Design of a Human Settlement on Mars Using In-Situ Resources

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Mars provides plenty of raw materials needed to establish a lasting, self-sufficient human colony on its surface. Due to the planet's vast distance from Earth, it is neither possible nor economically reasonable to provide permanent, interplanetary supply. In-situ resource utilization (ISRU) will be necessary to keep the Earth launch burden and mission costs as low as possible, and to provide – apart from propellant and life support – a variety of construction material. However, to include outposts on other planets into the scope of human spaceflight also opens up new psychological and sociological challenges. Crews will live in extreme environments under isolated and confined conditions for much longer periods of time than ever before. Therefore, the design of a Mars habitat requires most careful consideration of physiological as well as psychosocial conditions of living in space. In this design for a Martian settlement, the author proposes that – following preliminary automated exploration – a basic surface base brought from Earth would be set up. Bags of unprocessed Martian regolith would be used to provide additional shielding for the habitat. Once the viability of the base and its production facilities are secured, the settlement would be expanded, using planetary resources. Martian concrete – processed regolith with a polymeric binder – would be used as main in-situ construction material. To provide optimum living and working conditions, the base would respond to the environment and the residents' number and needs, thereby evolving and growing continuously. A maximum of adaptability in the interior configuration as well as flexibility in the layout of the base would enable the crew to configure the space according to their needs and living preferences. The proposed design shows how an elementary surface base on Mars could evolve into a settlement and gain increasing self-sufficiency by using local resources.

I. Introduction

MANY space agencies and private organizations have announced plans to send humans to Mars in the near future. This paper proposes a flexible habitat design, that aims to provide for enduring performance and to be a stepping stone for a long-term exploration and settlement of Mars. The project presented in this paper was developed as part of a master's thesis in architecture at the Vienna University of Technology. Therefore the work focusses primarily on the architecture of the habitat.

Obviously there are still a lot of technological hurdles to overcome until the first humans can set foot on Mars and missions like the one described in this paper can take place. For the spacefarers, such an enterprise will be physically very demanding. They will experience extremely different environments: from Earth (1 g) to space (0 g) to Mars (0.38 g) and back again. The necessity to protect humans from the harsh environmental conditions of Mars (ionizing radiation, atmospheric pressure and composition, temperature) and the psychological and sociological impact of prolonged isolation and confinement add to the complexity and risk of such missions. To reduce the launch mass and cost of future Mars settlements, progress in the technological readiness of in-situ resource utilization (ISRU) and on-site manufacturing systems, as well as the reliability of life support systems, are a requisite[1].

This proposal aims to increase sustainability and self-sufficiency of a Mars base by:

1) minimizing launch mass and the necessity of supply cargo through the use of in-situ resources,
2) using in-situ resources to shield the habitat against ionizing radiation,

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3) providing flexible habitat designs to provide optimum living and working conditions and enable base evolvement and growth.

II. Mission Elements

The mission concept for the habitat design includes the following surface elements and launch system. For this mission concept it is assumed, that all the following technologies have passed their development phase and are ready to use until mission start in 2029. Additionally, before the start of the cargo mission in 2031, communication satellites need to be launched into orbit around Mars and Sun.

A. Launch System

To send astronauts on their mission to Mars and transport all the necessary cargo into space, multiple launches of heavy lift rockets will be necessary. One possible, and momentarily the most favorable launch vehicle for this scenario is the Mars Surface Mission Configuration of NASA's Space Launch System (SLS), which is still in development. It will provide a 10 m fairing and a lift capacity of 130t to low Earth orbit[2].

The following rough calculations are done to estimate the number of launches necessary to establish the first inhabited "seed base" on Mars:

Cargo mission 2031:

Utility Rover	2 340 kg (Ref. 3)
2 Pressurized Rovers	6 000 kg (Ref. 4)
Power Generator (nuclear and solar)	10 000 kg
Science Equipment	1 500 kg
ISRU (Sabatier, Water Tent, etc.)	15 000 kg
Ascent Vehicle	22 500 kg (Ref. 5)
Surface Habitat and Greenhouse (incl. Accommodations, Integration, Suitport, ECLSS)	40 000 kg
	97 340 kg

Table 1. Estimated Surface Equipment/Payload for the 2031 Cargo Mission.

To land this estimated payload of about 100 t, three landers with the capacity of about 35 t would be necessary, one habitat lander and two cargo landers. Including the return vehicle that would stay in Martian orbit, four launches would become necessary in this scenario.

Crewed mission 2033:

To send the first crew of five and their supplies on their journey to Mars, two to three launches will be necessary.

B. Robotic Rover

The use of robotics will be an important element for a Mars base. The cargo handling system for this mission scenario will be based on ATHLETE (All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer), a versatile cargo handling system developed for lunar exploration by NASA JPL. Every one of its six limbs can be operated independently. It can carry payloads of up to 14 500 kg in Earth's gravity and it is capable of carrying whole habitats on its platform. ATHLETE can be equipped with a drill, scoop, gripper, hook and line, and various other tools[3].

As the ATHLETE is designed for lunar exploration, some adjustments would be necessary to apply the system on the Martian surface.

C. Pressurized Rover

The pressurized rover chosen for this scenario is the SEV (Space Exploration Vehicle). It was developed by NASA and has a range of 240 km and speed of about 10 km/h. It can house two astronauts for up to two weeks. In the case of an emergency it is even able to support four people. The SEV does not only have a small bathroom but also workspace and seats that can be converted into beds. It is 4.5 m long, 4 m wide, 3 m high and can be directly docked to the habitat. The rover has 360° pivoting wheels and can be endowed with attachments for cranes, cable reels, backhoes and winches[4]. It has suitlocks to avoid excess airloss and minimize suit-induced trauma[6].

The first crew to land on Mars will have two rovers at their disposal. If the rovers are not in use for exploration, they will be docked to the habitat to increase pressurized space.

D. Habitat

The habitat for the first crew will consist of a rigid cylinder in the middle, with two inflatables at each end. They bring about a large increase in volume, and facilitate efficient packaging. The cylinder provides two docking ports (one to the greenhouse, one to the suitport) and each inflatable provides one (to one pressurized rover each). As the mating system is androgynous, it allows for great flexibility and the configuration is rearrangeable. Multiple egress possibilities as well as the fact, that two inflatables are connected by a rigid part in the middle, make the design very safe and reliable. Should one pneu have a problem, it could be sealed off while the ring and the other inflatable would still be inhabitable. Also, still three docking ports would be available, and the pressurized rovers could be used to increase habitable space. The rigid ring also works as structural reinforcement of the cylindrical shape of the inflatables. The interior of the inflatables features a kit-of-parts mounting structure for increased flexibility and adjustability. The rigid cylinder holds the galley and kitchen as well as the wet rooms and health care. In the case of Solar Particle Events (SPEs) it doubles as safe haven for the crew. It will be made of a composite material called carbon filled carbon[7].

The later missions use the same habitat type, but connect multiple of those habitats with a central, inflatable torus, which will provide a large greenhouse and recreational facilities.

E. Infrastructure

It is important, that critical systems like the Sabatier unit, which produce oxygen and water, are located within short distance to the habitat, to facilitate maintenance and the exchange of full and empty tanks. Photovoltaic cells for the production of solar power will be located close to the habitat as well, so maintenance tasks require minimum effort. To shield the base from additional radiation, the backup energy source, a small Liquid Fluoride Thorium Reactor (LFTR) will be located at a safe distance, either buried or encased in thick sintered regolith walls, to facilitate maintenance. Both sources will be connected to the habitat via power cables. The landing and launch area (ca. 600 m^2) will be at a distance of ca. 3.5 km to the base, to prevent dust and debris from causing damage to the habitat, greenhouse or photovoltaic cells. Atmosphere control and supply, air revitalization, temperature and humidity control, water processing and waste management technologies and stores are integrated in the habitat (floor and ceiling) and the greenhouse.

III. In-situ resource utilization

To limit initial launch mass and subsequent supply needs and to promote self-sufficiency of a Mars base, the following technologies will make use of the native resources of Mars.

A. Power, Water and Life Support Production

For the colonization of Mars, sufficient energy on site is a prerequisite. Astronauts will need a reliable, durable power system already in place and working, before they even start their journey to Mars. Likely a mix of solar and nuclear power will provide assured energy supply of the settlement.

1. Solar Energy

The location of the settlement – Mawrth Vallis (23.9883°N, 341.0399°E) – is chosen to be in an area of maximum solar incidence[8]. Therefore, the amount of solar power, that can be gained, will get the astronauts far. In times of good insolation, the panels will probably produce redundant energy, which will be saved by batteries for times where little sunlight is available.

2. Nuclear Power

During global dust storms, the energy gain of solar panels will be diminished. Thus, a reliable backup, that can produce energy-amounts large enough to provide for the settlement, will be necessary. Also, energy needs of the colonies' in-situ production (construction elements, food etc.) need to be considered.

A Liquid Fluoride Thorium Reactor is a nuclear reactor that is much safer (no risk of nuclear meltdown, low pressure, leak resistance, dramatically reduced radioactivity of nuclear waste, can use existing nuclear waste as fuel) and more efficient than conventional reactors[9]. The area of Mawrth Vallis shows a relatively high abundance of Thorium, which could be used in such a reactor[10].

In the opinion of the author, it is the ultimate goal to phase out the use of nuclear fission as soon as an assured, continuous supply of renewable energy sources can be found on Mars (e.g. possible areothermal sources, in-situ production of photovoltaic cells, etc.).

3. *Water generation*

Per day, a typical human in space needs approximately 3.52 kg of water for drinking and about the same amount for cleanliness[11]. To mine water on Mars, it would not be necessary to excavate frozen material and bake it. Microwave beams could be used to vaporize the water ice so it could be collected. This process would only require small-scale drilling and little digging[12].

An even easier method has been proposed by Allen and Zubrin. They suggest that the water could be obtained by deploying a transparent tent made of 0.1 mm thick polyethylene and using the greenhouse effect occurring within it. Such a tent with 25 m in diameter and additional reflectors could gain 224 kg of water from soil containing only 3% water during an 8 hour interval[13]. This should sufficiently cover the crew's water need of approximately 35 kg/day[11], while also providing enough for the greenhouse. The light construction could easily be moved to a new field by a rover and already mined surfaces would rehydrate themselves, making continuous "farming" of an area possible[13].

4. *The Sabatier Process*

This simple, scalable and energy efficient way to produce methane, oxygen and water for fuel and life support on-site could be used to minimize launch mass and therefore costs of a Mars mission. The reaction involves carbon dioxide (CO_2) from the Martian atmosphere and hydrogen (H_2), either delivered from Earth or Moon or produced on the Martian poles.

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O \rightarrow CH_4 + O_2 + 2\,H_2 \qquad \text{(Ref. 13)}$$

5. *Oxygen Production*

Based on a typical profile for metabolic balance, a human in space needs approximately 0.84 kg of oxygen per day[11]. According to Allen and Zubrin, a small Sabatier reactor with the volume of 1 liter will produce sufficient oxygen for the crew's need[13]. Additional oxygen and fuel for redundancy could be produced by cyanobacteria and algae, which will be grown in the greenhouse for dietary supplementation[14].

B. Food Production

A mixed crew of five people is assumed for this mission scenario. For the sake of simplicity, an average mass of about 65 kg/person has been chosen to represent average astronauts[15]. In Reference 1, the authors calculated, that based on a typical ISS work schedule, such an average astronaut would need about 3000 kcal/day on Mars for sustained health and productivity[1].

The first interplanetary astronauts will bring an artificial eco-system with them. A greenhouse will enable the crew to grow fresh produce to supplement their nutrition. It will also serve a vital function in creating and sustaining a closed environment for the habitat by creating oxygen and absorbing carbon dioxide. Not only to see the plants grow and to literally harvest the fruits of the effort, but also the smell, taste and presence of vitamins in the plants will benefit physiological and psychological health of the astronauts. To avoid increase of humidity levels and disbalance in the oxygen levels of the habitat, the growth area will be separate from the habitat, though docked to it and easily accessible.

In a Mars One feasibility analysis, Do, Ho, Schreiner, Owens and de Weck, calculated that a system in which all food is produced on Mars needs slightly higher launch mass than a "stored-food-system" for at least twenty years of operation. Moreover, to meet the 3000 kcal/person/day demand, quite a substantial growth area would be necessary[1]. Yet, the greenhouse is an important factor for the self-sufficiency of a colony and besides the valuable psychological benefit, technological development and innovation and constantly improving plant-growth efficiency can be anticipated. Therefore this Mission scenario suggests that for the "seed base", half of the food be brought from Earth and half produced on Mars. The average crewmember needs approximately 0.62 kg food per day[11]. Using a high density packing scheme, the greenhouse could house about 130 m2 of growth area, which should produce enough food for half of the crew's food supply[1].

Once the base has more inhabitants, it will become worthwhile to add large scale, low pressurized greenhouses to make use of the carbon dioxide in the Martian atmosphere and lower energy needs. This sort of farming will mainly be done by robots.

C. 3D Technology

To manufacture new equipment and replacement parts on site would be an efficient way to limit transport risks and costs. Extensive materials research to study the effects of radiation, microgravity, temperatures on 3D-printed material will be necessary.

In their paper "Modular Additive Construction Using Native Materials" A. Scott Howe and his colleagues developed a concept for a freeform additive construction system (FACS) for the lunar surface, based on ATHLETE. The FACS system is a concept for 3D-printing construction elements made of solar/microwave sintered-regolith[16].

In this mission scenario, the ATHLETE-like rover will be used for building with regolith as well. It will be equipped to dig and grind regolith. However, instead of sintering the ground material, it will make 'in-situ fiber concrete' to create shells over the inflatable habitats for additional (GCR-)shielding, using the pneus as formwork.

D. Shielding with Regolith

The annual dose of Galactic Cosmic Radiation (GCR) received by a human on the Martian surface is estimated to be approximately 77 cSv (dose shielded by the Martian atmosphere and the planet itself already subtracted). The allowed annual dose for a NASA-astronaut is 50 cSv, while the career-limit of accumulated radiation is 1 Sv. During an eighteen-month-stay at the Martian surface, an astronaut would receive an estimated 1.2 Sv (depending on the location), which would clearly be too high. The occurrence of a Solar Particle Event (SPE) during an eighteen-month stay on Mars has a quite low probability of about 3-4%. But even when spent in the very well shielded safe haven of the habitat, SPEs could add up to an additional 10 cSv to the accumulated GCR dose of the astronauts. Also, it has to be considered, that on their journey to Mars, the astronauts are even more subjected to and harder to protect against radiation, as there is no atmosphere and no large planetary body to shield them from it[17].

The inflatable structure of the habitat does not only provide thermal, atmospheric and debris protection, the light elements of the polymeric fibers are also very good at shielding radiation (e.g. the polymer polyethylene, with a density of 0,93 g/cm3, and a front to back linear thickness of 15 cm, manages to reduce radiation doses by almost 44%. It is much better suited as shielding material in spaceflight than aluminum, which is a ferocious emitter of secondary neutrons)[7].

However, additional radiation shielding will be necessary to further reduce the radiation doses, to which astronauts are subjected to. A launch-mass-saving option for shielding the habitat is the use of in-situ regolith.

1. Phase 1

The easiest way to make use of regolith would be in its original or ground up form. The habitat could be simply 'buried' under it or covered with regolith-filled bags. The proposed mission scenario makes use of such regolith bags in the early stages of the mission (Figure 1). The shielding of the central rigid ring is improved by the mounting of such bags to the outer hull, to make it safe enough as a shelter for SPEs. The bags provide an easy, quick and flexible method of shielding.

2. Phase 2

For extended missions or colonization, the processing of regolith should be considered, to improve practicability and shielding efficiency. The following construction methods were considered to use for the extended mission scenario:

1) 3D-printed foam-like hulls of regolith around the inflatable habitat. A method for building a lunar base, developed by Foster+Partner in collaboration with the European Space Agency (ESA)[18].
2) 3D-sintered construction elements like bricks, slabs or shells[16]
3) 3D-printed concrete shells, using pneumatic formwork (in this scenario the inflatable habitat) to transform a plane, 3D-printed concrete plate into a shell[19,20,21].
4) Sprayed ice shells over inflatables[22] or sprayed concrete shells[23].

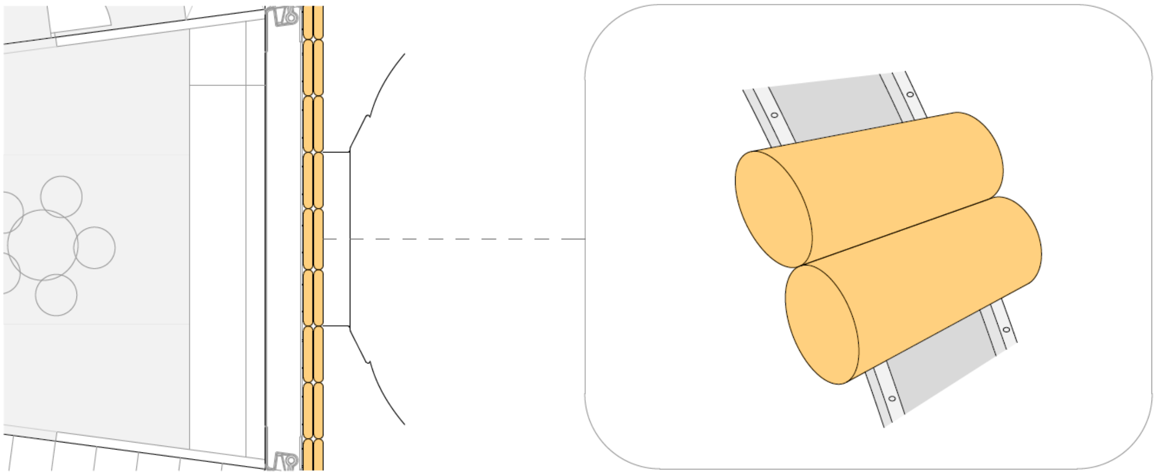

Figure 2. Phase 1 - Regolith Shielding. *Layers of 60x20x10 cm sized regolith pillows increase shielding. The modular system allows for adjustment to the landing site environment.*

The foam-like moonbase-structure, developed by Foster+Partner and ESA, requires a very thick hull[18]. The Moon has much harsher environmental conditions than Mars. Its complete lack of atmosphere provides absolutely no shielding against radiation and micrometeoroids. The temperature ranges are much more extreme, and also the day-night cycles are not as similar to Earth than on Mars. Therefore, burying the base under a thick hull makes perfect sense. Very good micrometeoroid-protection is required, and the foam-like structure is well fitted for that. But even on Mars, with its much more benign conditions, those hulls would need to be about 100 cm thick for significant shielding effectiveness. A thinner hull would be the more flexible and elegant way for the Martian environment.

3D-sintered elements or shells would be quite practical in their construction method. However, the elements would also need to be very thick for adequate shielding mass effectiveness (SE = Dose Reduction per Mass Thickness).

For this scenario, sprayed or printed ‘concrete’ shells are the most promising construction method. They are a simple, most flexible and economic way to cover the inflatables with permanent regolith-derived shielding.

However, to make concrete, a binder is necessary. Due to the added hydrogenous constituents, the use of a polymeric binder for the ground regolith can significantly improve its shielding mass effectiveness SE (Dose Reduction per Mass Thickness). The Authors of Reference 24 suggest to use the vented methane from the Sabatier process for synthesizing a polyimide called LaRC-SI, developed by Langley Research Center. This polyimide, LaRC-SI, is particularly well suited as a binder, because it possesses excellent mechanical properties, high thermal stability, good chemical resistance, can be produced without complex requirements and is quite simple in its use[24].

The shells can be reinforced with basalt-fiber-meshes or loose basalt fibers, to improve the mechanical properties of the shells even more. All over Mars, basalt can be found in large quantities. It would simply need to be melted and drawn into fibers[25].

Similar to the ATHLETE/FACS concept[16], in this mission scenario, the robotic rover will be used for building with regolith. It too will be equipped to dig and grind regolith. However, instead of sintering it, it will make ‘in-situ fiber concrete’. It will process the ground regolith, the LaRC-SI powder and the basalt fibers into fiber concrete and use a printer head or nozzle to apply 20 cm thick shells over the inflatable habitats. This way, the pneus can be used as formwork.

With the added shielding mass effectiveness of the polymeric binder and the reduced gravity of the Martian environment, 20 cm thick shells should be enough to reduce radiation doses inside the habitat to an acceptable level, and to provide a reliable structure over spans as large as 25 m. At this thickness, they should also still be light enough not to affect the inflatables.

IV. Mission Scenario

A. Mission Plan

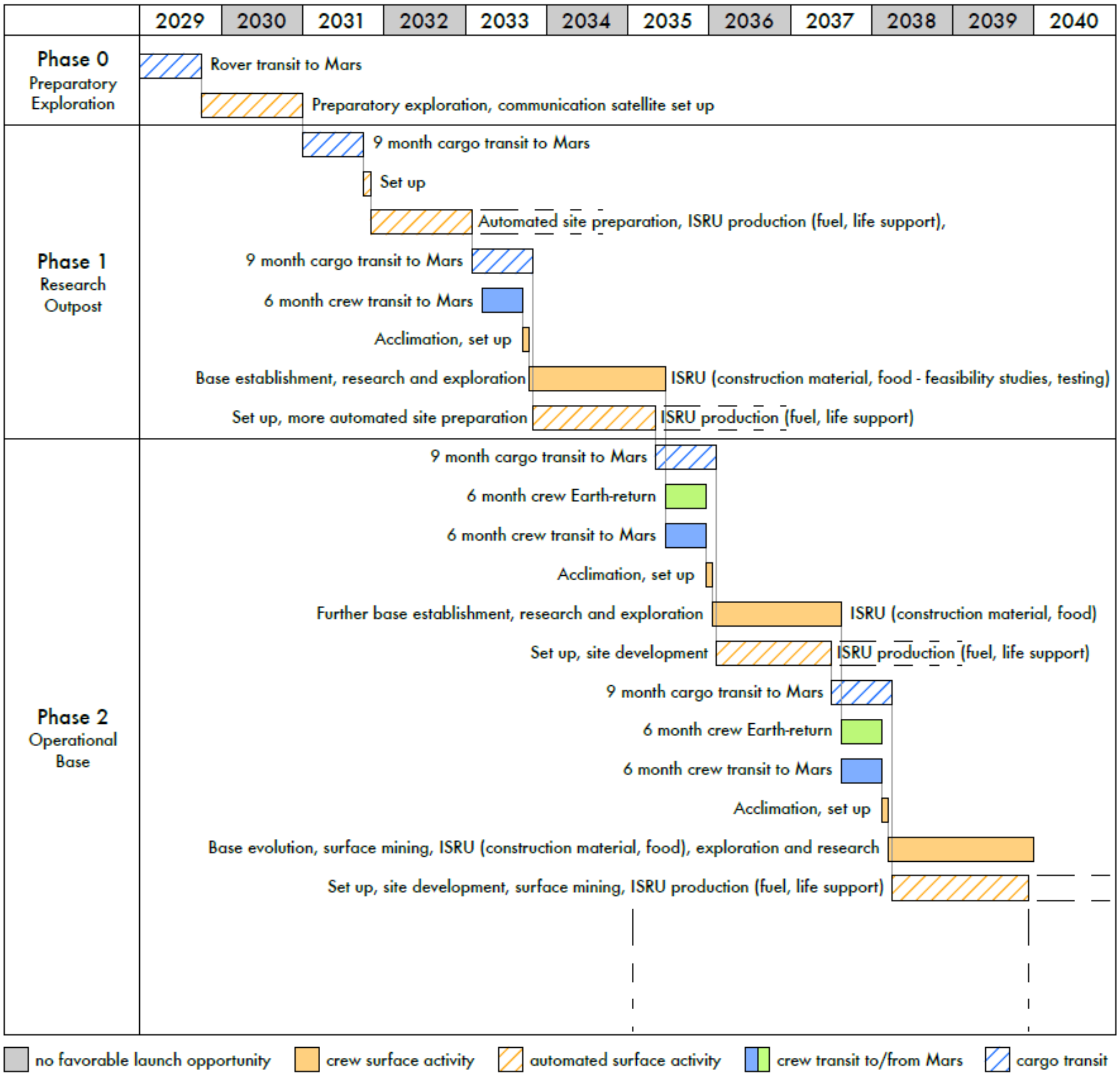

Figure 3. Mission Plan. *This mission plan applies to the first two phases of the mission scenario.*

B. Base development proposal

In the development of such a colony it is – literally – of vital importance to consider sociological factors. Not only in the earliest stages, when spatial resources are very limited and astronauts have to deal with intense contact with a very small number of people, but also when the development of the colony is already advanced and a larger number of people inhabit it.

In environments that are so very hostile to life, people will naturally want to satisfy their basic needs and look after themselves first. Their evolutionary instincts will most likely influence, how they will cope with setbacks or mistakes. What, for instance, happens, if crop failure occurs at one such habitat-cluster and the bases food supply becomes scarce? Will their neighbors support them? Or will they rather not endanger their own survival by helping out. Will people use their resources to gain power over others, maybe even to the point of using violence? These are all possibilities to consider, and which can be addressed and dealt with architecturally.

C. Phase 0

Phase zero is the preliminary automated exploration done by robots (Figure 2 – Phase 0). When the robotic exploration rover has found the perfect place for the first manned mission to land and the communication satellites are in place and working properly, phase one can start.

D. Phase 1

1. Overview:

This is the phase, in which the first crew will land on Mars (Figure 2 – Phase 1). In this mission scenario, the cargo for the first crew will be lifted off Earth by SLS 130 t (NASA Space Launch system with evolved lifting capability) in January 2031. After a nine month transit the cargo transfer vehicle will insert into Martian orbit. From there, three landers will be navigated to the chosen landing ellipse on the surface of the planet. They will carry a habitat with suitport and greenhouse, two pressurized rovers, a cargo handling rover, Sabatier process hardware, power generators, a water extraction unit and an ascent module for Earth return.

After one month of set up, automated site preparation will start. ISRU production of fuel and life support compounds will be carried out by the Sabatier process hardware. When the habitat-site is prepared - shortly before the crew arrives - the habitat, neatly packed for the transit to Mars, will be carried by the robotic rover to the base site, where it will be deployed. As soon as enough power, fuel and life support is generated, it is safe enough for humans to follow the robot pioneers.

The first crew ever to land on Mars will use the opportunity in spring 2033 for a fast transit (conjunction class) from Earth to their destination. They will undock their lander from the transit ship and land on the Martian surface. Following the landing, the crew of five will take the pressurized rovers to get to the spot where the habitat is already waiting. The robotic rover will handle the cargo. First, the crew will make the habitat ready to use. After that, the astronauts will have about 30 days for acclimation.

After settling in and establishing the first base with a small greenhouse (Figure 3-6), the five astronauts will primarily research and explore factors that determine, if a settlement on Mars can be viable and if such an enterprise would be scientifically and economically reasonable. During the next 500 days they will do small scale drilling with the help of the robotic rover and set up a test bed for surface mining. They will do feasibility studies on the ISRU production of food and construction material – especially regolith, basalt fibers and polymers. Meanwhile the Sabatier unit will go on producing fuel and life support elements.

About a month before the first crew will leave for Mars, another cargo ship will go on a nine month journey to our neighbor planet in early 2033. It will deliver two more habitats and an inflatable connecting hall, one more pressurized and one more robotic rover with tools, plus more infrastructure.

In spring of 2035, the astronauts will end their pioneering exploration of our neighbor planet, enter the ascent vehicle and blast off into Martian orbit to dock with the orbiting return vehicle. After a six month trip, they will enter the landing capsule and touch down on Earth.

2. Habitat Design for Phase 1

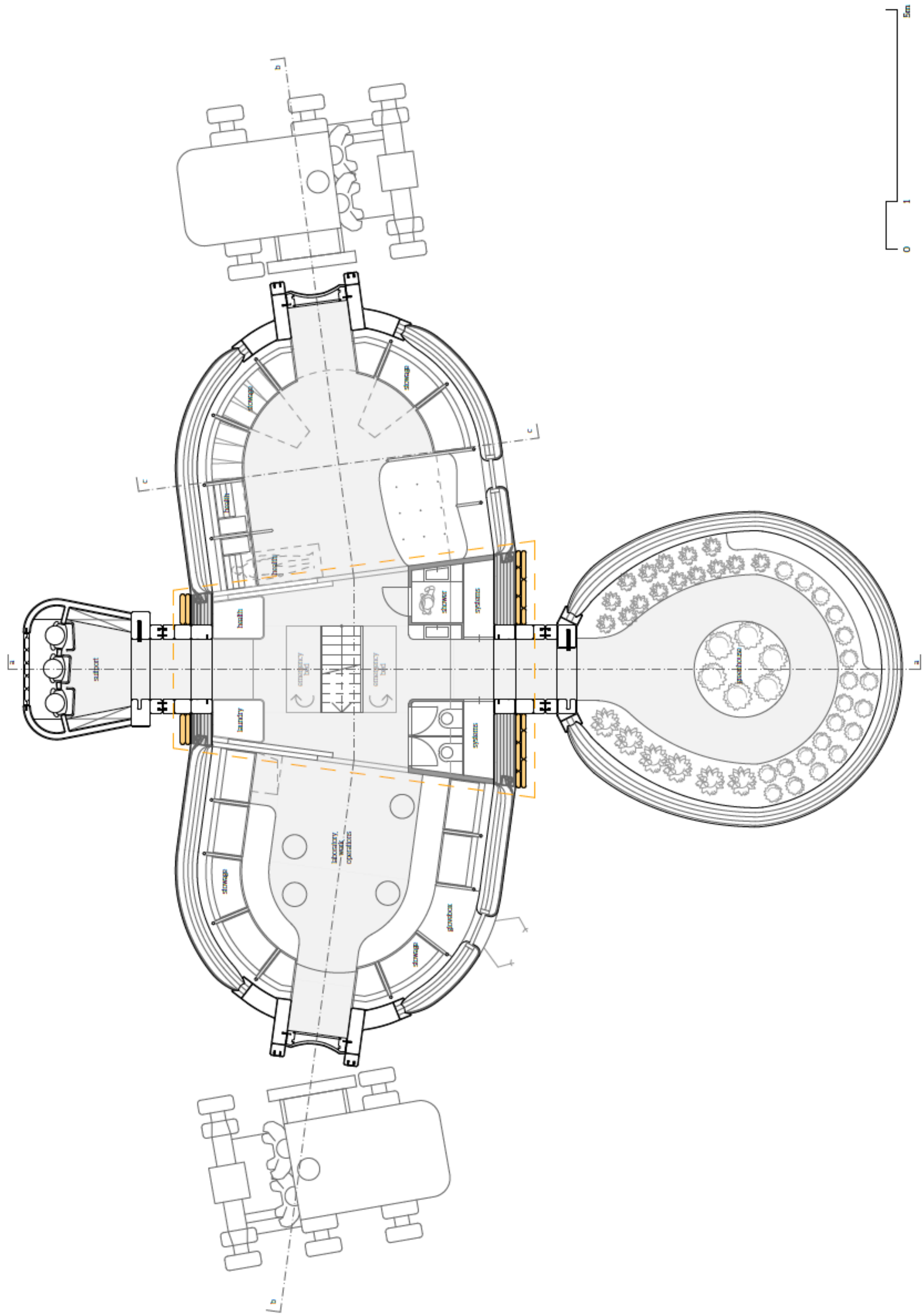

Figure 3. Habitat design for Phase 1 – Level 1. *Floor plan of the lowest level of the habitat, including the greenhouse, suitport and both pressurized roves. The drawing shows the crew quarters in the inflatable (top), the wet rooms and crew health provision in the rigid part (middle) and the laboratory and working stations (bottom).*

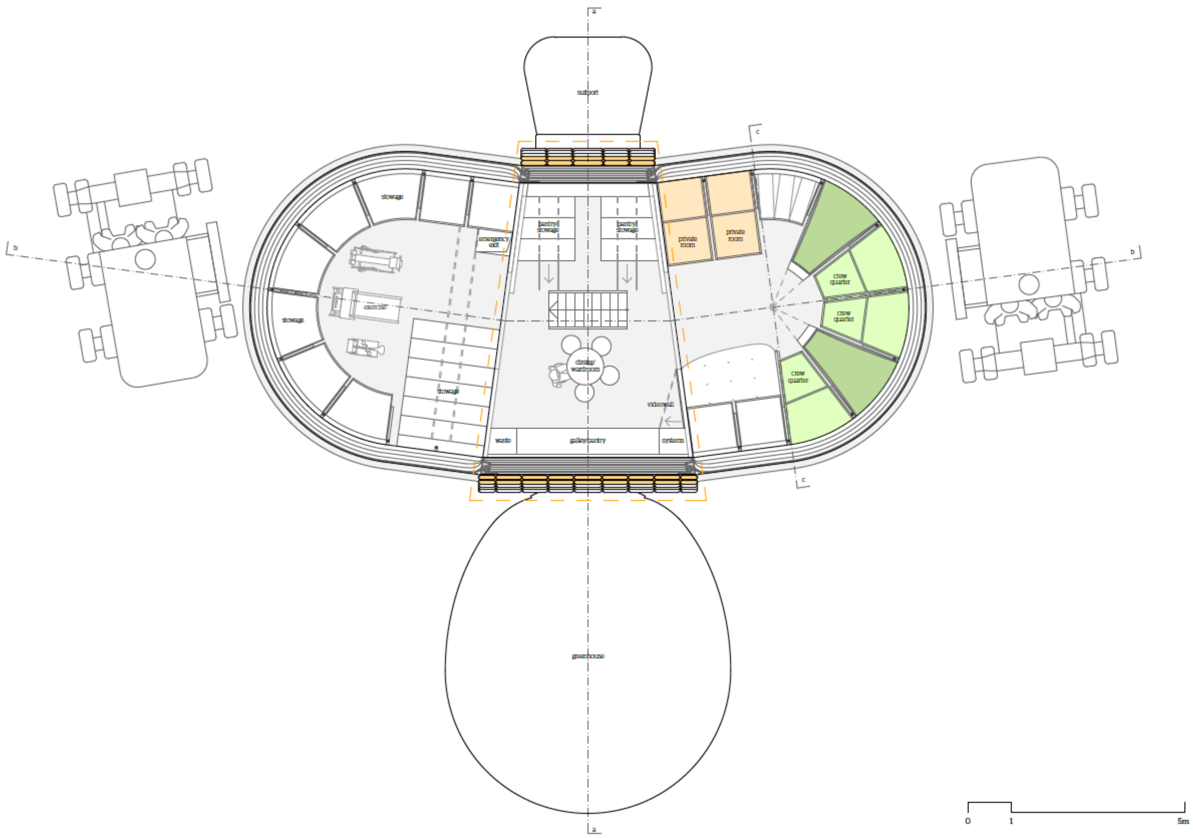

Figure 4. Habitat design for Phase 1 – Level 3. *Floor plan of the middle level of the habitat, showing the wardroom and galley in the middle, stowage and exercise facilities on the left and crew quarters on the right.*

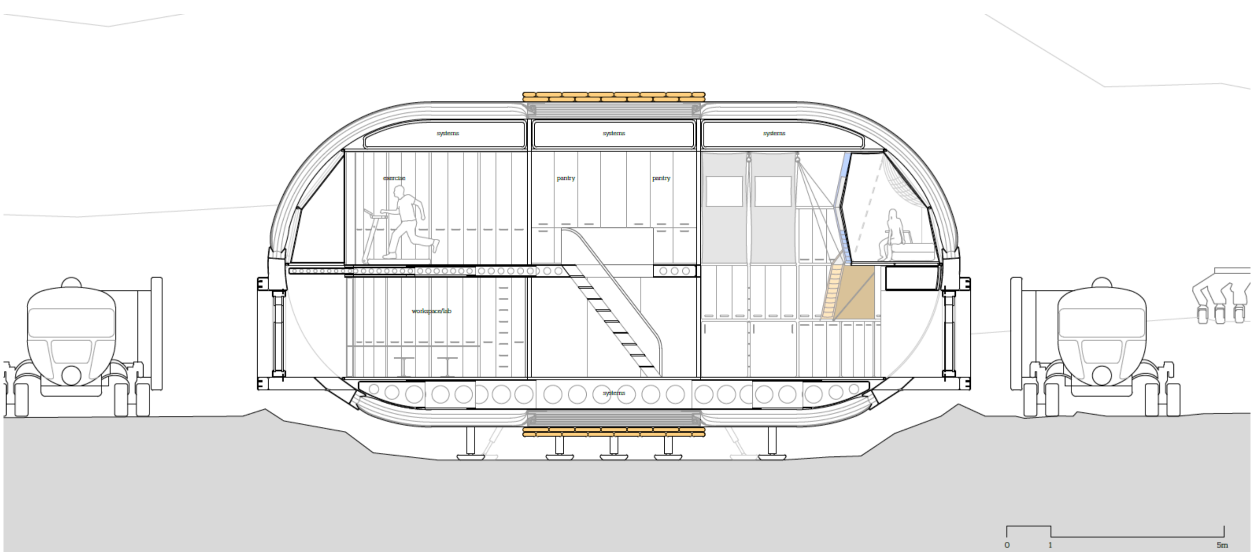

Figure 5. Habitat design for Phase 1 – Section. *Section through the length of the habitat, showing the laboratory and workstations and the exercise and stowing facilities on the left, the safe haven with wet rooms and galley in the middle, and a more open configuration of the kit-of-parts structure (Figure 6) in the crew quarters on the right.*

Figure 6. Concept for the Kit-of-Parts Mounting Structure with Crew Quarter Module. *This system is featured in the interiors of the inflatable parts of the habitat. It increases flexibility in the interior and allows the crew to adapt the configuration to their own needs. Crew quarter modules have interior windows with blinds to regulate social interaction. The modules can change their positions according to the preferences of the user. Additionally, the structure also provides private units for temporary use (for daydreaming, reading, recording private messages for family and friends, etc.), and open platforms under the top window (for socializing, stargazing, etc.). In phase two, this system opens up the possibility to interchange functions with the two other habitats.*

E. Phase 2

1. Overview

If it has been established at this stage, that further human exploration and settlement of Mars is reasonable and viable, three new crews of five will leave Earth while the first Mars-crew is on its way back. On arrival in Martian orbit, they will enter the descent modules and land on the planet. Also, like in the previous phase, cargo will be lifted off Earth in early 2035 in anticipation of the crew to follow (Figure 2 – Phase 2).

Each of the three new crews to land on Mars will have their own habitat and specialty (ISRU, biology/agriculture, geology). Each crew will have one habitat, but it will be possible, to change functions of the habitats and use them communally. E. g. if the astronauts decide, they want a stronger separation between work and crew quarters, they could all put up their quarters in one habitat and use the other two for work/laboratory and other activities. To facilitate rearrangement and enable the crew to configure the space according to their own living preferences, the habitats are flexible and adjustable. Reconfigurations can be made at any time.

Crew#1 will manage the ISRU production unit and will in its first configuration consist of two chemists, one materials engineer, one power systems engineer and one construction technician. Crew#2 will manage an experimental greenhouse and will comprise two biologists, one physiologist, one physicist and one power systems engineer. Crew#3 will consist of two geologists, one materials engineer, one mechanical engineer and one construction technician.

The habitats will be arranged around a central space that functions as an agora, so people from different crews will meet frequently (Figure 7-9). This central space can be used for meetings as well as recreational activities and exercise. This agora will help people on the base bond, especially with people from other habitats. It will also house a new large greenhouse for food production. People of every habitat will work at this greenhouse, so the potential for conflicts (e.g. about fresh food) is minimized. The small greenhouse of the first mission will be the new research greenhouse for the biologists. Besides the common food production, interdisciplinary projects can be helpful for group cohesion. The layout (e.g. docking positions of the habitats to the central hall) of this 'cluster-type' base is flexible and it is possible to add units (more external greenhouses, private space, workshops, common dining) later if necessary. Ideally, the ISRU production unit of the cluster will at some point be capable of making material for the inflatables to be used for such extensions in situ (polymer fibers as "by-product" of the Sabatier process[24]).

Configurations that work very well and are not probable to change, will become permanent. The inflatable will be used as formwork to be covered with "concrete" shells made of ground up regolith and a polymeric binder to act as added shielding. This process will be carried out automatically by one or both robotic rovers, which will be equipped with the necessary tools for this task.

2. Habitat Design for Phase 2

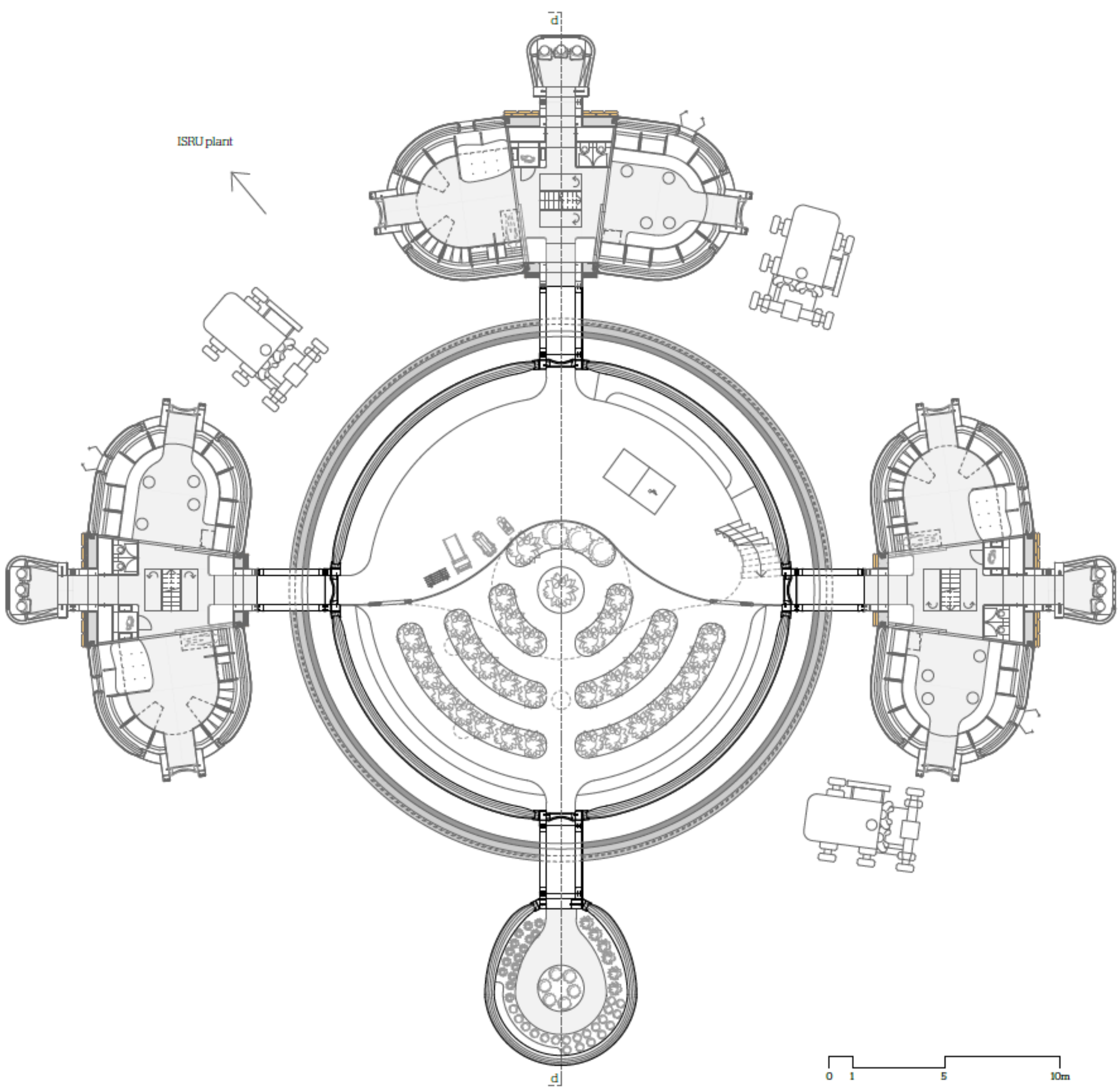

Figure 7. Configuration of Habitats in Phase 2 - Lower Level. *The original configuration provides each crew with one habitat of the same configuration, but functions in the inflatable parts of the habitats are interchangeable. The connecting inflatable includes a common greenhouse, generous exercise facilities and space for social interaction, common dining, workshops etc.*

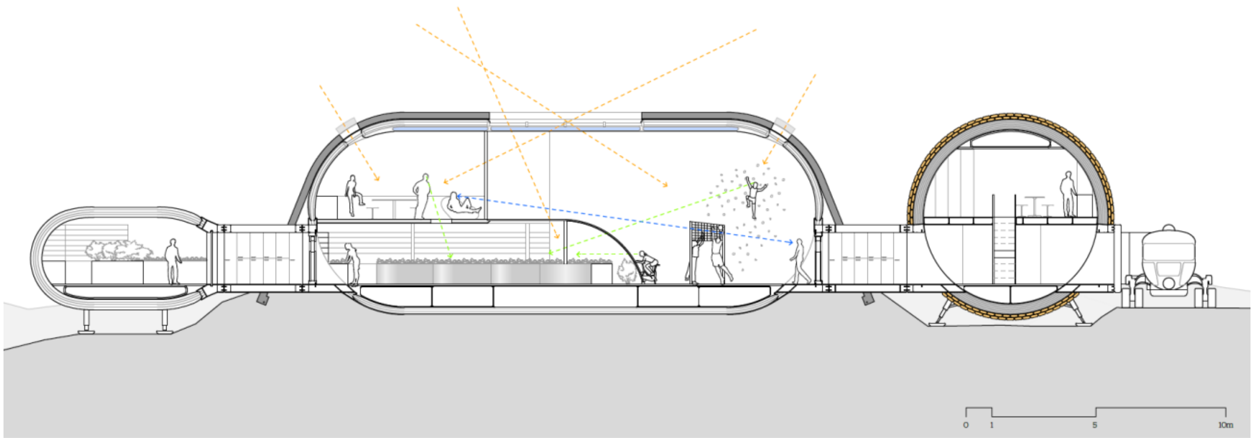

Figure 8. Base design for Phase 2 - Section. *Section through the central inflatable (middle - showing the greenhouse, exercise facilities and common area for all three crews), the experimental greenhouse on the left and one of the three habitats on the right. The central inflatable is protected by a "concrete" shell made of native regolith, basalt fibers and polyimide. The shielding of the rigid cylinder of the habitat on the right is increased by regolith-filled pillows that can be mounted on the outside.*

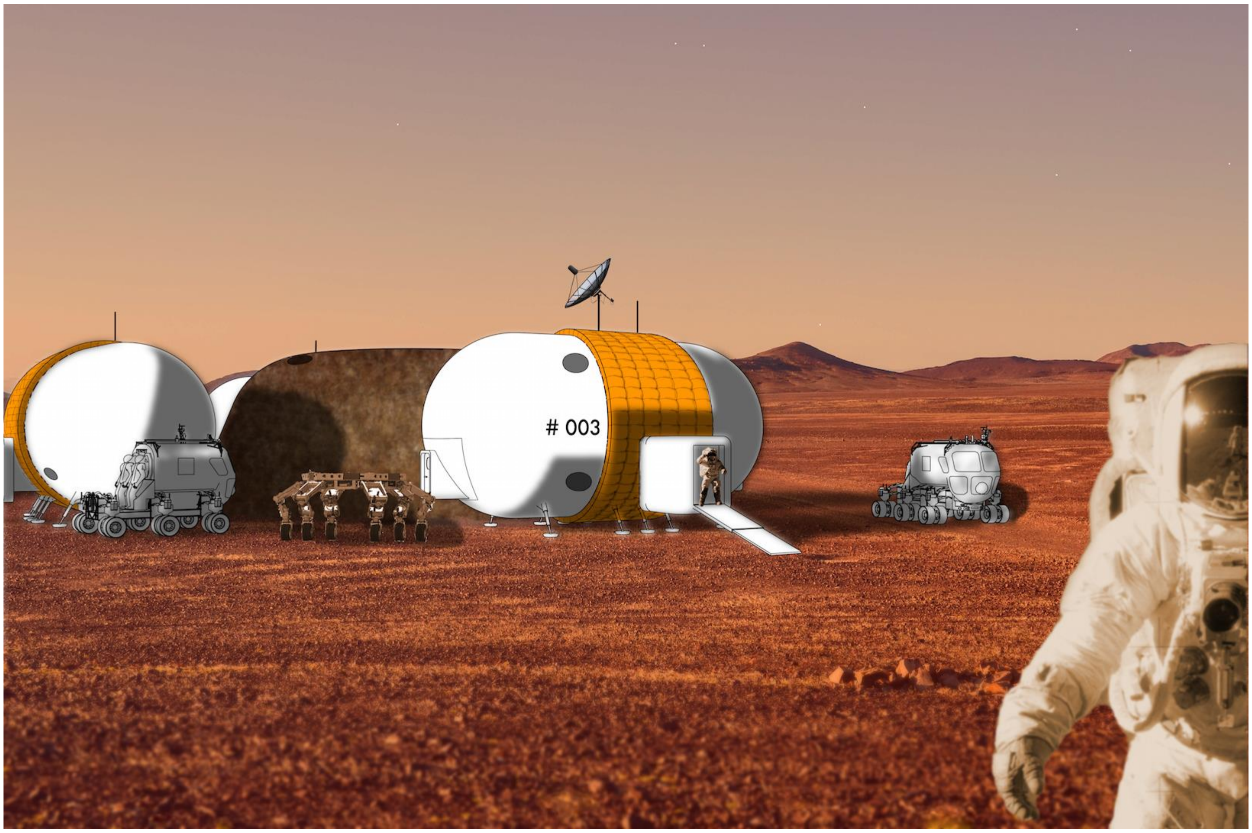

Figure 9. Visualization of Phase 2.

F. Phase 3 Outlook

If it is established, that: the base is working successfully and no hostilities have occurred, the base is strong enough to sustain itself and, in a potential emergency, even to take in refugees, more and varied clusters can develop. First those would be built in the vicinity of the base, but at later stages outposts in new, scientifically interesting places would be possible and increase scientific gain. From now on the settlement should evolve continuously and become increasingly independent from Earth.

In the far future, this phase should culminate in the settlement reaching autarchy from Earth and becoming a self-sufficient colony.

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