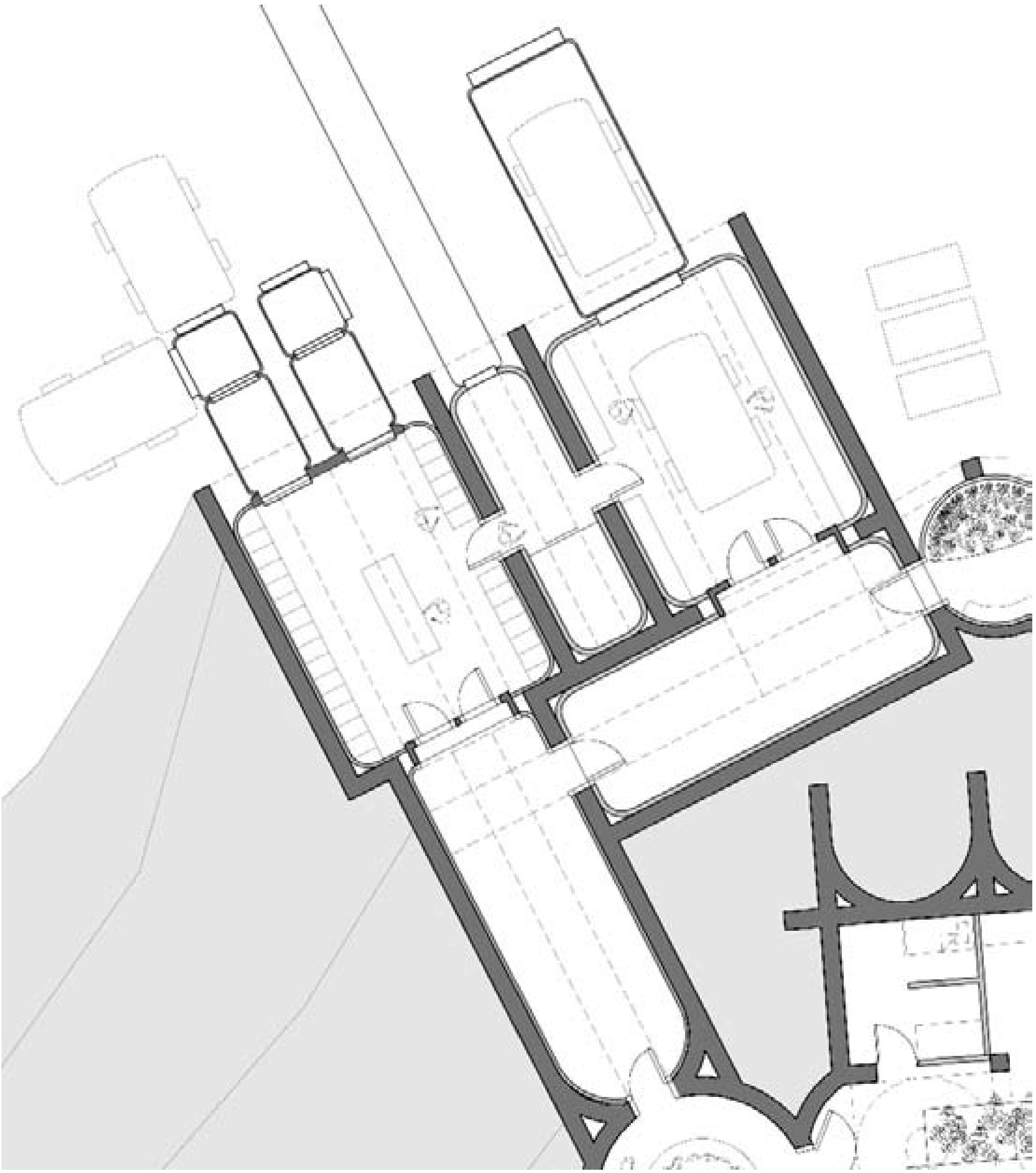


fig. 93 entrance, scale 1 : 200

Private Quarters

The private quarters are housed in inflatable modules protected by masonry vaults and regolith cover. Each inflatable provides space for four individuals on two levels and can be subdivided into a number of ways to allow the maximum flexibility for different living arrangements (see figs 103-112). Every unit has a window and an area for a personal garden. One has the opportunity to look out to the red Mars through the green of the plants. Connection to the main power and air supply utilities are also provided. Every segment has a pair of modules forming a neighborhood of eight people that share a common connection to the rest of the settlement and a common sanitation space.

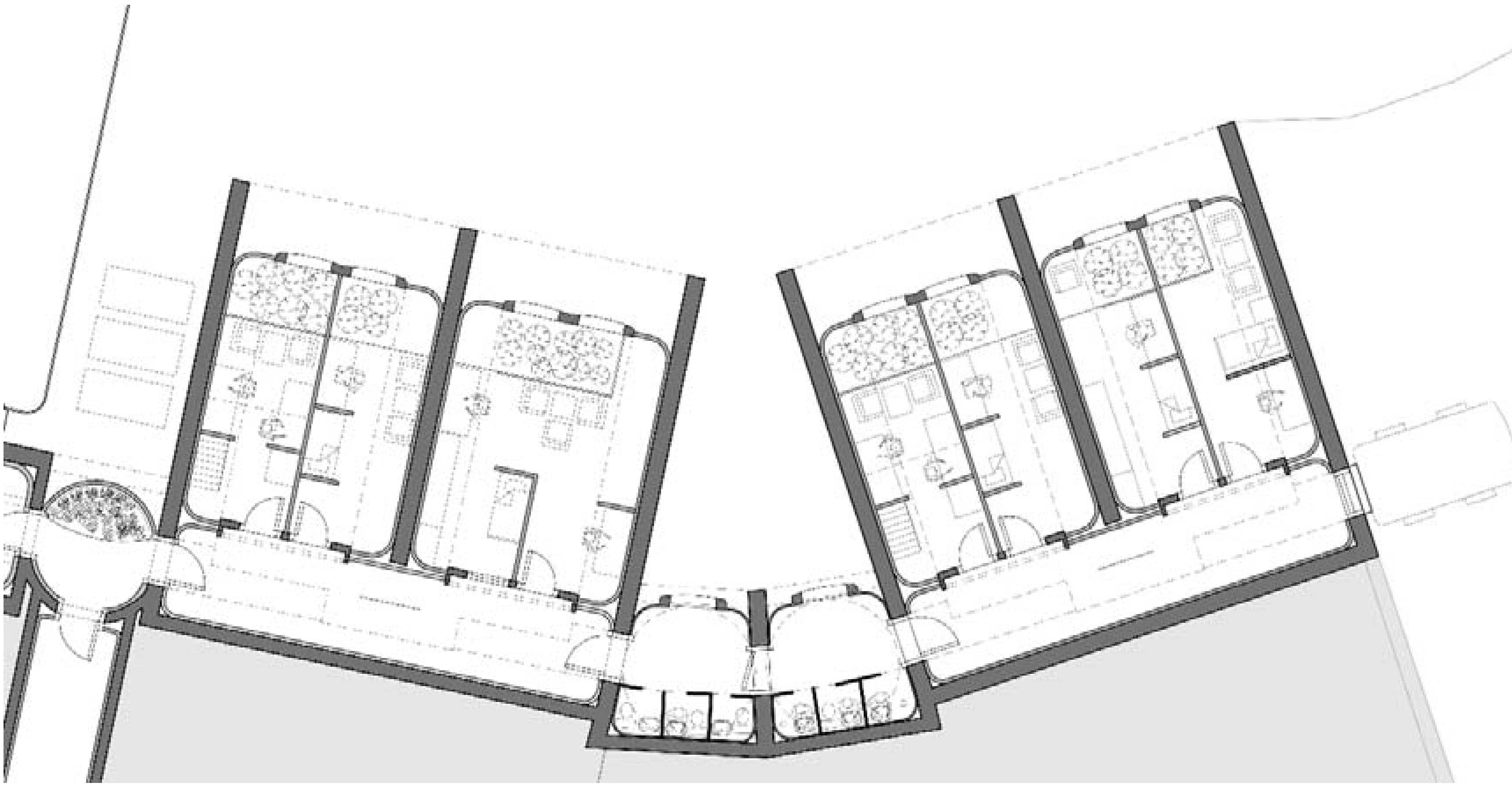


fig. 94 private quarters, scale 1 : 200

Laboratory

The scientific laboratory segment houses three types of spaces. One half is devoted to scientific work and the other to growing trees, providing circulation, and smaller gathering spaces (see section BB in fig. 98).

Open laboratories and an enclosed medical area are located on the lower level. Individual work stations for personal work are on the mezzanine above, overlooking the public space (fig. 92).

A green belt of bamboo and other trees runs down the middle of the public space, flanked by two levels of circulation on either side of the vegetation. The lower, narrow path serves the laboratories, while the higher, wider path serves as the main thoroughfare of the segment.

Across the green belt from the laboratories is a meeting and communications room that can be used by anyone in the settlement for gatherings or to make presentations to Earth.

The downhill side of the segment is supported by buttresses against the lateral thrust of the internal pressure, by using the weight of the regolith above to prevent the interior pressure from blowing out the side of the hill. Assuming 1500 kg/m^3 regolith density and 60kPa internal pressure – the buttresses need to be 4.5 meters long.

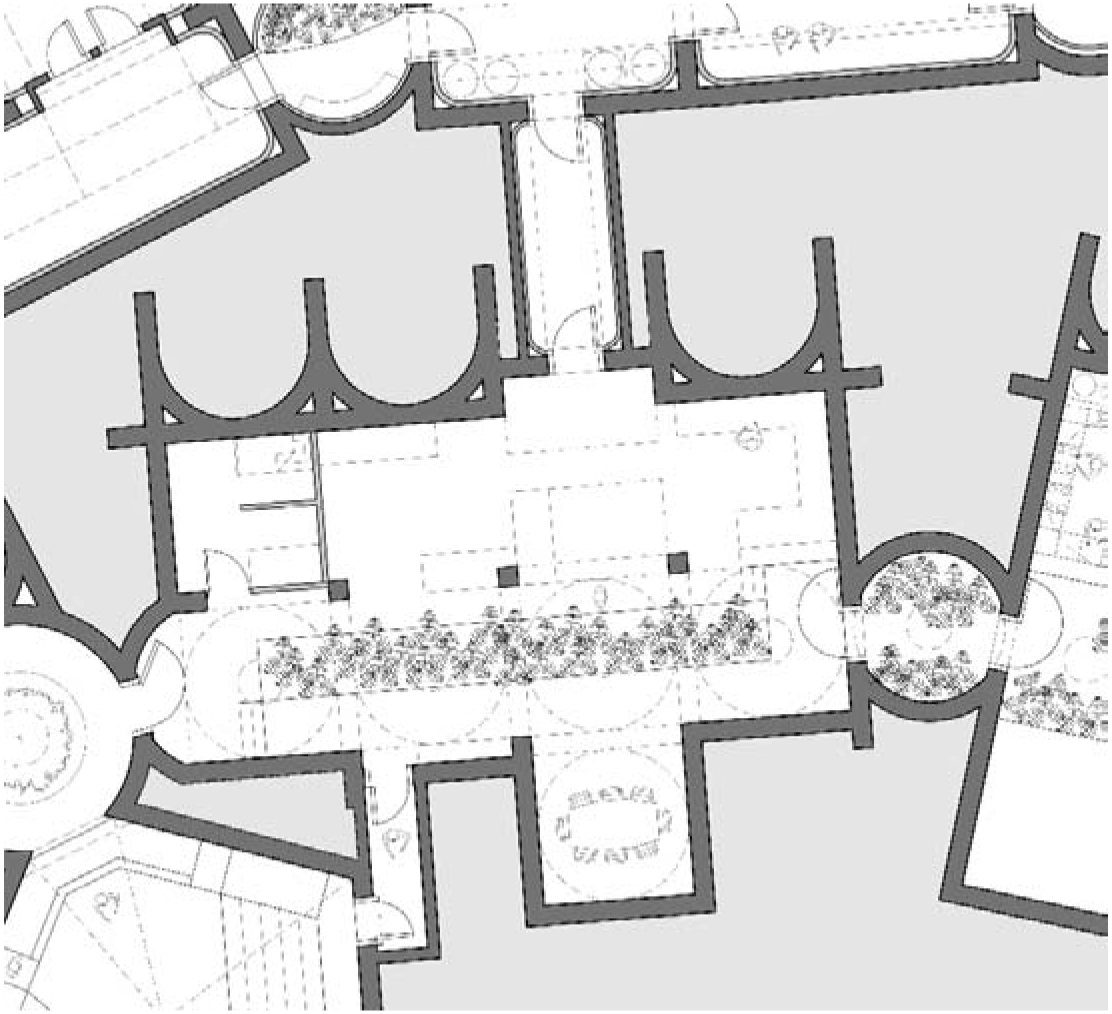


fig. 95 laboratories - lower level, scale 1 : 200

Social Spaces

Social spaces are arranged around a central space where bamboo and other trees are grown. This is where the community comes together informally on a daily basis.

The kitchen and dinning area for the whole first phase of the settlement are here. In most human cultures the sharing of food is an essential part of building social cohesiveness, and is 'almost required at most gatherings' [Boston 1996]. The two bays above the dinning area are covered with a continuous barrel vault marking this as a special subspace of the segment. Along the sides and on the second level are spaces for activities like exercise and multimedia entertainment. These can be subdivided into a number of various ways using partitions made of bamboo. They can be open to the central green space or can be completely closed off for more private activities such as meditation.

The domes along the middle have shafts that reach to the surface where light is collected by lenses and brought down to an opening in the top of the dome where it is spread out again by another lens, so trees can be grown in this area (see sections). The connecting dome between the social and laboratory segments is also used to grow vegetation. Due to the offset in orientation between the two segments, from each side one sees only green when looking to the adjacent segment.

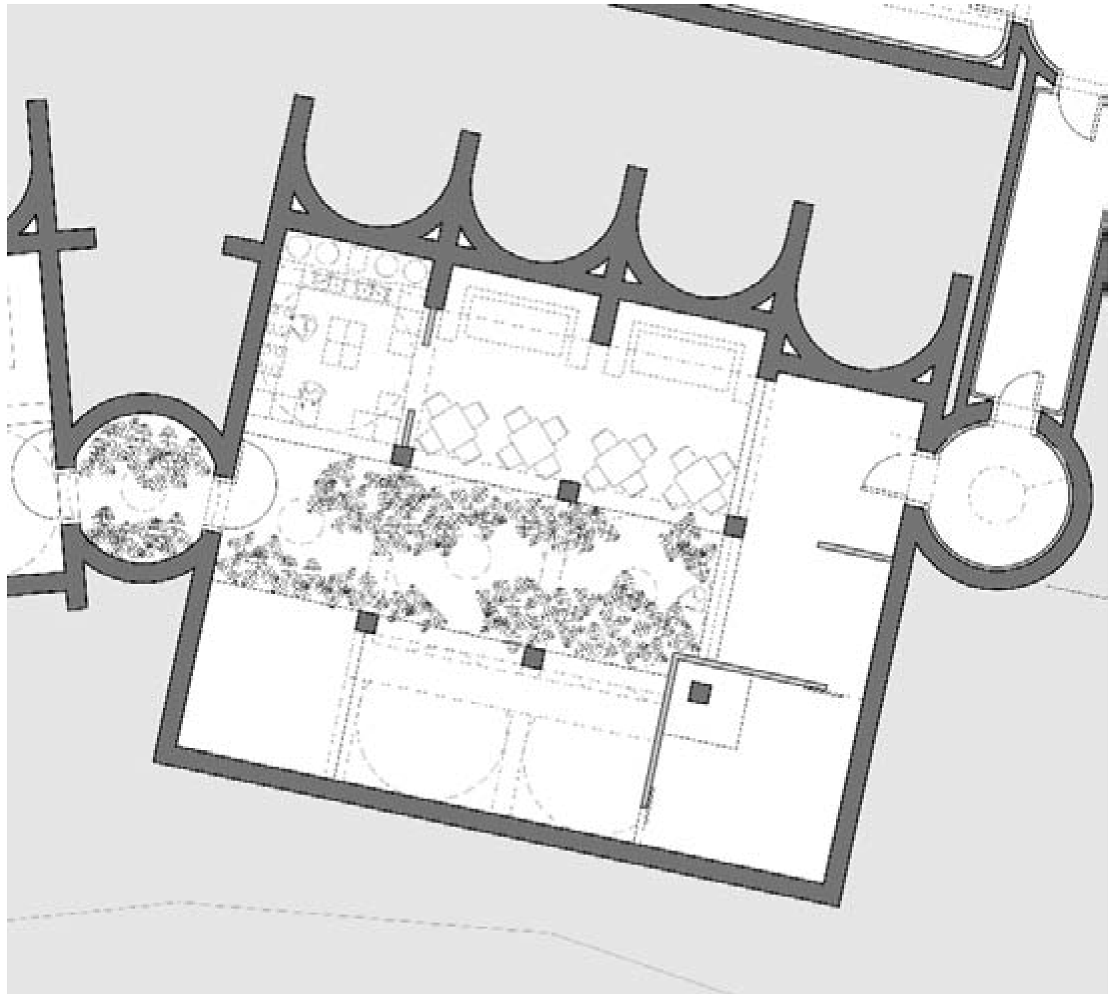


fig. 96 social spaces - lower level, scale 1 : 200

08-2 Sections

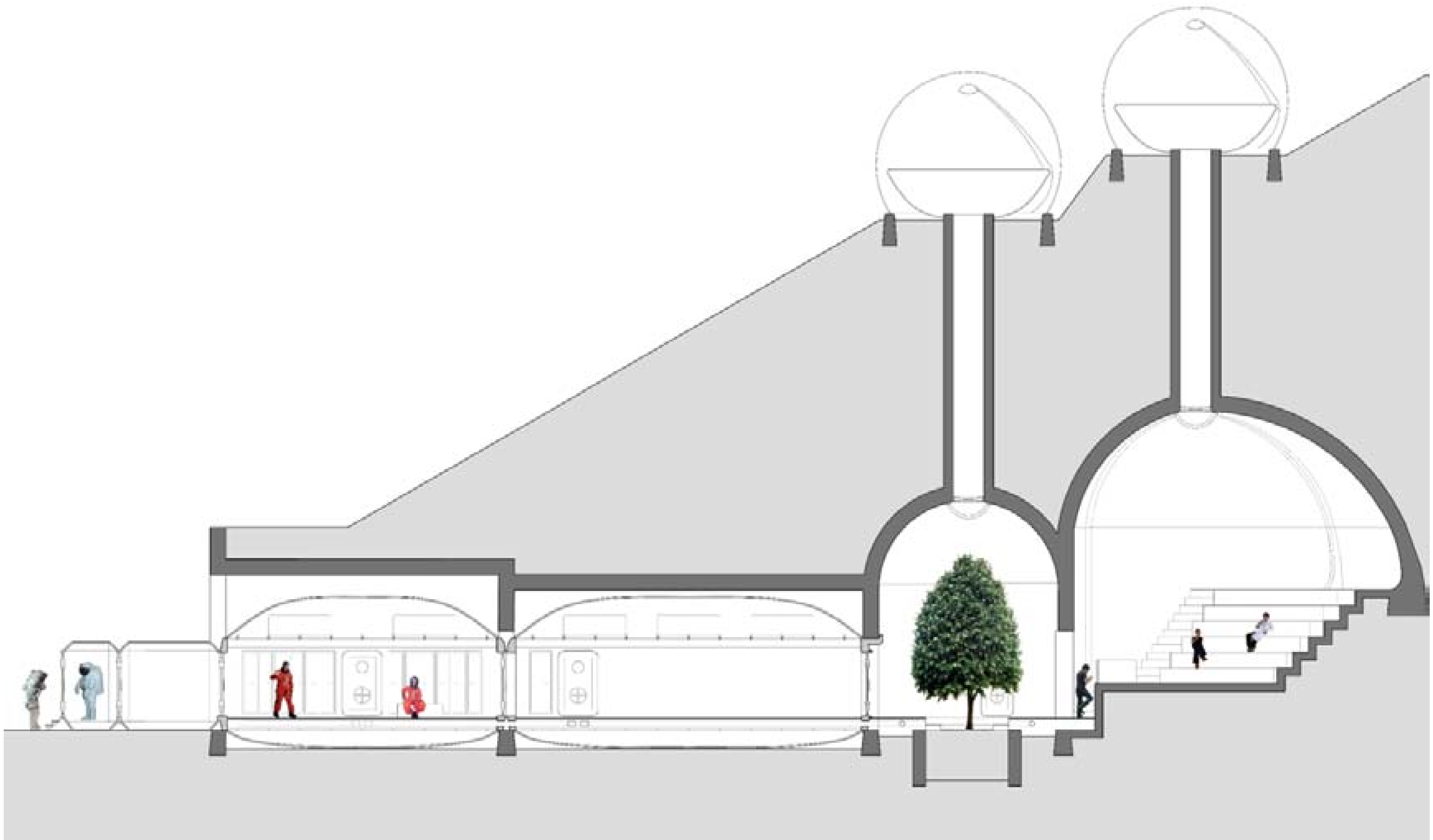


fig. 97   section AA, scale 1 : 200

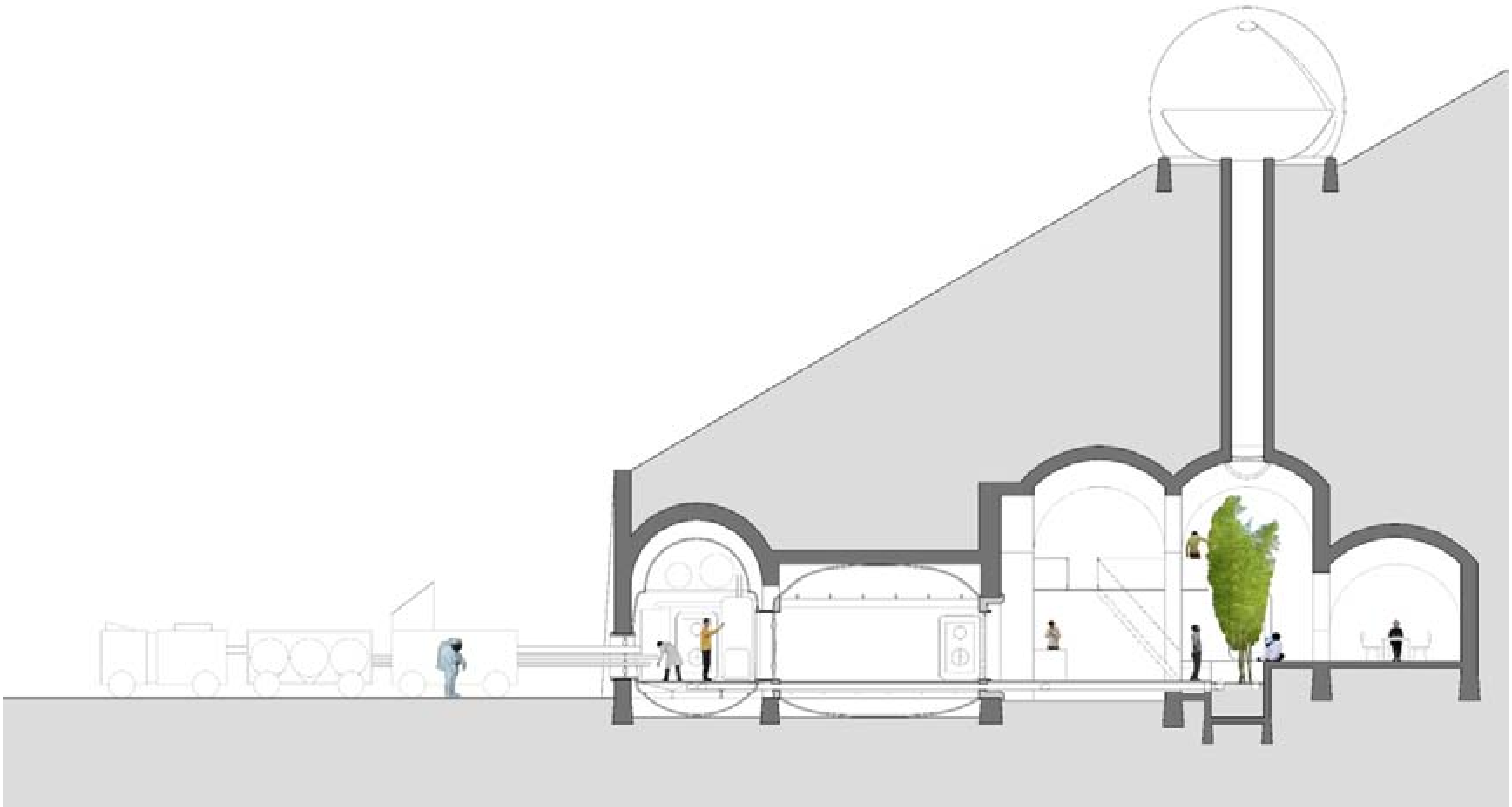


fig. 98   section BB, scale 1 : 200

08-3 Renderings

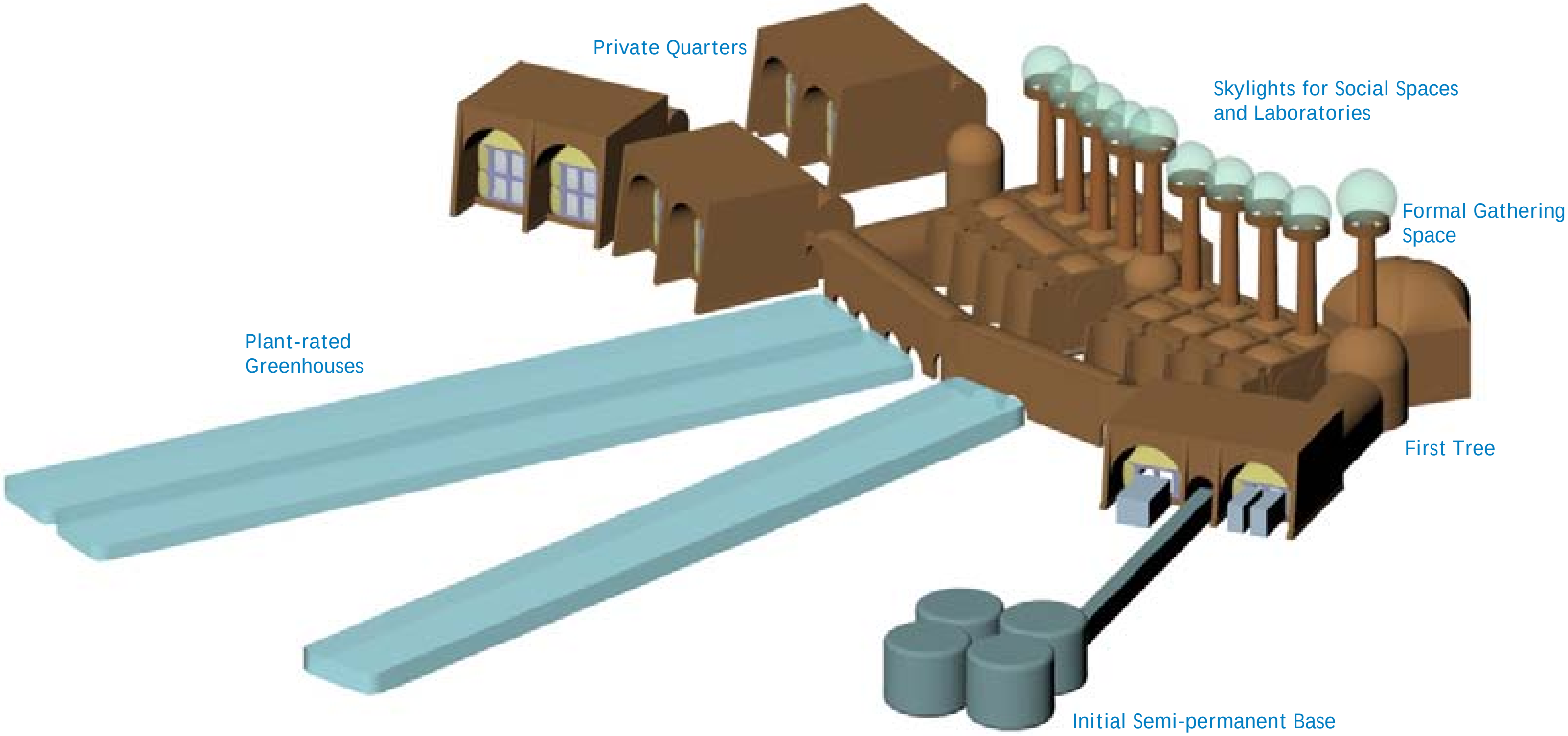


fig. 99 computer model without the site

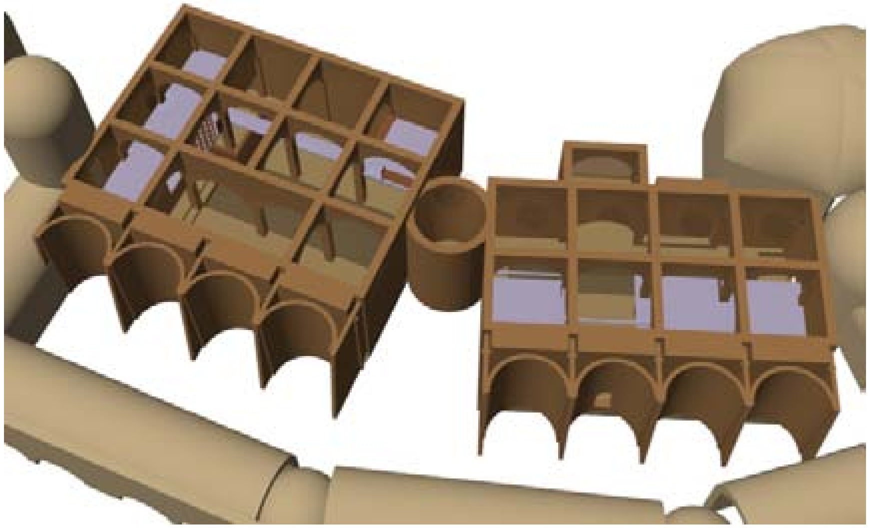


fig. 100 View inside the social spaces and the laboratories with the domes removed

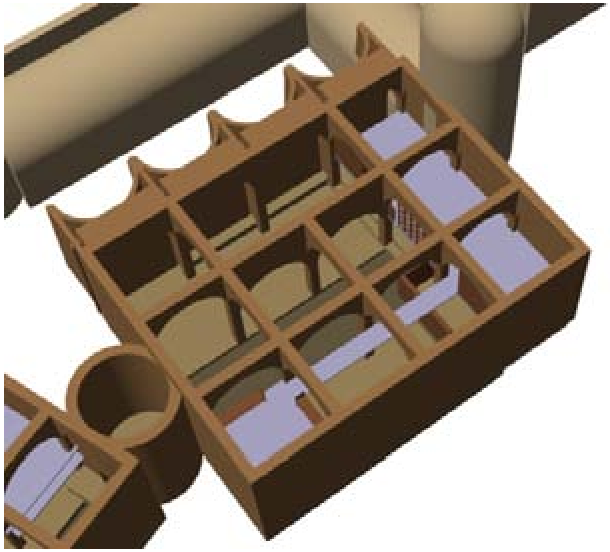


fig. 101 social spaces

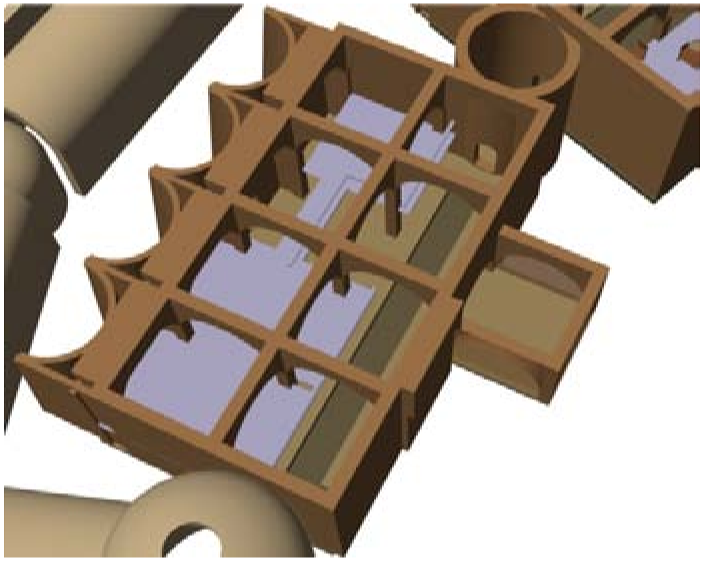


fig. 102 laboratories

08-4 Inflatables

The inflatable modules arrive folded in cargo-only transfer vehicles on long energy efficient trajectories. On Mars they are brought to their location in the construction, unfolded, connected, and inflated. The modules sit on a masonry foundations, inside a masonry dome.

The bladder and frame resist the internal pressure.

The masonry serves four functions:
1- holds one meter of regolith for radiation protection
2- maintains overall stability if pressure is lost to one unit
3- protects bladder from abrasion by dust storms
4- protects bladder from meteorites

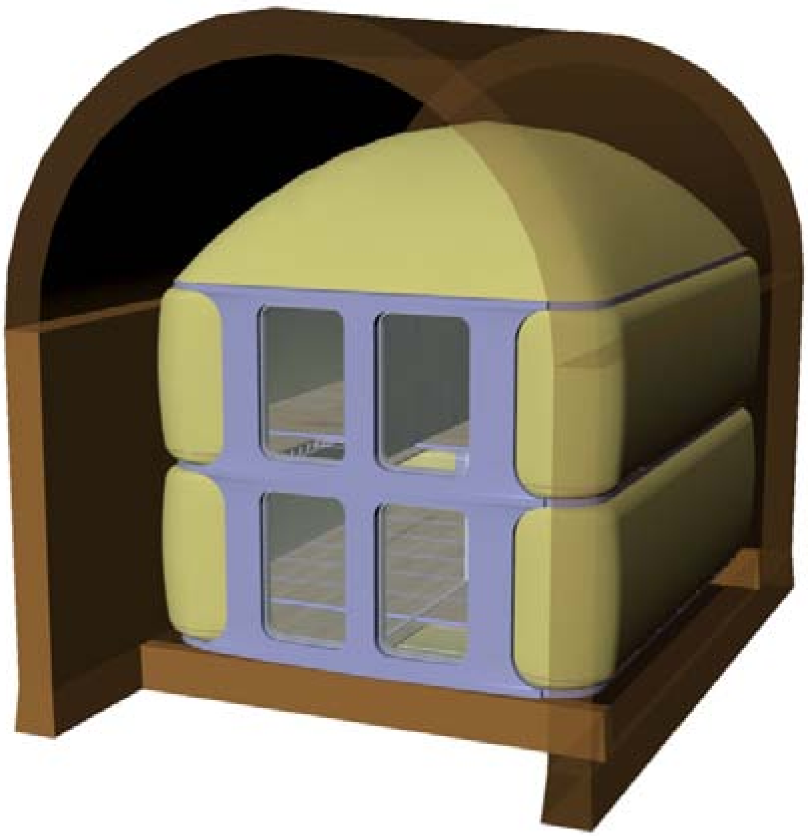


fig. 103 exterior view of one inflatable module inside its masonry protection

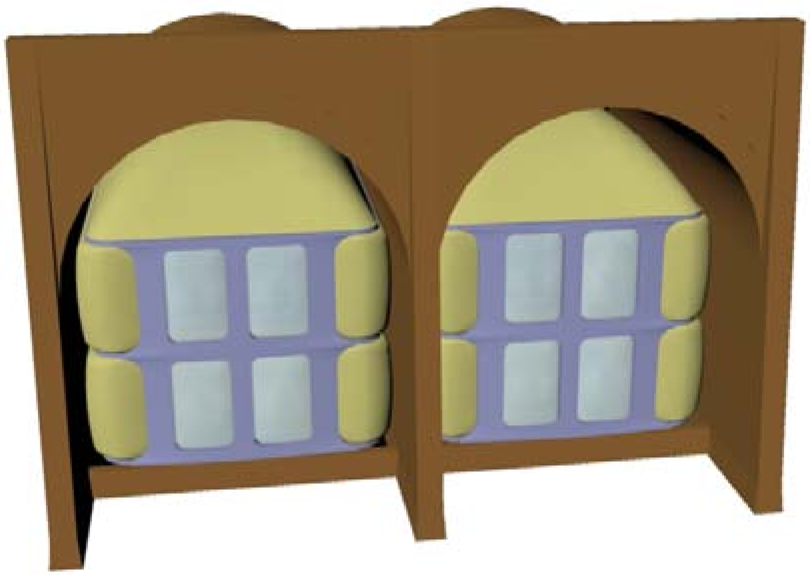


fig. 104 A segment of two inflatable modules

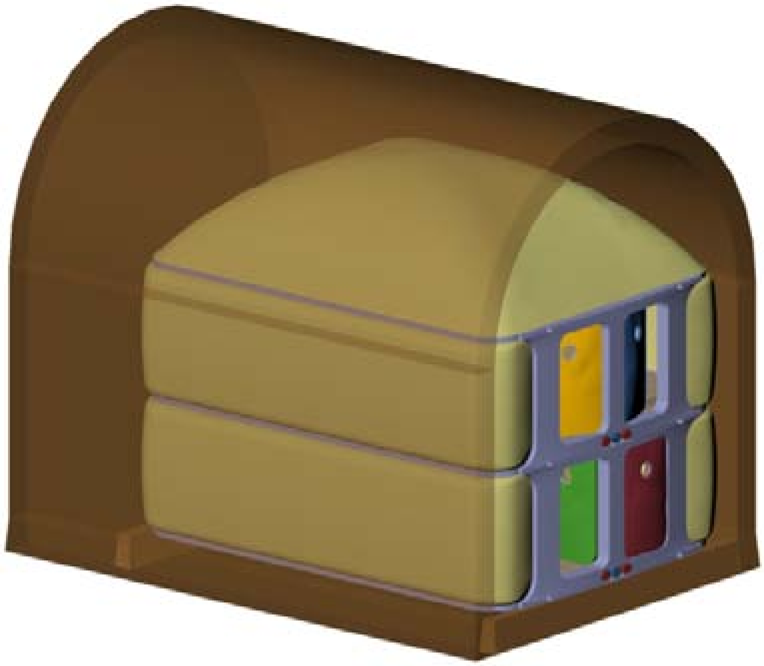


fig. 105 Rear view of one inflatable module inside its masonry protection

Frame

Frames at opposite ends support windows and doors. Belts and transverse cables force the bladder into a roughly prismatic form that is more convenient for habitation.
Longitudinal beams resist gravity live loads. The wholes in the webs of the beams reduce weight and allow the transverse cables to pass though.

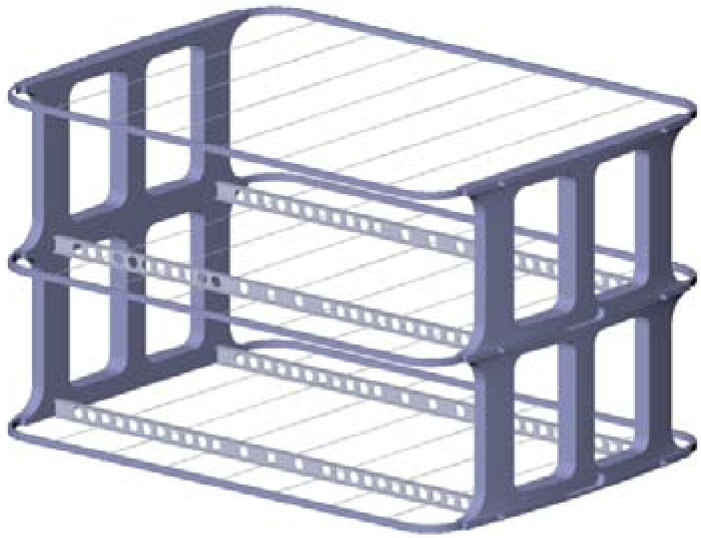


fig. 106 rigid interior frame

Utilities

Air ducts and power lines run in the floors and sit above the transverse cables. Connection to the main utility lines occur inside the thickness of the floors.

Tray in front of the windows allows each resident to grow some personal plants. Air is supplied from the plant area, providing sensory stimulation, through sound, smell and movement of the plants. The air return is at the opposite end of the spaces. Each of the four units in the module has a separate power and air supply.

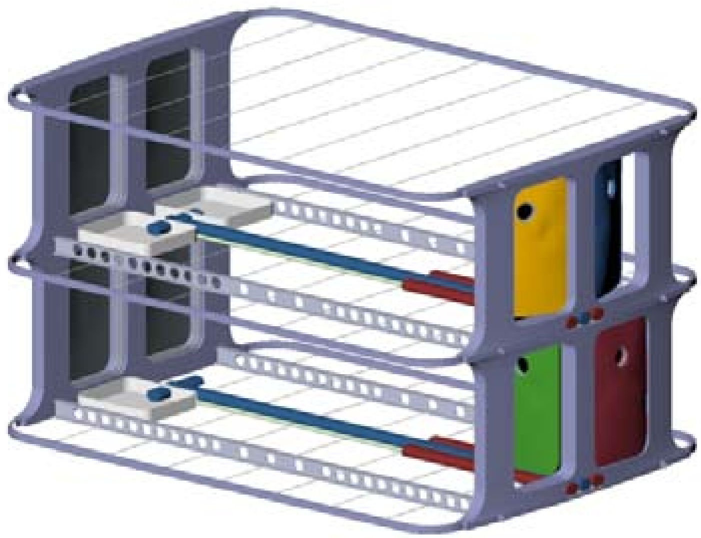


fig. 107 utilities, doors and windows

Interior Partitions

Initially interior partitions will be imported from Earth, but eventually locally grown bamboo will be used.

Floor panels span between the beam and cantilever out to the bladder. Vertical partitions will also made in modular sizes that attach to the superstructure. Such a flexible system will allow a great deal of customization within each unit.

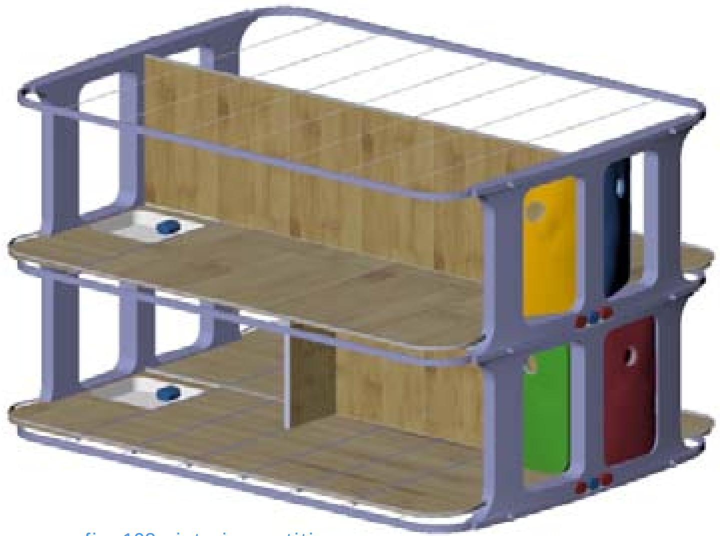


fig. 108 interior partitions

Inflated bladders

The membrane (or bladder) that encloses the inflatable modules will be thinner and lighter than the enclosure developed for the TransHab, because of lower functional requirements. First, there will be the structural layer to resist the interior pressure. Second, there will be an insulation layer, which will be thinner because the masonry will provide a more thermally stable environment than outer space or the open Martian surface. The micrometeoroid debris shield will not be a necessary, because the module will be protected by the masonry vault.

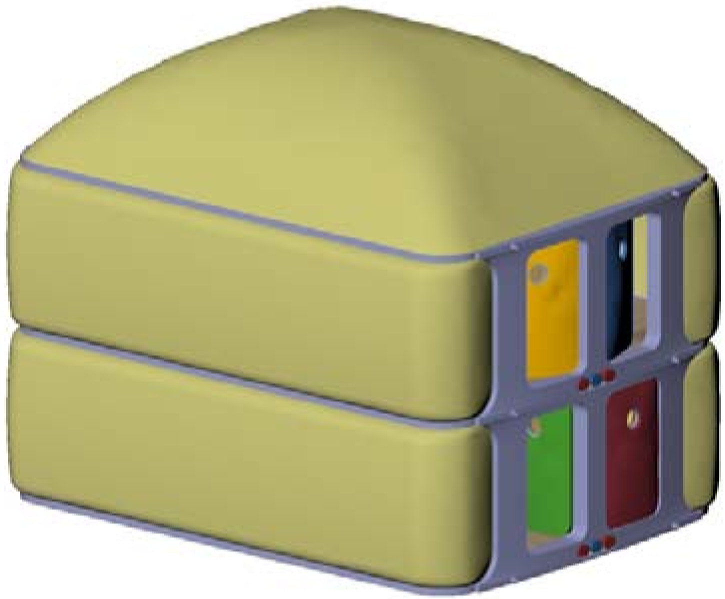


fig. 109 inflated bladders

Elevations

The end frames of the modules rest on the masonry foundations and span in between, allowing the pressure on the bottom to be resisted by a bladder (fig. 110). The space above the second level can be used as storage or as an attic sleeping areas. Ducts connect to the main utility lines between the floors (fig. 111).

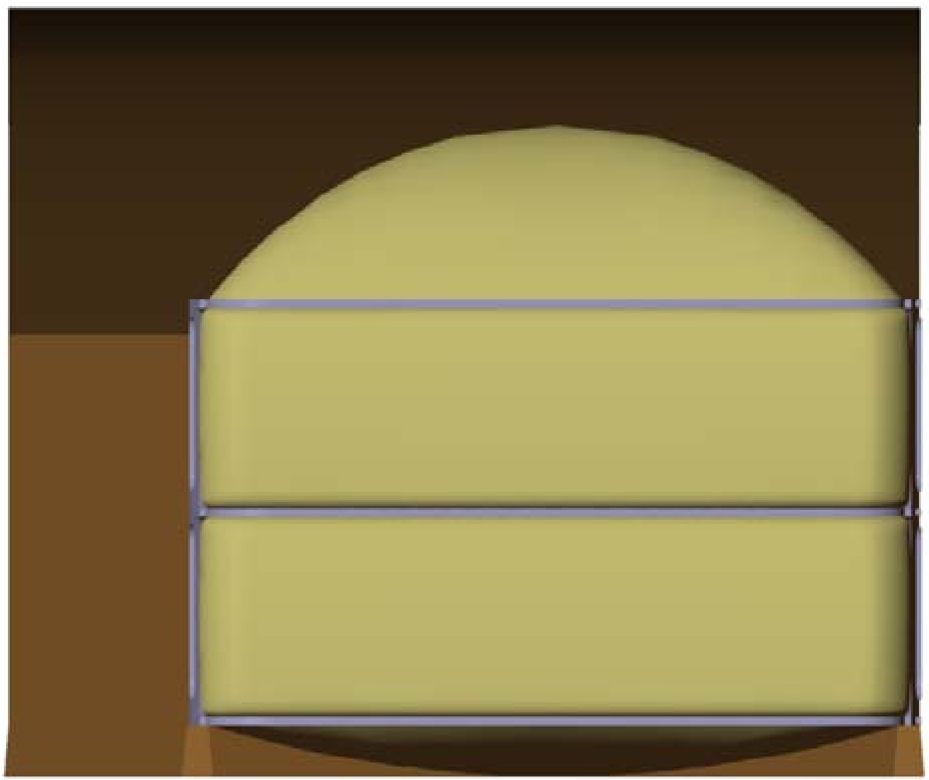


fig. 110 Side elevation showing how the module spans between supports

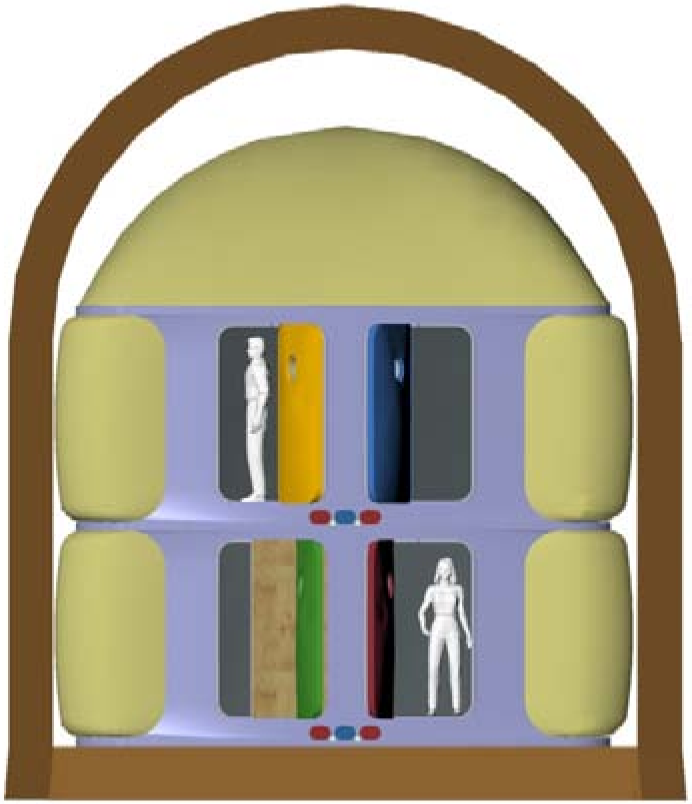


fig. 111 Elevation showing the side that is connected to the rest of the habitat

Configurations

The interior of the modules can be configured in a number of ways, allowing a variety of living arrangements. In general there will be a mixture between single and double units. A residence for a couple can be made by connecting quarters of the module vertically (fig. 112) or horizontally (fig. 113). The modular partitions allow easy reconfiguration as couples form or fall apart.

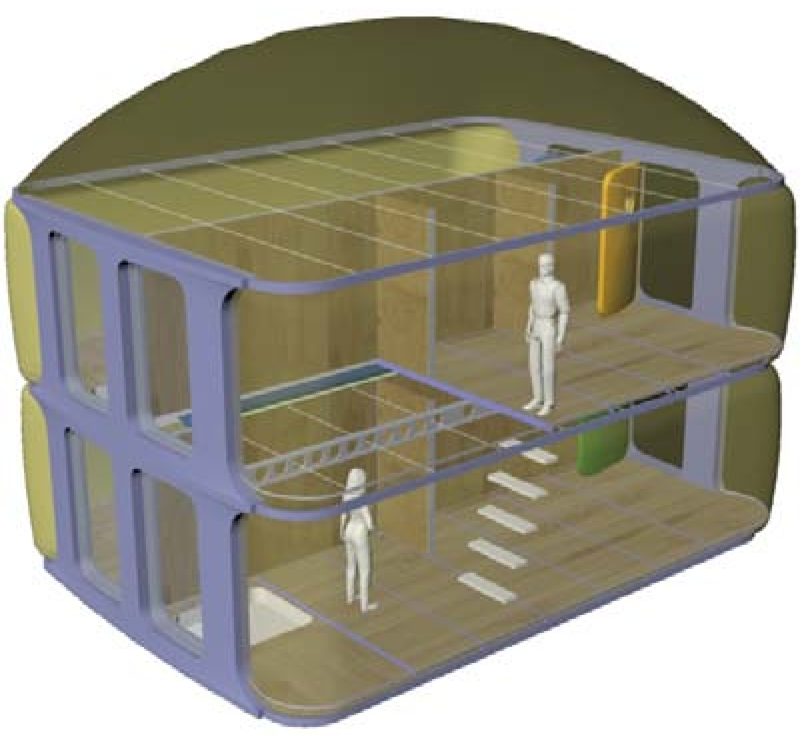


fig. 112   Double unit made by a vertical connection

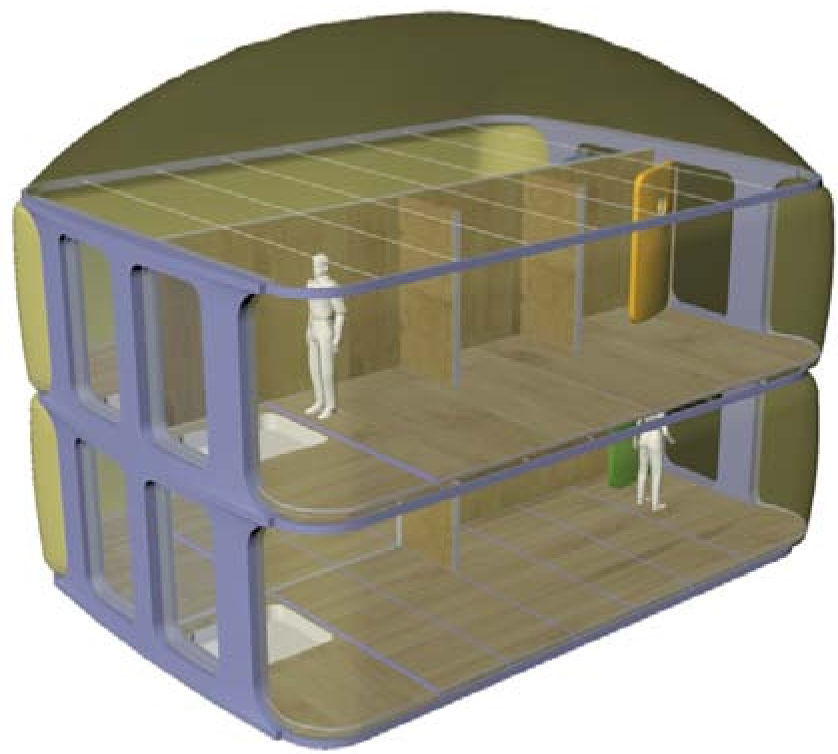


fig. 113   Double unit made by a horizontal connection

08-5 Social considerations

Careful attention was paid to the social implications of the design. The most important aspect of this issue is the need to provide spaces for each stratum of the community, and an understanding of which spaces are claimable by individuals, two people, informal and formal groups or by the whole community.

Individual

There are spaces that one person can access in order to be alone, such as rovers that are parked at various locations of the settlement, the single housing units, and private areas within double units (fig. 114).

Two people

The rovers and private quarters are areas where two people, can be alone.

Informal Subgroups

Informal subgroups of the community made of friends formed on the basis of shared language, interests or other binding factors that are not formalized, have a number of possible gathering spaces (fig. 116).

Formal Subgroups

Subgroups will also form along characteristics that are formalized in the division of labor. For example, the scientists, farmers and engineers have distinct requirements for their work, and thus must be housed in separately.

Whole Community

Finally the whole community can come together informally in the dinning area or the planted thoroughfare and formally in the auditorium that can accommodate all100 residents of the complete settlement (fig. 118).

One cautionary note in this narrative is that I was consciously aware of the danger of thinking like a social engineer. I was aiming to balance between the need to develop a complete design that demonstrates the feasibility of the ideas and the need to allow for the uncertainty of what life will be like on Mars. In other words, the goal is to enable choices through architecture.

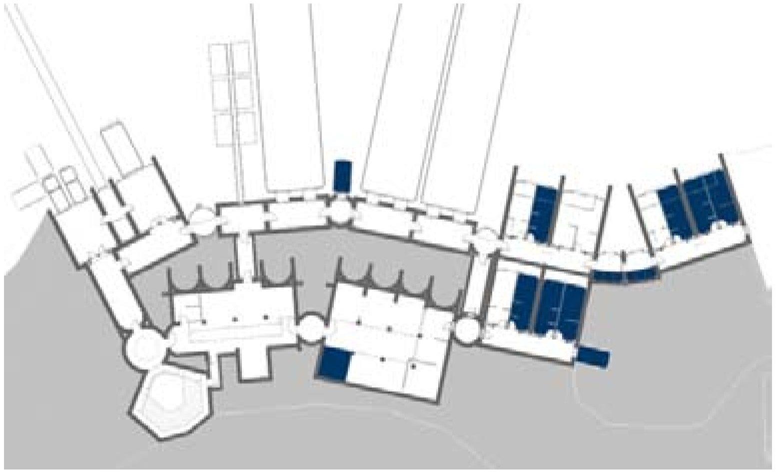


fig. 114 Spaces that may be used by an individual

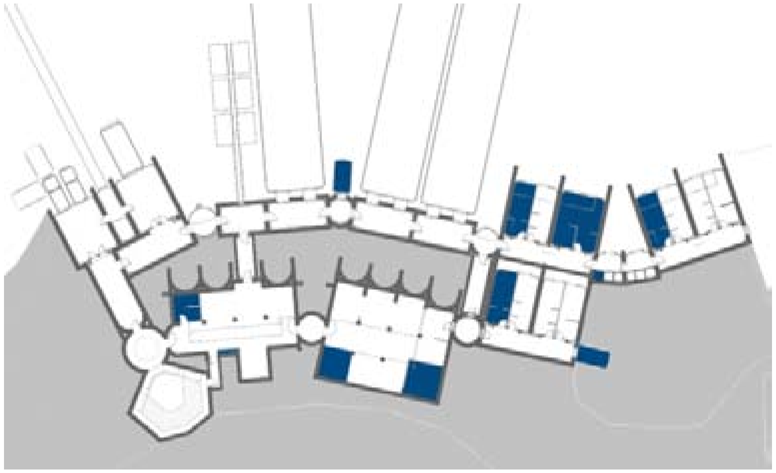


fig. 115 Spaces that may be used by two people

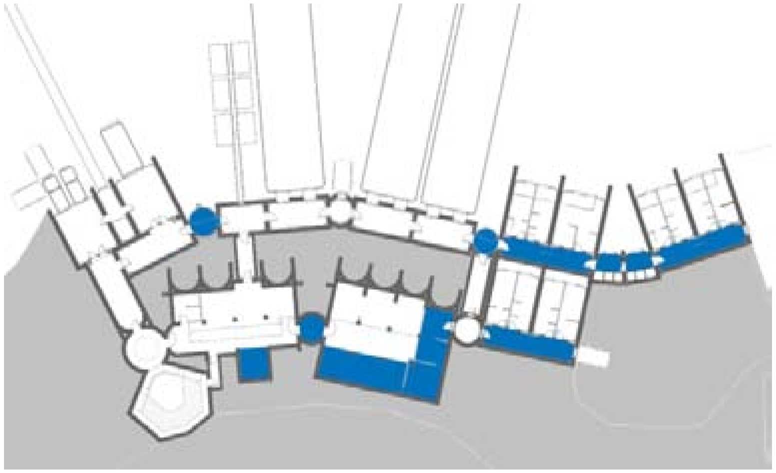


fig. 116 Spaces that may be used by informal subgroups

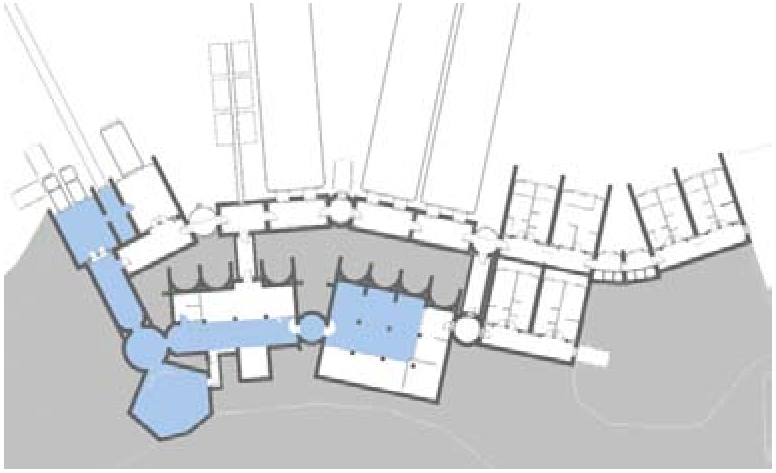


fig. 118 Spaces that may be used by the whole community

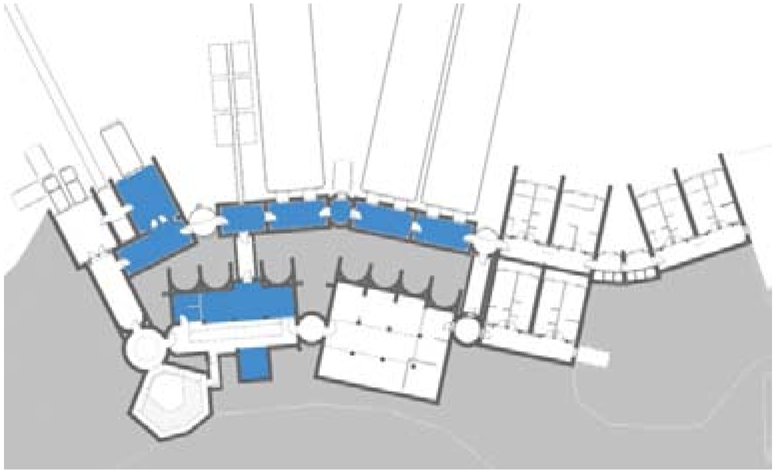


fig. 117 Spaces that may be used by formal subgroups

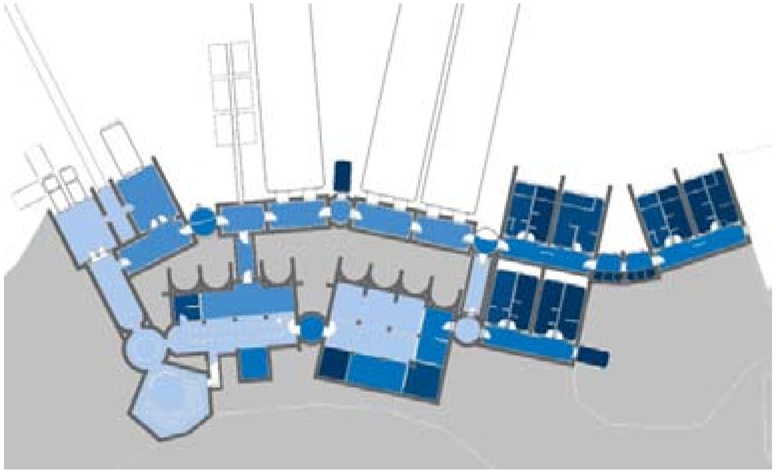


fig. 119 Gradient of social spaces

08-6 Growth

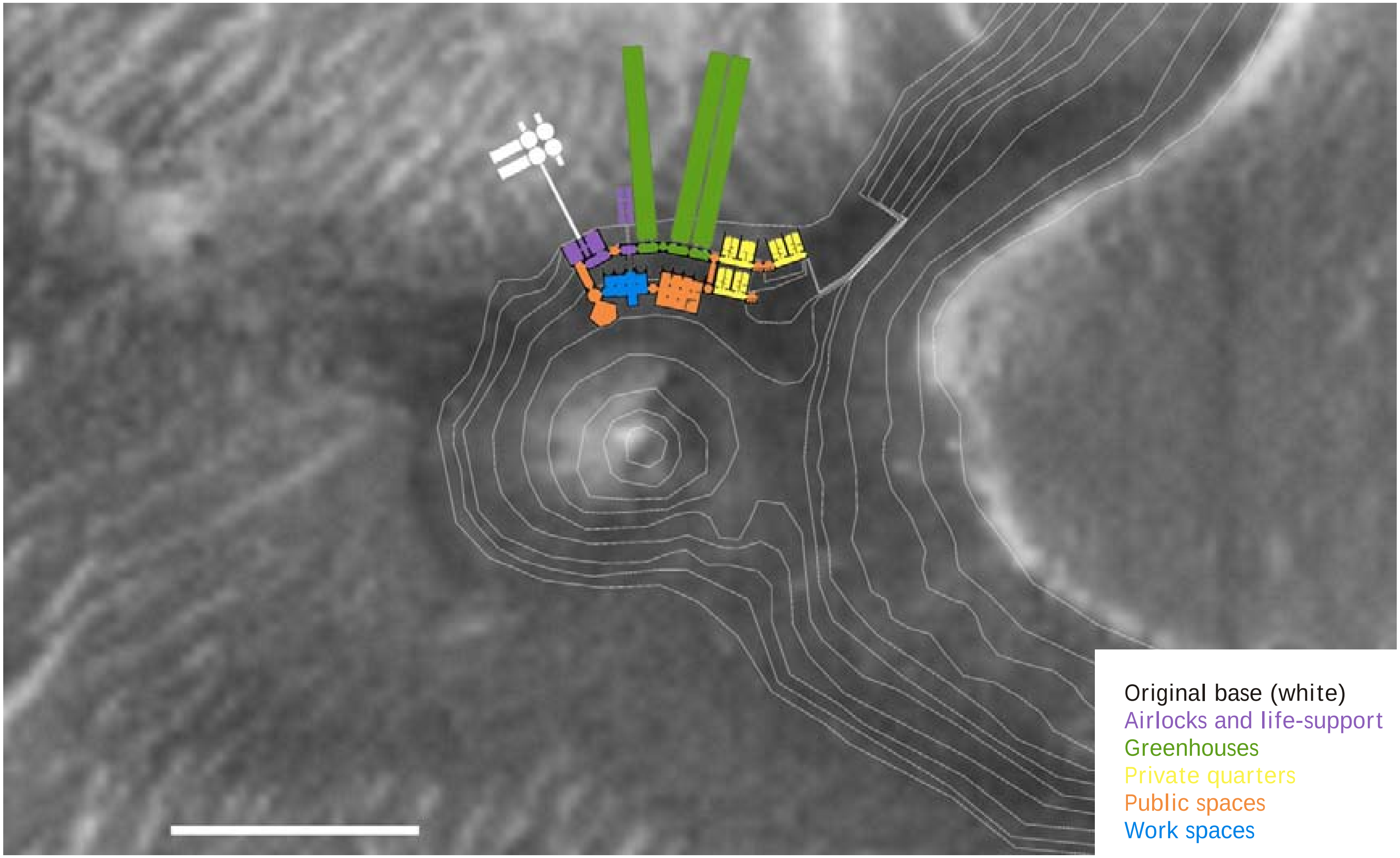


fig. 120 Site plan of phase I - 24 inhabitants, white bar = 100 m

Complete settlement

The settlement will continue to grow along the base of the hill as new segments are completed to accommodate new arrivals. Private, public and work areas are arranged in clusters, forming small neighborhoods. Special spaces, like a large public bath, occur at various places along the two belts of development.

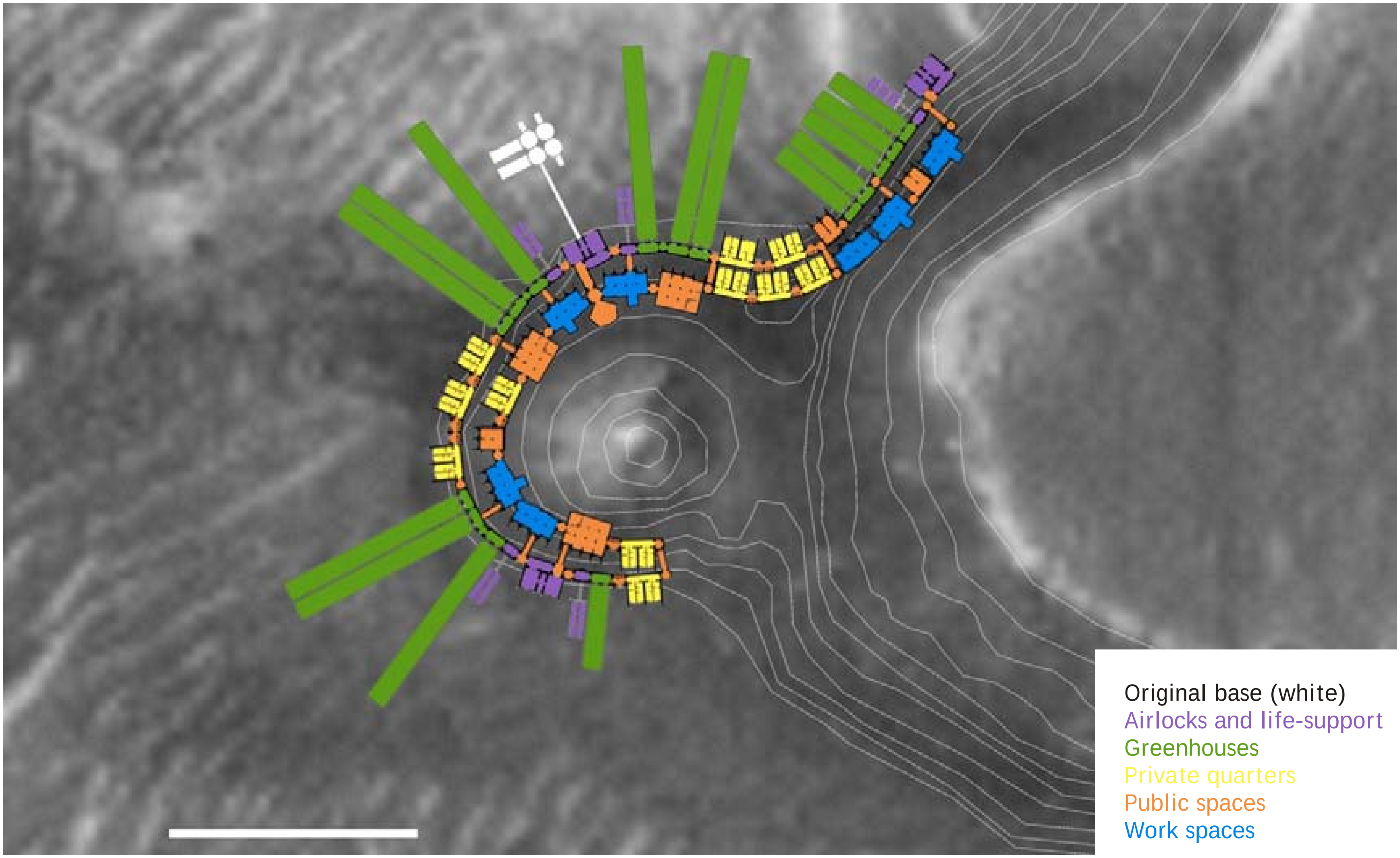


fig. 121 Site plan of complete settlement for 100 people, white bar = 100 m

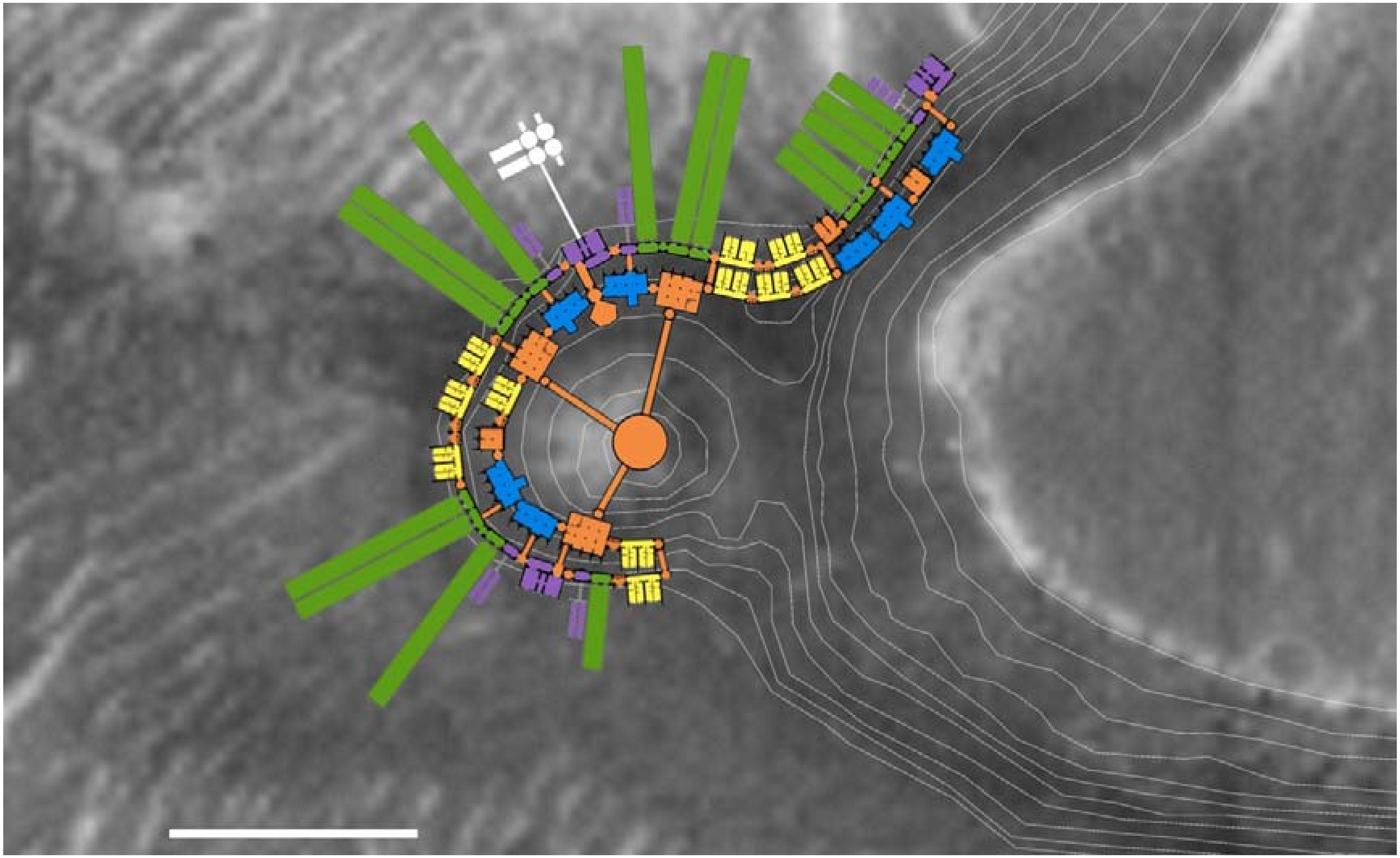


fig. 122 Site plan of complete settlement for 100 people
with possible expansion to the top of the little hill,
white bar = 100 m

fig. 123   View from the north-east of the settlement at the completion of phase I

09 - Construction Time and Material Estimates

Importance of Estimates

Our knowledge of Mars is improving rapidly. As I am completing this work, the Spirit rover has just successfully landed on Gusev Crater and everyone is eagerly anticipating the treasure of new data. With a number of important missions planned for every launch opportunity in the following decade it is certain that by the time the first humans land on Mars, scientists will have a much better understanding of the geology, the atmosphere, and the water, than we do today. We will also have accumulated valuable experience of working in space. None the less, in order to facilitate the comparison of this proposal to other possible solutions, it is important to attempt to estimate the time and mass that will be required to construct the habitat based on our current understanding of Mars, our experience in space construction and by extrapolating from technologies used here on Earth.

Excavation vs Tunneling

Excavating the side of the hill rather than tunneling into it was chosen for a number of reasons. First, excavation requires lower precision and offers greater safety. Tunneling relies on the strength of the material of the site, while excavation and re-covering guarantees the properties of the cover. Excavation can also be carried out in a larger variety of geologies, thus expanding the possibility that the project can be carried out on the desired site. Finally, excavation will be necessary in any case for extraction of resources, thus the same set of machinery can be used for both the construction and mining operations.

Construction operation units

Mining and construction projects on Earth are conducted in a series of separate tasks call operation units [Gertsch 1997]. The units that are required to complete the settlement are fragmentation, excavation, transport, processing, and placement. Each unit is a task that has its distinct goals and procedures, simplifying planing and training. On Mars, many of the operations will have to be automated and more than one unit will be incorporated into single machine. One approach to reducing the mass of the necessary equipment is to use interchangeable attachments to a single rover cabin. A number of other modification to current technology will have to be made, before the exact set of equipment and procedures can be established. For the purpose of this thesis, estimates were derived based on terrestrial practices as summarized by Leslie Gertsch [Gertsch 1997].

fig. 124 Rover mounted drill working on a steep slope
drilling rate = 6 m/hour

fig. 125 Slusher mock-up built by a team lead by Greg Maryniak at MIT during a lab at the International Space University in 1988.

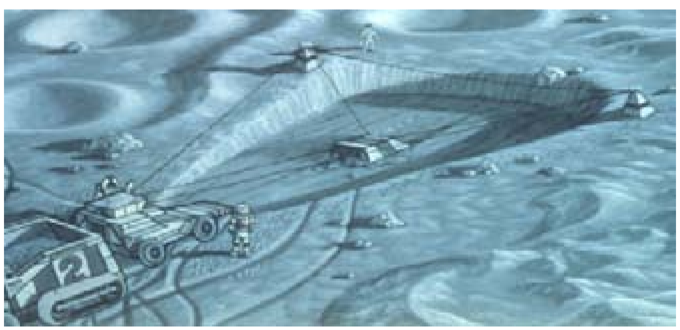


fig. 126 Slusher proposal for mining on the Moon

Fragmentation

Fragmentation, breaks up the soil and rock into small pieces that can be handled by the available equipment. This step might be obviated if the bottom of the hill is in deed a debris apron as it appears on the available images. If some fragmentation is needed, it can be accomplished by using locally manufactured methane as an explosive that is placed into drilled holes and then detonated.

Excavation

After the material has been fragmented, it has to be removed. The excavation can be accomplished in a number of different ways. The simplest and most mass-efficient method of moving loosened material is a slusher (figs. 125 & 126). 'Slushers can handle relatively deep and steeply sided excavations well, and can be combined with other forms of material transport if the haul distance is greater than about 100 m' [Gertsch 1997]. Where more precision is needed, or an excess of large boulders impedes slusher operations, a backhoe (fig. 127), and a front end loader (fig. 128) will be used. Backhoes offer high precision and can develop high force, however they have a complex hydraulic system. Front end loader can be used for excavating, loading, and transporting material. Their main advantage is good mobility.

Transport

There are several options for transporting material between the excavation hole and various processing sites. If the distances are short, the excavation equipment such as the front end loader can be used directly. For longer distances the most versatile machine is a simple trailer that is hauled by a rover (fig. 129). A more exotic technology is a ballistic transporter. Similar to terrestrial snowblowers this technology will take advantage of the lack of strong winds to disturb the stream [Gertsch 1997]. For later stages of the settlement's development the material that is excavated for the construction of a new segment can be directly used to cover the vaults that have just been completed.

Processing

One of the three primary goals of the settlement is conducting applied science to learn how to live on Mars using the in-situ resources. Therefore all excavated material will be used productively. If, as conjectured, there is abundant permafrost, then the first step will be to extract the water, followed by separation of other useful substances. These steps will be carried out in the harvesting and processing plants that will be attached to the settlement. A large portion of the regolith will be used to make the brick for the habitats, in a largely automated or teleoperated process due of the need to access the kiln located near the nuclear power plants.

Placement

The construction of the masonry will be carried out by both humans and robots. Traditionally on Earth, the master mason begins the first critical course of masonry, that guarantees a strait wall and then the interior is finished by the apprentices. An analogous situation can be imagined on Mars where humans perform the critical assembly and robots finish the repetitive tasks. Bruce Mackenzie has proposed that the construction be carried out inside a pressurized tent, making the use of bulky and extremely tiring pressure suits unnecessary. The tent can be filled with CO_2 (rather than valuable oxygen), requiring workers to wear only oxygen masks and normal clothing [Mackenzie 1987]. Burying the finished structure can be accomplished using the ballistic transporter, either from a stockpile of processed material or directly from new excavation.

fig. 127 hydraulic excavator (backhoe)
0.4 m^3 bucket -> 10,000 kg machine mass
cycle time 15 sec -> 1.6 m^3/min

fig.128 front end loader
1 m^3 bucket -> 6000kg machine mass
cycle time 30 sec -> 2 m^3/min

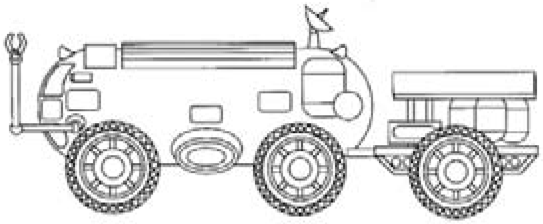


fig. 129 Moving material with a rover-hauled trailer

Time Estimates

Four members of the initial crew of 12 are dedicated full time to building the permanent habitat. They have all of the equipment that has been described in chapter 05 on the surface of Mars at the time of their arrival. The next crew of 12 arrives in 2.5 years, leaving a total of 4(52)(2.5) = 520 man-weeks for the construction of Phase I. All time estimates are made in man-weeks.

Excavation:

30° slope
30 meters deep
45 meters long
Total excavation = 11500 m^3
Slusher with 0.5 m^3 bucket -> 23000 cycles
assume 1 cycle = 2 minutes -> 767 hours
two people = 20 man-weeks

Drilling and blasting	– 4 man-weeks
Setting up slusher	– 4 man-weeks
Slusher excavation	– 20 man-weeks
Backhoe excavation	– 2 man-weeks

Total Fragmentation & Excavation = 30 man-weeks

Manufacturing Bricks:

2200 m^3
Use material from excavation of hill

2 kilns, 1.5 m^3 capacity each.
Firing time 8 hours – 2 batches/day
6 m^3 of brick/day
370 days to make the brick

Automated pressing and firing
Only human intervention is for
maintenance of equipment

Total Brick Manufacturing = 20 man-weeks

Masonry Construction:

8 vaults - 3.25m radius x 10 m long
6 vaults - 2m radius x 8 m long
3 vaults - 1.5m radius x 13 m long
3 vaults - 1.25m radius x 8 m long
28 small domes - 2m radius
1 large dome - 5m radius

On Earth each of the small domes and vaults can be built in 2 days. Assume on Mars it takes 3 times as long. Including arches and walls, each unit takes 2 weeks or **4 man-weeks**. The large vaults are twice as big, so they'll take **8 man-weeks each**. The large dome will require special construction so assume **50 man-weeks**.

Total Masonry Work = 298 man-weeks

Total Construction Time:

1. Fragmentation	– 4 man-weeks
2. Excavation	– 26 man-weeks
3. Transport	- 20 man-weeks
4. Processing	– 20 man-weeks
5. Placement (masonry)	- 298 man-weeks
6. Placement (cover)	- 20 man-weeks
Total	**= 388 man-weeks**

Total available for construction (2.5 years, 4 builders) = **520 man-weeks**

132 man-weeks - for safety and helping the engineers with installation of inflatables.

fig. 130 Construction time estimates

Mass Estimates

The mass estimates contain the greatest uncertainty. The only project that can serve as comparison is the 'Mars Habitation 2057' proposal for a base of 150 people by the Obayashi corporation [Ishikawa 1997]. Their design did not take advantage of in-situ resources for the construction of the habitats, thus their total launched mass estimate is 4002 tons, or 26 tons/person.
The launch mass estimate for this thesis is 1977 tons, or 20 tons/person. The savings are mainly from the use of local resources.

Construction equipment mass:

Estimates based on terrestrial equivalents from [Gertsch 1997]

Slusher	- 2,000kg
Front end loader	- 6,000kg
Back Hoe	- 10,000kg
Truck	- 5,000kg
Ballistic transporter	- 5,000kg
Drill	- 2,000kg
Crane	- 5,000kg
TOTAL	**- 35,000kg**

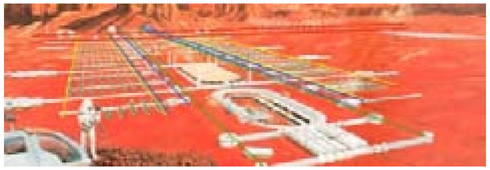


fig. 132 Mars Habitation 2057
launched mass/person = 26 tons

Total launched mass:

100 Humans	9 tons (90kg/person)
Construction equipment	35 tons (see above)
Greenhouses	400 tons (from Obayashi Corporation estimate)
12 Nuclear Reactors	128 tons (SP-100 reactor = 10.7 tons)
Life support machinery	32 tons (extrapolation from Mars Reference Mission)
Science equipment	30 tons (extrapolation from Mars Reference Mission)
Initial food cache	219 tons (20kg/person/day x 12 people x 2.5 years)
2 long range rovers	50 tons
4 pressurized rovers	20 tons
125 Inflatable modules	625 tons (5 tons per module)
Skylights and mirrors	100 tons
Subtotal	1648 tons
20% Safety	329 tons
TOTAL	**1977 tons**
Per person	**20 tons**

fig. 131 Mass estimates

fig. 133 Current proposal
launched mass/person = 20 tons

10 - Conclusion

Mars is closer than it appears

Currently the biggest obstacle to space ventures is the high risk and high cost of existing launch vehicles. Fortunately there are several projects that aim to develop new reusable vehicles that promise to lower the cost of launching material to orbit. Taking a cue from the early days of aviation, the X-prize has been set up to further invigorate private research into new types of launch vehicles. Currently there are 20 teams registered to compete for the $10 million prize to fly their vehicle, carrying three passengers, twice within a 14-day period. Interest is further enhanced by the emerging realization that there is considerable interest in space tourism even at the currently exorbitant prices. Probes like NASA's Lunar Prospector, Mars Global Surveyor, and Mars Odyssey are revealing that many of the necessary materials are already available at our destinations and would not need to be carried from earth. Most importantly, advances in material science and nanotechnologies, combined with in-situ resource utilization, continue to reduce the mass required for space structures. All of these developments are bringing the price of sending humans to Mars to acceptable levels.

Widening the discourse

By constructing space settlements, and eventually colonies, we get a chance to create a human community that will be free from any predispositions and historical pressures. This creates a valuable opportunity for architects to challenge many of the underlying assumptions about how to structure a community and about architecture's relationship with engineering.

The future of humanity is among the stars. I think that architects should play a vital role in shaping this future and I hope that this thesis will be a helpful step towards widening the discourse on how to live on Mars to include architects and designers.

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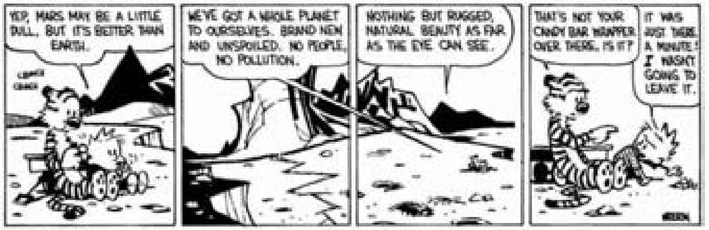

fig. 134 May we behave better on Mars, than we do at home