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HABITAT ON MARS

BUILDING AUTONOMOUS LIVING UNITS IN EXTREME CONDITIONS

INIMASULA MARSIL - AUTONOOMSETE ELAMISÜKSUSTE EHITAMINE EKSTREEMSETES TINGIMUSTES

Master thesis

Student / Anna Solts
Supervisor / Jaan Kuusemets

Tallinna Tehnikaülikool
Inseneriteaduskond
Ehituse ja arhitektuuri instituut

Tallinn 2021

EESSÕNA

Käesolev magistritöö on koostatud Tallinna Tehnikaülikooli Inseneriteaduskonna arhitektuuri eriala integreeritud õppe raames.

Soovin tänada kõiki, kes käesoleva magistritöö valmimisele on kaasa aidanud. Tänan oma juhendajat Jaan Kuusemetsa, inspireerivate mõttevahetuste, nõuannete ja julgustuse eest magistritöös.

Rohkete nõuannete ja tagasisidega olid väga abiks magistritöö koostamisel Jelena Kazak, Marta Volchek ja Ervin Golvih.

Lisaks tänan oma perekonda, kelle toetus on olnud väga oluliseks kogu protsessi vältel.

ABSTRACT

The field of space architecture is novel and challenging. As two large companies - NASA and SpaceX, are currently actively working on planning Mars missions, it is safe to say that new space race has begun. Launch windows to Mars only open every 2 years, therefore the first manned mission is inevitably going to be long-term, which means that colonization of Mars is going to happen within our lifetime.

In the current planning of Mars mission, the focus lies on technological aspects and the process of getting to Mars. But as these fields pave the way for Mars to become an opportunity for exploration and basically the dates for Mars missions are set, there is still a huge gap in the field of Martian architecture and design (Welch 2020).

The building process of the habitats needs to be as independent from Earth as possible, considering the travel time (6-8 months) and communication delays (between 3-22 min). Therefore, it is important to create a design with an emphasis on efficient construction method.

The requirements of habitat for human Mars mission have always been extreme and efficiency-oriented, but recently the human-centric experience is being highlighted. Studies have concluded that natural light and engaging environment are crucial to human mental health. This is the part where architects and designers are needed to get involved.

The main objective of this master's thesis is to explore the methods of building an autonomous habitat on Mars which not only protects the inhabitants from Martian extreme environment, but also considers human comfort. The analysis of several methods has indicated that mycelial-based construction complies to most necessities that are set for the Martian habitat, therefore it was selected within the framework of the architecture project.

Based on the study, an autonomous habitat has been designed on Erebus Montes, a location in the northern hemisphere of Mars.

Keywords: architecture, space, Mars, habitat, Master Thesis

ANNOTATSIOON

Kosmosearhitektuuri valdkond on uudne ja väljakutseid täis. Kaks suurt ettevõtet - NASA ja SpaceX tegelevad aktiivselt Marsi missioonide kavandamisega ning võib kindlalt öelda, et uus kosmose võidujooks on alanud. Reisiaken Marsile avaneb ainult iga 2 aasta tagant, seetõttu on esimene inimmissioon vältimatult pikaajaline, mis tähendab, et Marsi koloniseerimine toimub meie elu jooksul.

Praeguses Marsi koloniseerimise arutelus keskendutakse peamiselt Marsile jõudmise teaduslikele ja tehnoloogilistele aspektidele. Need väljad annavad teed Marsi uurimisvõimaluseks ning põhimõtteliselt on Marsi missioonide kuupäevad paika pandud, kuid Marsi arhitektuuri ja disaini valdkonnas on endiselt suur lõhe (Welch 2020).

Marsi asulate ehitusprotsess peab olema võimalikult sõltumatu Maast, arvestades pikaajalise reisi kestvust ja aeglast kommunikatsiooni vahetust. Seetõttu on oluline, et ehitusmeetod oleks autonoomne.

Nõuded Marsile projekteeritava asulale on alati olnud rõhuasetusega efektiivsusele: luua võimalikult madala hinnaga elujõulise keskkonna. Kuid viimasel ajal on üha rohkem esile tõstetud visuaalse kommunikatsiooni olulisust mugava ja töö- ja elukeskkonna loomiseks teadlasmeeskonna jaoks. Mitmed uuringud on jõudnud järeldusele, et loomulik valgus on inimese vaimse tervise jaoks ülioluline, eriti ekstreemsetes oludes. Kvaliteetse elukeskkonna tagamiseks on oluline kaasata arhitekte.

Selle magistritöö põhieesmärk on uurida Marsi autonoomse inimasula rajamise meetodeid, mis mitte ainult ei kaitse teadlasmeeskonda Marsi ekstreemsest keskkonnast, vaid võtab arvesse ka inimeste heaolu. Mitme meetodi analüüs on näidanud, et mütseeli- (seeneniidustiku-) põhine ehitusviis vastab enamusele Marsi elupaigale seatud vajadustele, seetõttu valiti seda ehitusmaterjaliks arhitektuuriprojekti koostamisel.

Uurimusele tuginedes on käesoleva arhitektuuri eriala magistritöö ülesanne kavandada Erebus Montes alal autonoomset elamisüksust teadlasmeeskonnale.

Võtmesõnad: arhitektuur, kosmos, Marss, asula, magistritöö

CONTENTS

1 INTRODUCTION

1. INTRODUCTION

1.1. Context

„The Earth is the cradle of humanity, but mankind cannot stay in the cradle forever" - Konstantin Tsiolkovsky.

Humans have always been interested in exploring the unknown, pushing the boundaries of scientific and technical limits. Exploring the space helps to answer fundamental questions about our place in the Universe and the history of our solar system and beyond (NASA 2013). Due to the specialized technology needed to explore space, scientific advancements are often made while developing these tools. Exploration is not just about curiosity, it is a necessity for advancement.

Although, half a century has passed since humans left footprints on the Moon, the interest in the space exploration has been renewed by high levels of private funding, advances in technology and growing public-sector ("Space: Investing in the Final Frontier" 2020). Two large companies are currently focused on manned space missions: NASA and SpaceX.

The National Aeronautics and Space Administration (NASA) has announced its Journey to Mars program in 2015, with intention to send the first humans to Mars by the year 2030 for expanding the human knowledge of the Universe, of the planet Mars but also of our own planet (Mahoney 2015). In order to advance the construction technology for Martian housing, NASA held 3D-Printed Habitat Challenge, which was completed in 2019. NASA's recent achievement was the 2020 launch of its Martian Perseverance rover which was sent to explore the past habitability of Mars and test the technology for oxygen generation from the Martian carbon-dioxide atmosphere (NASA 2021).

SpaceX is a private company which has a goal of making life multiplanetary and launch the first manned Martian mission in 2026 (Sissi Cao 2020). The greatest achievement of SpaceX is lowering the cost of the space launch industry by inventing first reusable rockets. Currently SpaceX is developing a first fully reusable transportation vehicle for Moon and Mars missions – the Starship. On April 2021 NASA announced they have selected Starship to land the first astronauts since the Apollo program (1972) on the lunar surface as part of the Artemis mission, which goal is to send humans to the Moon by 2024 (Lopatto 2021). Recently, on May 5th, 2021, a Starship prototype has successfully completed SpaceX's flight test and safe landing for the first time (SpaceX 2021).

As interest in the space progressively grows in recent years, and the economic implications of space exploration expand into new industries, there are huge opportunities for the architectural and engineering field. The prospect of building habitats in space has become a real possibility and in the coming years it is likely for space architecture to become a fast-growing industry, and its professionals will be in high demand (Williams 2020).

Today, as the topic of interplanetary travel is gaining traction, there is a shift happening in the space architecture profession. Traditionally, space architect was equal to a systems engineer, but currently, space companies are recognizing the importance of design, as it supports wellbeing of people, which is critical in long space missions (Williams 2020).

1.2. Problem statement

The mass is needed to protect habitants from Martian harsh environment. The habitat should protect from radiation, extreme temperatures, dust, and the surrounding (non) existing atmosphere (van Ellen 2018). The habitation system, together with assembling robots and life support systems should make the most efficient use in terms of mass.

Currently, the main issue companies are working on is minimizing the cost of space transportation; SpaceX is able to send payloads to Mars for 5,357 $ per kg, using their Falcon Heavy rocket, which is an improvement since Falcon 9 performance- 15,422 $ per kg (SpaceX n.d.). Therefore, the main goal of space architecture is to create such design for habitats, that would minimize payload while ensuring the psychological comfort for humans to be able live and work in space.

As it is impractical to bring mass from Earth, the use of autonomous building methods and local materials is crucial to sustainable Mars mission.

1.3. Objectives

The main objective of this master's thesis is to explore the methods of building an autonomous habitat on Mars, which not only protects the inhabitants from Martian extreme environment, but also considers human comfort. Based on the study, the vision of Martian habitat is designed.

1.4. Approach and Methodology

In this thesis, reasons for colonizing Mars and current Mars mission program have been discussed, Martian environment and its conditions have been analyzed with a literature study approach. As a case study several existing Martian habitat projects and concepts have been evaluated.

1.5. Research contents

Master thesis consists of two parts- theoretical research and an architectural project. The theoretical part gives an overview of Martian environment as a building site, building technologies, available local materials, and the current approach through the analysis of various reference projects. In the second part, an architectural design solution is presented, where an autonomous habitat is designed based on the conclusions made in the theoretical part.

2 DESTINATION - MARS

2. DESTINATION – MARS

2.1. Why Mars?

Humans are exploring species, which is what made us dominant on this planet. We love a target – something to shoot for, to aim for, build a plan to make it happen. Today, almost an entire planet Earth has been colonized by humans. Curiosity has fueled most of the great achievements that humans made in the world, especially trough technology. Considering such idea, the question inevitably arises as to what will be the next step for exploration?

Elon Musk, founder of SpaceX, believes that history is going to bifurcate along two directions. One path is that humans stay on Earth forever and then eventually history suggests there will be some doomsday event. The alternative is to become a space-faring civilization and a multiplanetary species (Musk 2017) This is what humans do – explore, therefore going to space is an obvious next step, and many space agencies hope that is the right way to go.

Why Mars? According to aerospace engineer and author Robert Zubrin, there are three reasons why humans should go to Mars: for the science, for the challenge, and for the future (Jorge Salazar 2011).

First, by exploring the surface of Mars could determine if life is a general phenomenon in the universe or if it is a phenomenon unique to the Earth. Scientist are convinced, that Mars once had liquid water on its surface. Therefore, life should have existed on the Red Planet, even if it's subsequently went extinct. It means that, if the fossils of past life will be found, the development of life as a general phenomenon in the universe will be proven. Or alternately, if plenty of evidence of liquid water will be found, but no evidence of fossils or development of life, that would mean that the development of life from chemistry is not a natural process that occurs with high probability, but includes elements of freak chance, means that Earth could be the only living planet in the universe. The role of life in the universe is a fundamental question of science, which is could not be answered by going to the Moon, for example.

Secondly, the challenge of going to Mars would enormously benefit society, by investing in intellectual capital. Out of this challenge, society will get millions of scientists, engineers and researchers. Going to space changes a perspective about the Earth. Exploring space gives an opportunity to address fundamental issues on earth, by giving people something optimistic to pursue. Humans are currently in a phase of solving the problems of our own planet. But at the same time, there are problems that may have a solution when exploring space and through that make discoveries, which would be helpful on in solving the problems on Earth.

Finally, space exploration is the future. Mars is the closest planet that has many resources needed to support life and therefore civilization. Colonizing Mars will let humans become multiplanetary species and open new world for exploration (Jorge Salazar 2011).

It is clear that the colonization of Mars will certainly take place during our lifetime; not necessarily in a way of sending thousands of people to space, but in sense of establishing an outpost, like in the Age of Discovery (15th-18th century), when explorers established outposts with a mission to provide a presence, so next explorers can reach it.

Building living spaces on Mars cannot be left to chance, as the journey to Mars is risky and costly, so it is important to define a way of how to integrate technical knowledge and space quality when creating habitation in extreme conditions to ensure a good living environment for people on Mars.

2.2. Planet Mars – general information

To properly understand the Martian environment, a further in-depth analysis is made.

The planet was formed 4,6 billion years ago along with the rest of the solar system. Mars is the fourth planet from the Sun and is situated at an estimated distance of 54,6 million kilometers from Earth.

Like Earth, the planet has a solid inner core, a mantle, a crust and an atmosphere. Mars gets its red color from the rusting iron present in the rocks and dust forming the crust (Foley et al. 2008). Martian atmosphere is mostly CO2 and it is very thin, less than 1% of Earth's. Scientists believe that Mars once had an atmosphere similar to Earth's, and even had water lakes and warmer weather.

Launched in 2011 NASA's Curiosity Rover has provided plenty of apparent evidence that Mars even may have hosted life before (Voosen 2018). The potential evidence was found in Martian soil, which contained a combination of specific molecules, that could have supported the formation of life. There is no exact confirmation if Mars have been once habitable, but many facts indicate the possibility (NASA 2013).

Earth and Mars have quite many things in common. The area of Mars is 145 million km2, which is approximately equivalent to the area of the Earth's land mass. Thanks to similar rotation speed Mars has almost the same 24-hour cycle, which means that all biological species that have accustomed to Earth's cycle are going to function fine on Mars. Mars has the same seasonal tilt of 25 to our planet's 23 degrees, so there are similar four seasons and temperature variations as we have on Earth. Both are rocky planets with metallic cores and similar mineral composition, they have similar surface structures including mountains, canyons and deserts (NASA n.d.).

	EARTH	MARS
Average Distance from Sun	93 million miles	142 million miles
Average Speed in Orbiting Sun	18.5 miles per second	14.5 miles per second
Diameter	7,926 miles	4,220 miles
Tilt of Axis	23.5 degrees	25 degrees
Length of Year	365.25 Days	687 Earth Days
Length of Day	23 hours 56 minutes	24 hours 37 minutes
Gravity	2.66 times that of Mars	0.375 that of Earth
Temperature	Average 57 degrees F	Average -81 degrees F
Atmosphere	nitrogen, oxygen, argon, others	mostly carbon dioxide, some water vapor
Number of Moons	1	2

Figure 1. Mars compared to Earth (NASA)

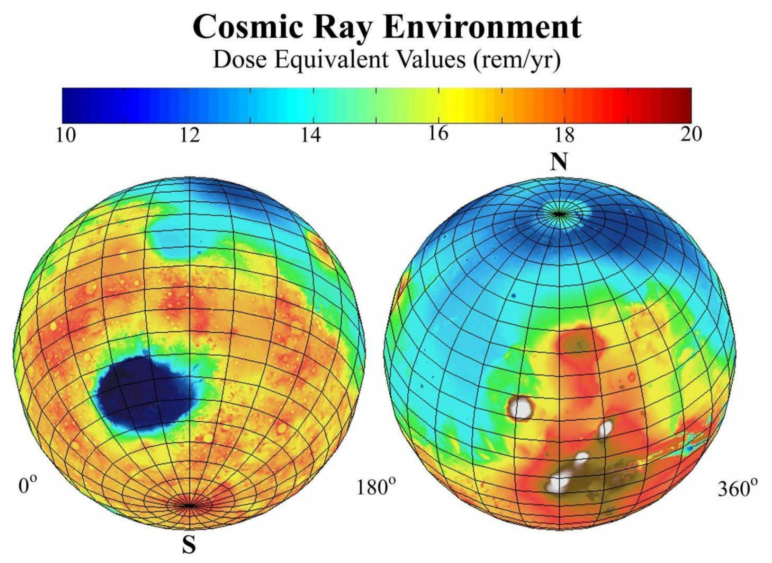


Figure 2. Effective radiation dose rate on the surface of Mars (NASA)

The main environmental factors that would influence the architecture of Martian habitats are following.

2.2.1. Radiation

Mars has a magnetic field which is less extensive than that of Earth because Mars has no inner dynamo to create this field. Therefore, the Martian atmosphere is also less thick than that of Earth with a gravitational force of 3,711 m/s2 (van Ellen 2018). This thin atmosphere protects against small asteroids and large temperature fluctuations but doesn't protect against radiation and large celestial objects. It means that most of the solar radiation on Mars reaches the surface, which is one of the most serious challenges for space exploration due to the health problems it causes. There are two main types of harmful radiations which can have a dangerous impact on humans: the Sun's and cosmic radiation.

The most dangerous radiation is solar radiation. It is created by a stream of highly charged particles, mostly protons and alpha particles, which moves with enormous speed from the Sun to the external surface of our Solar System (). Fortunately, waves of such radiation reach Mars rarely, and they are not so intense each time. The most intense waves of this radiation are strictly connected with solar flares, and as having been under astronomers observation for many a year, they are now more predictable (Behrens 2019).

A cosmic radiation consists of highly energized ions. Its intensity is much lower, but it is still very dangerous for humans, because it constantly bombards the surface of Mars. The dosage rate is expressed in rem. Humans on Earth are being radiated with it only with a fraction of rem per year. During one solar flare (one time event) about 10 rem of radiation may reach Mars. A similar dosage of cosmic radiation is observed after a yearly exposure there (Badhwar 2004)neutrons, and heavy ions, are pre-requisites for human exploration. The MARIE experiment on the Mars-01 Odyssey spacecraft consists of a spectrometer to make such measurements in Mars orbit. MARIE is measuring the galactic cosmic ray energy spectra during the maximum of the 24th solar cycle, and studying the dynamics of solar particle events and their radial dependence in orbit of Mars. The MARIE spectrometer is designed to measure the energy spectrum from 15 to 500 MeV/n, and when combined other space based instruments, such as the Advanced Composition Explorer (ACE. Such a dosage is concerned as a cause of cancer, the same as smoking is. Radiation causes mostly damage to human tissues and/or organs and the effect depends on the specific tissues and organs exposed as well as the radiation source, the amount of radiation and the exposure time (McPhee and Charles 2009).

Despite popular misconceptions, Mars is not rendered utterly inhospitable by cosmic radiation (Zeitlin 2004). However, to avoid long-term health concerns, appropriate shielding must be provided to reduce exposure by 80% in order to fall within terrestrial safety limits.

Influence on the architecture

- The amount of light reaching Martian surface is limited. The challenge is to provide as much sunlight as possible to achieve physical comfort for the habitants, but also protect them from radiation.

- Due to constant exposure of cosmic radiation, the protective barriers will be needed to be constructed inside the habitat structure. Although they are not required for every part of interiors, as cosmic radiation is less harmful.

- Additional purpose-based protective shelters should be incorporated in the design, to protect from solar flares, that may occasionally happen.

- It is important to consider influence the dosage of radiation reaching the surface when selecting a landing site.

2.2.2. Weather

Mars is drastically colder than Earth, averaging- 60°C with brutal lows of - 125°C in the winter and highs of 20°C in the summer on the equator (Sharp 2017). The planet can't retain heat, because of its thin atmosphere.

Because Mars is further from Sun than Earth, solar power is not as effective. Martian dust storms can last for more than 3 sols (days on Mars), hiding the sunlight and casting shadows (Landis et al. 2013).

However, it is unlikely that these storms will be dangerous to the astronauts nor the large technical equipment. The strongest winds on Mars are 90 km/h, but because of the difference in atmospheric density it is hard to compare wind speed. For example, to break an umbrella on Mars, the wind would need to blow much faster than on Earth (Hille 2015).

The bigger concern is Mars' dust. The particles of dust on Mars are dry and electrostatic, which means that they will stick to everything, like spacesuits, external layer of habitat, equipment etc (Hille 2015). It has been found that Martian soil is filled with extremely toxic elements for humans (Leonard 2013). Constant exposure could lead to fatal outcome and it would be impossible to avoid carrying it inside of the habitat. This problem can still be conquered by having spacesuits always connected to the outside of the habitat.

The southern hemisphere of Mars experiences the most temperature differences, because Mars's going around the Sun in an elliptic way. Less significant temperature differences are detected on the equator, where charts of yearly temperatures fluctuations similar to the ones in Earth cities (picture) (Kozicka 2008).

It can be observed that the closer to the equator, the more stable temperatures are.

Influence on the architecture

- The external layer (especially windows) of the habitat should be smooth, to prevent dust from covering and damaging it.

- The entry should be designed in a way that spacesuits never get inside the habitat.

- The challenge is to protect habitats from low temperatures, as well as their seasonal changes.

- Construction of the habitat should be resistant to the low and changing temperatures.

- The landing site should preferably locate in place close to equator, where changes in temperature are small.

- Solar power alone will not be enough to provide energy for the habitats. Wind power plants are unreasonable, as Mars lacks atmosphere and the winds are not that powerful to use them for energy production.

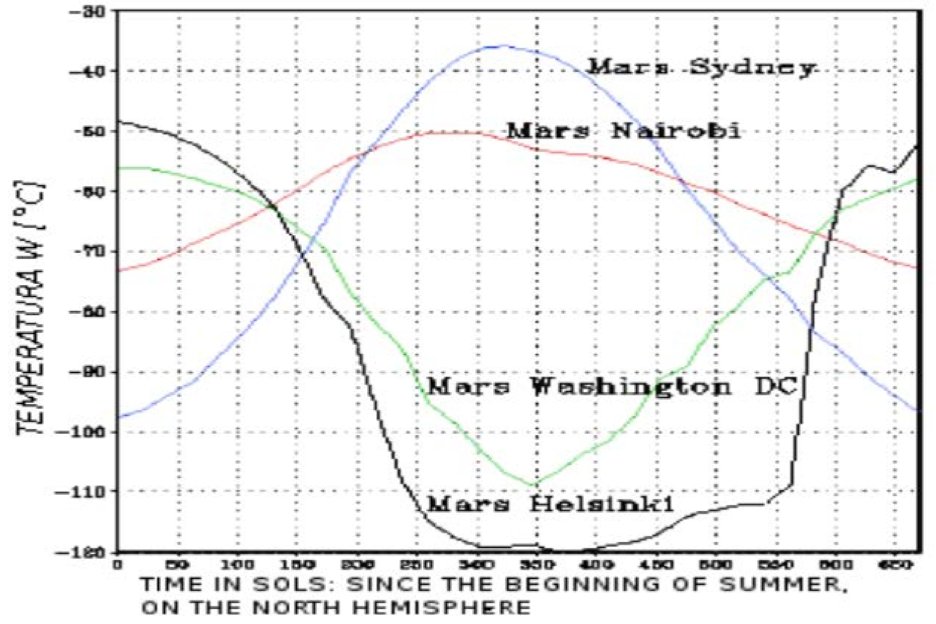


Figure 3. Yearly changes of Martian temperature on latitudes similar to cities on Earth (Mars GCM Group)

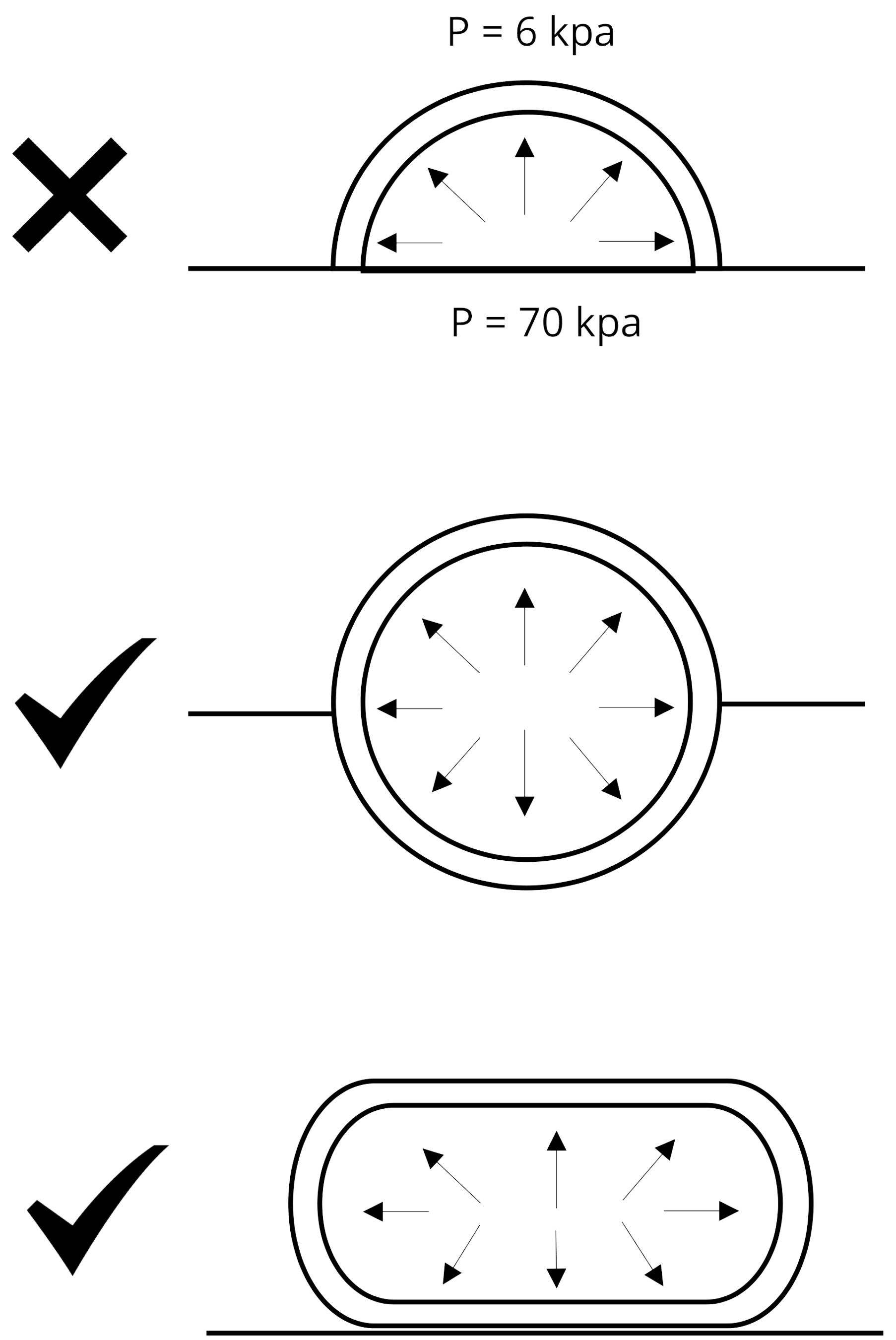


Figure 5. Smooth shapes handle pressure better

2.2.3. Atmospheric pressure

Martian atmosphere is very thin and mostly consist of CO2. It's low density also influences a very low atmospheric pressure. The average pressure is 610 Pa (NASA 2020), and it is less than 1% of the Earth's pressure (101,325 Pa). The density of the atmosphere is higher on the equator. If any changes in temperature occur, Martian atmosphere reacts rapidly, leading to pressure fluctuations. Daily temperature changes in the atmosphere cause the process of cyclical carbon dioxide sublimation and condensation. Carbon dioxide in state of gas drifts up and mixes with the atmosphere causing its higher density and higher pressure. The warmer day, the more carbon dioxide sublimates, and the higher the pressure is (Kozicka 2008).

Influence on the architecture

- Habitats must be hermetic and pressurized. Filled with oxygen.

- Flat walls and corners are weak points because of the low pressure, and will need heavy constructions to balance out the forces. Rounded and smooth shapes will handle the pressure better.

- Pressure will be one of the biggest forces that influences how structures will look and work. The material used for habitat structure should be very strong to hold against outwards pushing interior pressure.

2.2.4. Gravity

Gravity on Mars is only 3,711 m/s2, it's only 1/3 of Earth's (9,807 m/s2). Low gravity could cause cardiovascular problems and bone loss. Members of the crew should exercise a lot to slow the degradation down (NASA n.d.).

Influence on the architecture

- Lower gravity will influence the ergonomics, which should be taken in consideration during building process. It will also allow for new ways of moving inside of the habitat.

- Gym should be incorporated in the room program for the habitat.

2.3. Mars space program

Building on Mars is quite a challenge. Two large companies focusing on Mars exploration are NASA and SpaceX. For this master thesis, the plans of SpaceX were taken as a base program. Space missions include different specifics and technological aspects that need to be considered while designing a habitat on Mars.

2.3.1. Mars entry

Mars' distance from Earth varies as solar system is in constant movement. The longest distance is 401 million km and shortest is about 54,6 million km (van Ellen 2018). Some launch dates are better in order to reduce the time span of the travel. This travel window opens roughly every two years (26 months) (NASA/JPL 2016). This means that first Martian settles need to stay on the planet until new travel window opens, and if the in case of emergency, Earth would not be able to help.

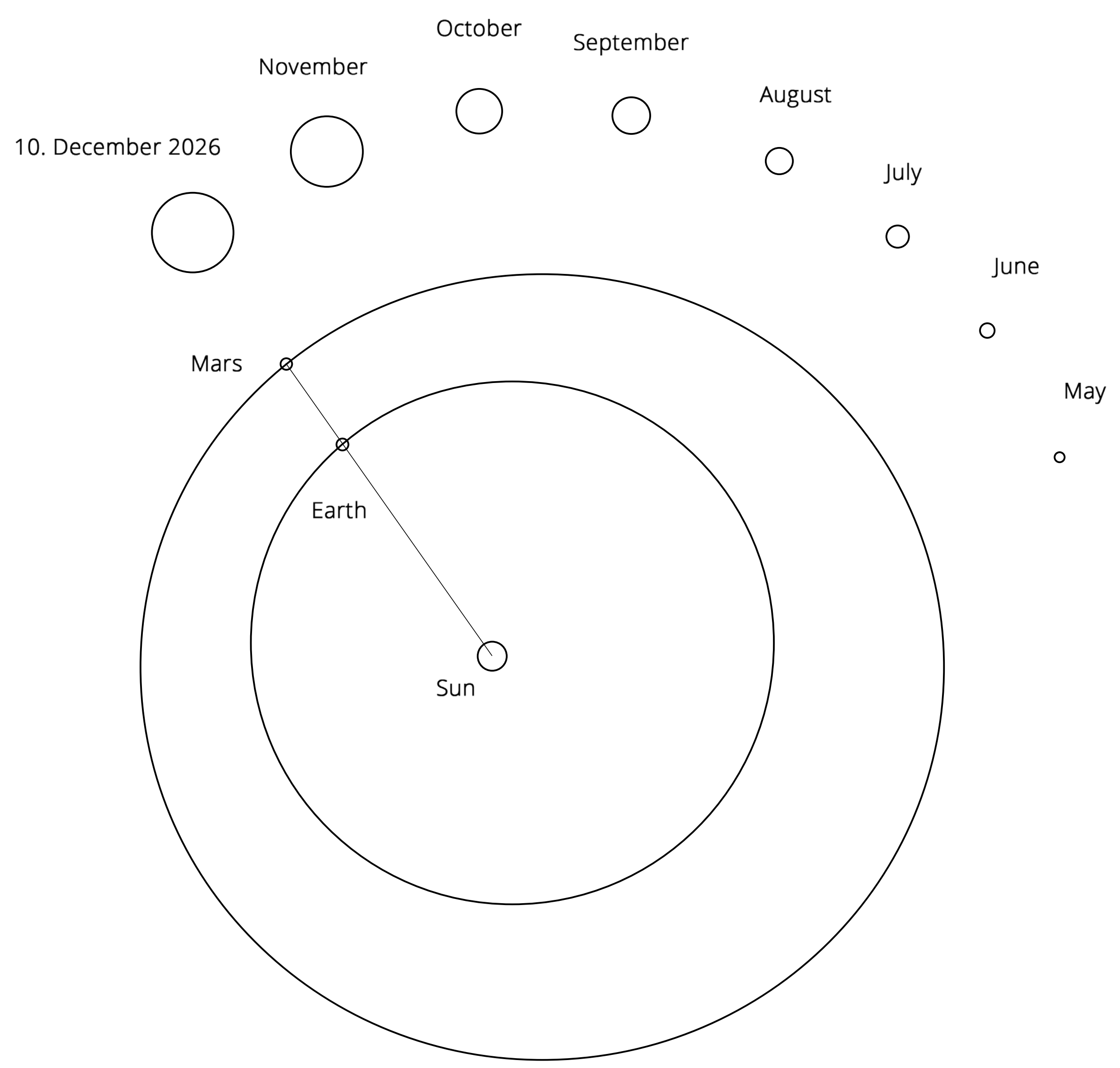


Figure 6. SpaceX is planning first Mars missions in 2026, and the time travel window will open in December.

Figure 7. Starship and Super Heavy (SpaceX Starship users guide)

SpaceX is planning to use Starship transportation system for Mars missions. It is a fully reusable vehicle, which is composed of the Super Heavy rocket (booster) and Starship (spacecraft) powered by sub-cooled methane and oxygen (SpaceX 2020). Starship is capable of carrying 100 people and hold a payload up to 150 metric tons.

2.3.2. Mars mission goals

First cargo missions are targeted in 2025. The plan is to send at least two spaceships to orbit, refill the tanks, and then they'll travel to Mars and land. The goal of the mission will be to confirm water resources on the site and place power, mining and life support infrastructure for future flights (Musk 2017). The population on Mars will be made entirely of robots. The cargo ships will deliver life support systems, solar panels and maybe even the first habitation pods, which would be autonomously constructed prior to crew arrival. Existing rovers could flatten the surface, to prepare a flat landing area. It will increase the safety for the next landings, by reducing the kick-up of dirt and rocks.

As first order business will be to start building a propellant production plant needed for return fuel and oxygen, robots will confirm the exact location and run some tests. Mars has a CO2 atmosphere and plenty of water ice available. Using the Sabatier Process, ice water is mined and refined, CO2 is drawn from the atmosphere and then with heat and pressure CH4 and O2 are created and stored (Musk 2017). Similar process has already been tested on Mars by Perseverance rover: it produced oxygen from CO2 atmosphere using solid oxide electrolysis (Potter 2021).

New launch window opens after two years and four ships carrying astronauts and cargo land on Mars. With six ships on the site there will be plenty of mass to construct the propellant depot.

For some period the crew may have to live in their ships. When the construction of the habitats will be completed and safe environment confirmed, the crew will move in and start testing the fuel, cultivate the Martian soil and start growing plants, that were genetically engineered to grow on Mars (Candanosa 2017). After two years one starship launches heading back to Earth.

Influence on the architecture

- Heavy objects are difficult to send to space. Lightweight structures are cheaper to transport.

- Design of the habitat will be influenced by the program of the mission, such as mass, power, time and number of settlers.

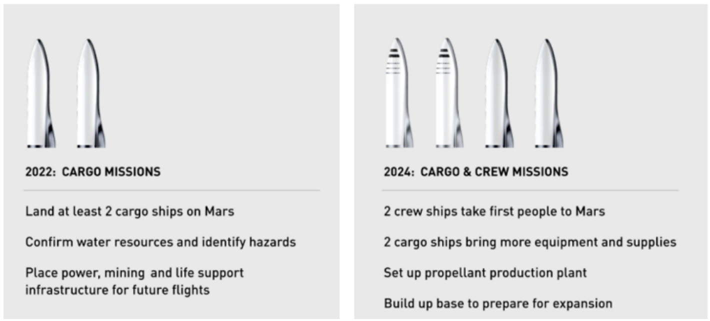


Figure 8. Initial Mars mission goals from 2017 (SpaceX)

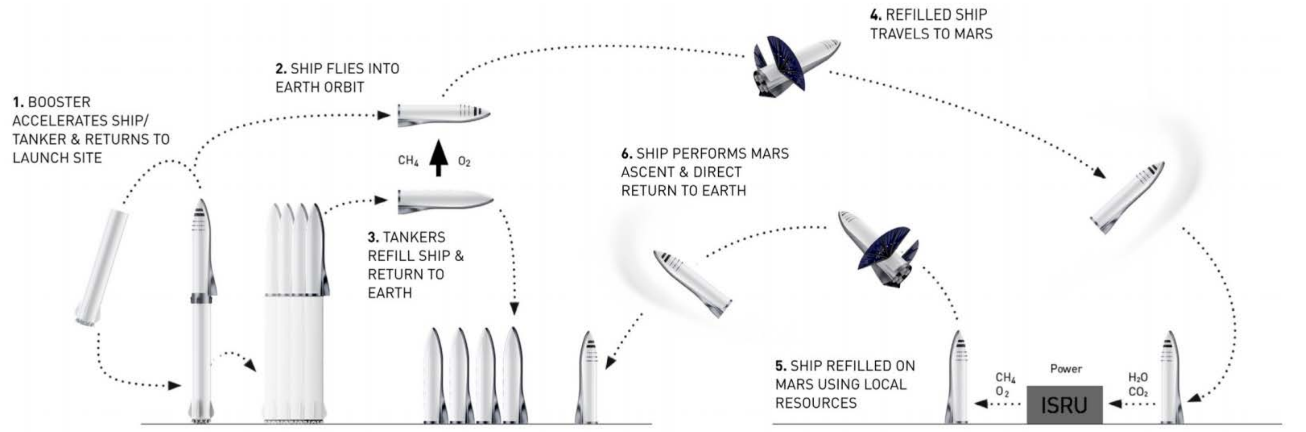


Figure 9. Mars transportation architecture (SpaceX)

2.4. Landing site selection

One of the first steps in designing a habitat on Mars is location choice. SpaceX considers following factors important in site selection:

SAFE LANDING

Landing on Mars is difficult due to its thin atmosphere. It is challenging to slow down the large spaceship so it would not smash into the ground. It is better to land at a low altitude (< 40°, lower is better) to take maximum effect of atmospheric breaking. The terrain should be relatively smooth and flat to reduce the kick-up of dirt and rocks.

USE OF RESOURCES

Site needs to be close to the points of interest, which should also be diverse and accessible. One of the main aspects in choosing a landing site is ice water accessibility, which is needed for fuel and oxygen production. There is definitely ice near the poles, but balancing that against power and thermal considerations, it is better to get down, closer to the equator.

DAILY LIFE

Landing site should be on the safe distance from pre-deployed structures. There should be multiple purpose-based locations within a few kilometers from each other. Temperature and weather are important factors as well. Building a colony is easier near the equator, where seasons are not so extreme, and solar panels can work.

(Wooster 2018)

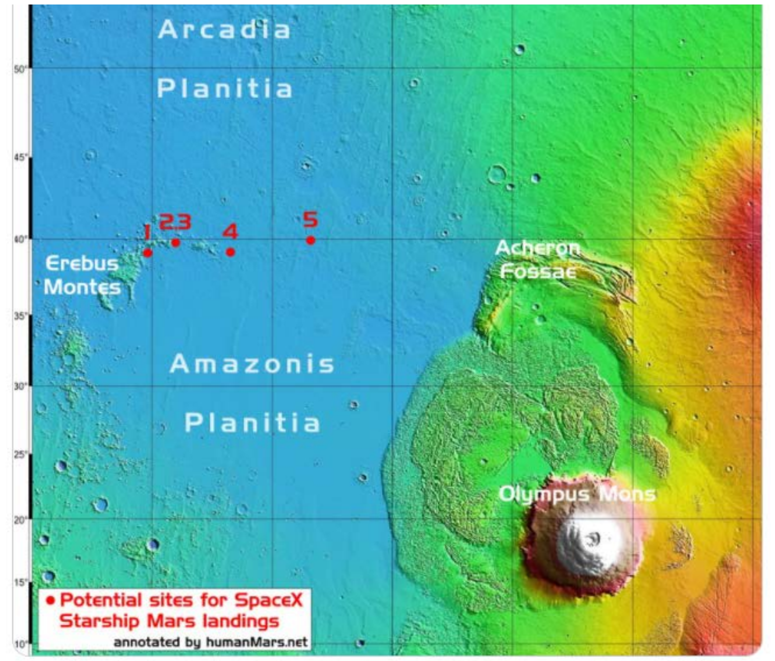


Figure 10. Potential landing sites for SpaceX (Young)

Possible landing sites for SpaceX's Mars mission have been revealed in 2019. The information has not been confirmed by SpaceX, but it seems that they are making some quiet decisions on the ideal landing site (Young 2019).

"SpaceX's current landing site candidates for Mars were shown, having been chosen to provide access to near-surface ice, few landing site hazards (such as large rocks), and enough space for potentially growing a sizeable outpost. The ice sites are in high mid-latitudes and the search for lower latitude candidates, which are preferred, continues." - Paul Wooster, SpaceX's principal Mars development engineer.

The emphasized regions are located on the border of Arcadia Planitia and Amazonis Planitia lowlands.

The main landing sites: Site 1, Site 2, Site 3, Site 4, and Site 5 are located in Arcadia Planitia (Young 2019). It locates in the northern hemisphere of Mars. It was formed by free-flowing lava flows around 3 billion years ago, making the regions among the smoothest on the planet. The soil in the region is rich in hydrogen, which suggests that the water ice is right below the surface.

A strong evidence for the presence of glaciers in Arcadia Planitia has been discovered in May 2021 (Pappas 2021). The location is broad and flat, which is ideal for landing. Most importantly, the area is likely to be ice-rich, so the astronauts could have a water source easily at hand. One more advantage is a mild climate of all of the locations, because they are roughly 40° latitude (Young 2019).

An attractive location nearby is Olympus Mons, the largest volcano in the solar system, which is an important point of interest for the scientists.

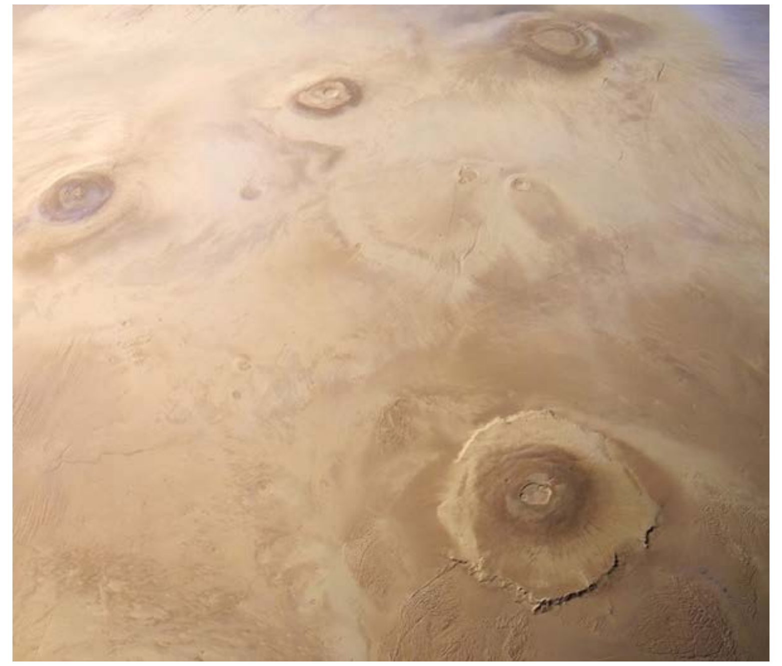


Figure 11. Olympus Mons (Cowart)

3 ARCHITECTURE ON MARS

3. ARCHITECTURE ON MARS

3.1. Concept of the habitat

Building a habitat on Mars is obviously very different from building on Earth. The main concept stays the same – habitat should protect people from harsh external environment. The influence of the environment on the architecture was elaborated in section 2.2.

Nevertheless, it is important to create a space, where it would be safe, but also exiting and comfortable to live in. The architecture should first and foremost serve people. Extreme missions cause great psychological stress, thus it is needed to avoid creating a cumbersome space, which is layered by heavy equipment; like in the International Space Station (ISS).

Studies show that natural light is beneficial to human mental health. Even though many experiments intended to replace sunlight with artificial lights, the results indicated that substitutes do not hold the same circadian variance or ability to balance a crew's mental and physical health as does experiencing the sun's actual and unmediated daily cycles (Edwards and Torcellini 2002). Habitants should have a visual connection with exterior.

The construction used to build the colony has a massive influence in this. Even in this kind of harsh Martial environment, there is not one answer to building strategy, only certain constraints due to the new environment - considerations such as material availability, pressure, radiation, and temperature influence all the design choices.

In the following paragraph there are analyzed several construction methods and materials, that are possible to use on Mars.

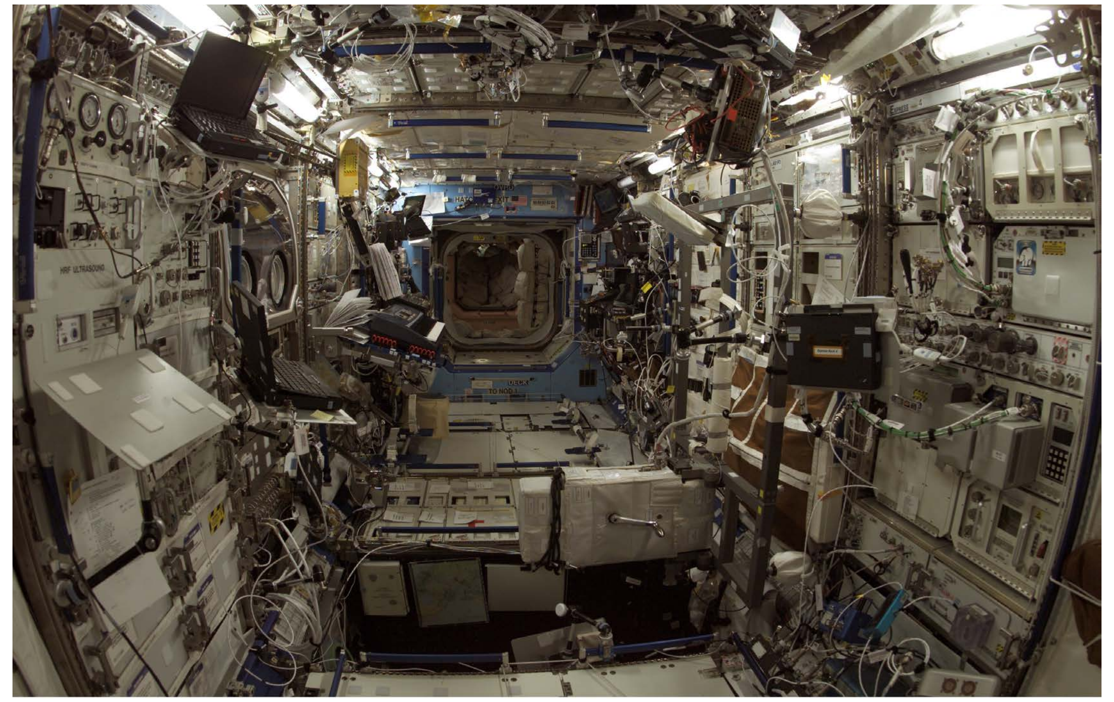


Figure 12. International Space Station (Google search)

3.2. Construction methods and materials

On Mars humans cannot rely on traditional construction methods, there will be no industries to supply building materials. Only few tools and basic valuable materials can be brought.

Some of the construction methods are:

TUNNELS

Tunnels or excavated structures in general will provide full protection, however, cover from daylight and views. Tunnels are energy and time consuming to build. Using Martian lava tubes as habitats is not very reliable, because they might collapse.

+	-
TOTAL RADIATION SAFETY	NO DAYLIGHT
TOTAL METEORITE SAFETY	NO VIEWS
BUILT OF LOCAL MATERIALS	TIME CONSUMING TO BUILD
	HEAVY-DUTY ROBOTS NEEDED
	SOIL CONTAINS PERCHLORATES (TOXIC)

3D- PRINTED STRUCTURES

3D-printing habitats reduces the amount of building material needed, and therefore, waste material. It allows flexibility in the type and shape of structures. Using in-situ resources reduces the amount of money to launch and transport heavy items like construction materials.

+	-
CAN BE BUILT USING IN-SITU RESOURCES	COMPLICATED PRINTING PROCESS
CAN BE PRESSURIZED	COMPLICATED TO ACHIEVE AIRTIGHTNESS
CAN BE RADIATION SAFE	HEAVY-DUTY ROBOTS NEEDED
PROVIDE SECOND LAYER OF SAFETY	COMPLICATED TO PRODUCE MATERIAL FOR 3D-PRINTING
FLEXIBLE IN SHAPE	

INFLATABLE STRUCTURES

Inflatable structure is ideal for having a pressurized environment. But it offers little protection against radiation and meteorites. They must be transported from Earth, which increases payload.

+	-
PROVIDE AIR PRESSURE	NOT RADIATION SAFE
EASY TO INSTALL	NOT METEORITE SAFE
DOES NOT COLLAPSE IMMIDIATELY	HAVE TO BE TRANSPORTED
PROVIDE SECOND LAYER OF SAFETY	
FLEXIBLE IN SHAPE	

(Ingels 2017)

Figure 12. Martian arcitecture project references
Hassel Studio, Za Architects, AI Space Factory

In conclusion, robotic systems will need to be involved because the entire principle of the deployment mechanism for the habitats that have been proposed need to be completely autonomous. Meaning, they need to operate entirely on their own, robotically, prior to any human arrival or any crew being a part of that process. So, it is important to have a fully functional system that deploys, builds, and closes the habitat before people even arrive.

3.2.1. Regolith

Regolith is soil on Mars. It is composed of extremely fine dust and solid rocks. This dust contains nanophase ferric oxide (npOx), which gives reddish hue to Mars (van Ellen 2018). Martian dust can be toxic to humans, when ingested into the lungs.

Regolith is excellent radiation shielding material. It is difficult to estimate the radiation stopping power of the soil, but according to the studies (van Ellen and Peck 2018), a thickness of at least 975 mm is needed to ensure that the crew won't be exposed to higher doses of 50 mSv/year. It can be used as passive shield, placed as thick layer on top of the habitation modules.

Regolith can be used as a material for 3D-printing technology. Minerals that make up the Martian soil contain sodium and silicon dioxide. Two such minerals are albite and sodium bentonite. NASA proposes to use ionic liquids to separate the sodium and silicon dioxide in the minerals, and then employ chemical processes to transform the material into a 3D printable binder material – sodium silicate (NASA 2020).

Another possible way of using regolith in 3D printing was demonstrated by AI SpaceFactory during NASA's 3D-Printed Habitat Challenge. They have formulated an innovative mixture of basalt fiber extracted from Martian rock and renewable bioplastic processed from plants grown on Mars. This recyclable polymer composite is three times stronger than concrete in compression, and five times more durable than concrete in freeze-thaw conditions (AI SpaceFactory, n.d.). The technology is still very new and needs further testing.

Overall, regolith can be used in different ways. It is easy to work with when used by itself, but as a 3D-printing material it needs further development and testing to provide required mechanical properties. Regolith provides radiation protection, but due to it having a lot of salts and oxides, it is toxic to people. It means that alone, regolith cannot be used inside the habitat.

Figure 13. 3D-printng tests with regolith (NASA)

Figure 14. Martian soil (Google search)

Figure 15. AI SpaceFactory prints a habitat for NASA's challange (Staedter)

3.2.2. Ice/water

As mentioned before, ice is one of the in-situ resources on Mars. Ice is H2O frozen in the solid state. The pressure and the temperature on Mars have their influence on state of the water. Liquid water is less likely to find on the Mars' surface, therefore ice immediately sublimates (van Ellen 2018).

The strength of the ice varies because it is heterogeneous. But in general, it acts similar to concrete which has a tensile strength of 1/10th that of its compressive strength. According to studies, average tensile strength of ice is 1,43 MPa. The strength of ice increases when the temperature decreases (van Ellen 2018).

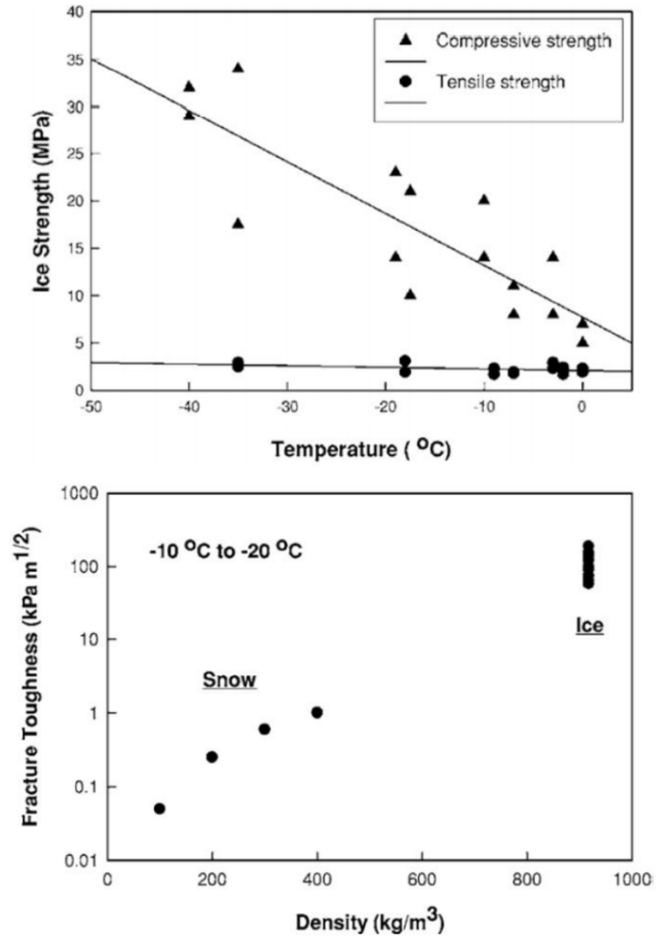


Figure 16. Strength of ice versus temperature od ice (van Ellen 2018)

Ice can be ductile and brittle. The higher the stress (increase of the temperature/impurity like air bubbles) the higher the possibility of the creep. One of the solution for the brittleness, is to keep water moving under the surface (van Ellen 2018). Another issue – water sublimates. Ice structures will need to be covered with additional plastic layer.

Ice is a complicated material, which is inconsistent with influence of the temperature, formation process and structure. Nevertheless, it has a lot of advantages that manifest themselves in building on Mars.

Water, being high in hydrogen, is very good for radiation protection. It is more effective for radiation protection than regolith – to protect habitants from higher doses of radiation (50 mSv/year), three times more regolith material is needed than water (van Ellen and Peck 2018).

One of the biggest reasons to use ice or water is the fact that it is clear and allow light to go through. It appears that there is a psychological benefit in viewing space outside from the interior (Morris et al. 2016). Clear walls allow creating visual connections to the landscape, allowing more psychological comfort for the habitants.

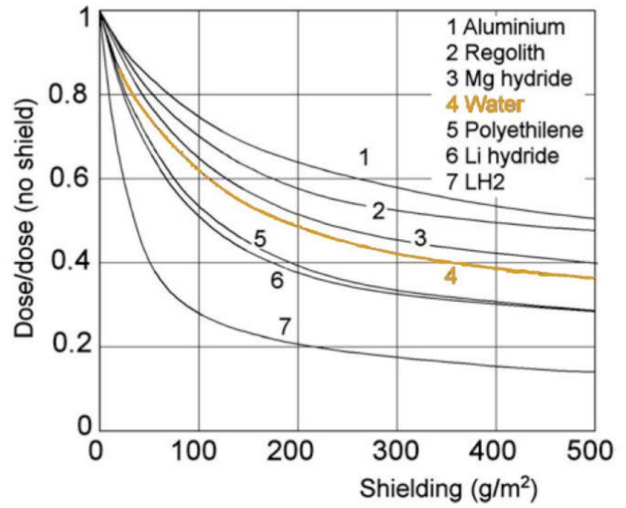


Figure 17. Radiation shielding properties of different materials (Genta, 2016)

There are many different techniques of building using ice. On Mars it is reasonable to use an ice printing method. The water is collected in the vapor and then printed using robots that hold onto construction while using additive manufacturing to build the structure (van Ellen 2018).

There are some disadvantages to using ice as a main building material in the habitat. The inner temperature of the habitat should be around 20°C. Due to the temperature differences between exterior and interior, ice would always melt on the inner side. Ice will constantly vaporize because of the low pressure on Mars and a transparent membrane layer outside will be needed to hold the steam until it freezes again. This process will put a high pressure on the membrane; therefore, it will be fully exposed to dust storms and micrometeorites, so it needs to be reinforced to withstand that pressure. This makes building process much more complicated and difficult to test on earth.

In conclusion, ice/water is complex building material. Ice can be ductile and brittle, but it has some astonishing qualities, that could be crucial in designing human centered habitat. It serves as radiation barrier and allows light through. It is hard to test on earth and there is a lot of room for mistakes because of ice' structural and mechanical properties.

Figure 18. Concept of ice 3D printing robot in Mars Ice House (Montes, 2016)

3.2.3. Mycelium

In 2018 the myco-architecture project was published by NASA's Ames Research Center. The concept of the project was "growing" habitats on Mars, using the process of growth of mycelium and cyanobacteria.

Mycelia is the threads that fungi use to build themselves. With use of mycelia, it is possible to make structures of various shapes and sizes, and in this project, scientists were working on manipulating the mycelia into making structures on Mars that people can live in. Materials made from mycelia, already commercially produced, are good for insulation, fireproof and their flexural strength superior to reinforced concrete (Rothschild 2018).

The mycelia could be used as a building material via its natural processes and cyanobacteria. "Cyanobacteria are oxygenic photosynthetic organisms that could convert water and the carbon dioxide from the Martian atmosphere into oxygen and biomass." (Rothschild and Maurer 2018). This process is similar to Photosynthesis, but instead of just making food for itself and exhaling Oxygen, it's helping make the mycelia. According to the research, mycelia are more flexible and ductile than regolith.

Material	REGOLITH	ICE	MYCRETE
Modulus of Rupture	40 MPa	3 MPa	19 MPa
Ultimate Compression	40 MPa	4.9 MPa	6.7 MPa
Modulus of Elasticity	-	5100 MPa	5334 MPa
R-value (per inch)	-	0.45 r/in	3.8 /in
Tensile	-	1 MPa	TBD
Temperature to Produce	-	> 0 °C	15 – 30 °C
Thickness for radiation shielding	97 cm	30 cm	90 cm

Figure 19. Comparison of the materials by Nasa Ames Research Center (Rothschild 2018)

In the project, the outer layer of the habitat is made up of frozen water ice. It serves as a protection from radiation and trickles down to the second layer – the cyanobacteria. This layer takes water and photosynthesizes using the outside light that shines through the icy layer to produce oxygen for astronauts and nutrients for the final layer of mycelia. That would make the interior for the habitat and additional radiation protection. It would be hardened to decrease the risk of damaging the structure (Rothschild and Maurer 2018).

These types of building structures could be extremely beneficial to the Mars mission, because mycotectural habitat could significantly reduce the energy required for building – in the presence of food stock and water it would grow itself. Melanized fungal mycelia could provide radiation protection, as melanin has the ability to absorb radioactivity. Additional radiation protection can be provided as water can accumulate in mycelium.

The technology allows flexibility in the design of the habitat. Habitation pods will be produced on Earth. The mycelia and dried feedstock will be placed in a deflated habitation pod that will be folded and sterilized before the departure. At destination, the robots will deliver water and carbon dioxide to the folded pod, which will activate the mycelium growth. It will stop when all of the cyanobacteria will be consumed, or heat reduced. The big advantage of mycotectural structure is the fact that it can be healed by adding water, heat and feedstock. The final dimensions of the habitation pod will be configured with struts.

Another big advantage is that with this new biocomposite material that can grow itself, a new way of designing habitats will be possible, and it will be cheaper, faster and safer. Only few robots will be needed for the construction and the astronauts can reside in the spacecraft they came down while the mycotectural habitat grows, and then once it's ready, they can live in it full-time.

In conclusion, the study shows that mycelia would have many applications on a Mars colony. It can grow without light, all it needs is water and substrate. But the research is still in early stages of development and the prototype with mycelia and deploy has yet to be produced.

Figure 20. Production process. 2 weeks of growth (Rothschild 2018)

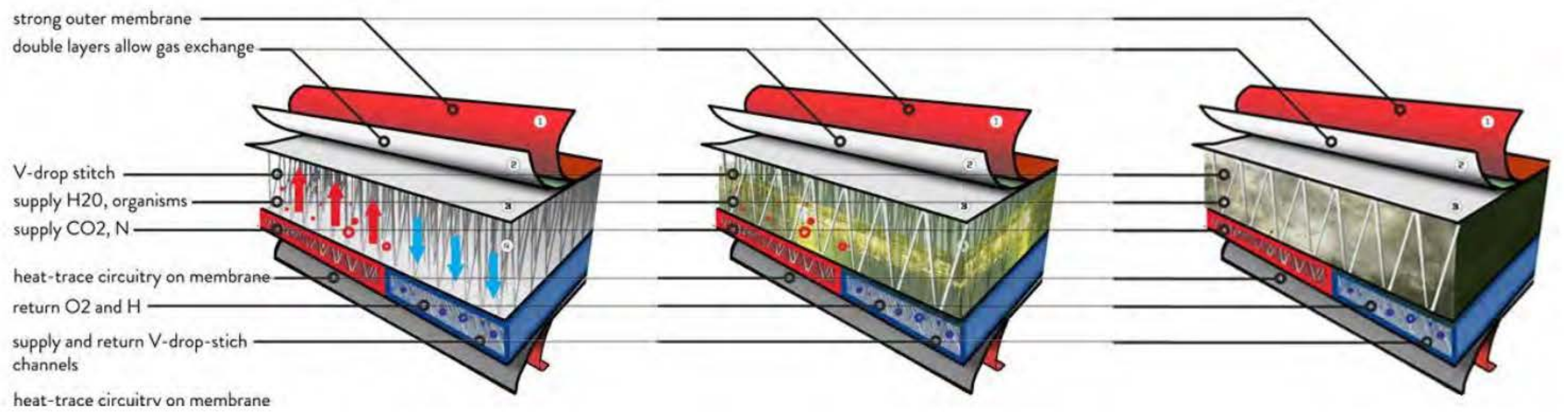


Figure 21. Multilayered system of habitat walls proposed by Nasa Ames Research Center (Rothschild 2018)

3.3. Reference study

No habitat has been built on Mars yet, but several architectural and engineering contests and projects have been done over the past years. A few recent examples are analyzed below.

3.3.1. MARS COLONIZATION / ZA Architects

The goal of the project was to build permanent settlements on Mars, using robotics and local materials to reduce the price and risks (ZAarchitects 2013). The proposal is to create a big network of caverns that will be situated below the surface of the planet. Robots are going to do all the work: carve caves into basalt bedrock and weave a web, that will be used to move around and hold the technical facilities.

This architectural concept proposes bunker-like solution, where human experience is buried underground to protect from radiation. But according to the studies, Martian soil contains perchlorates, which are toxic to humans impairing the proper function of the thyroid by inhibiting the uptake of iodine ions (Morris et al. 2016).

In general, tunnels are uncertain to create on Mars, because we lack knowledge of what is below surface conditions. Even today, rovers can have problems with putting small drills into the ground (Kooser 2020). To live underground a lot of soil will need to be transported, and this process will be extremely energy demanding.

Similar concepts were elaborated in many early projects, suggesting that lava tubes could be the safest place for explorers to live on Mars (Letzter 2020). The knowledge about them comes from collapsed lava tubes seen on Martian aerial photos. But this means that lava tubes can be unstable.

Figure 22. Mars colonization / ZA Architects (2013)

+ TOTAL RADIATION SAFETY
+ TOTAL METEORITE SAFETY
+ BUILT OF LOCAL MATERIALS

- NO DAYLIGHT
- NO VIEWS
- TIME CONSUMING TO BUILD
- HEAVY-DUTY ROBOTS NEEDED
- SOIL CONTAINS PERCHLORATES (TOXIC)
- ENERGY DEMANDING PROCESS

3.3.2. MARS ICE HOUSE / SEArch + Clouds AO

The project was the winner of the first phase of NASA's 3D Printed Habitat Challenge. The proposal is to build a hybrid structure out of ground ice. Instead of burying the habitat underground, the design suggested using surface ice to create a shell that would not only protect from radiation, but also bring light to the interior.

First, spaceship delivers a pressurized translucent Ethylene tetrafluoroethylene (ETFE) membrane. This is a base to which ice-printing robots hold onto. They collect ice in the vapor form from the surface and print 5 cm thick ice walls. The concept of the construction relies on these robots capable of scaling the wall they have already constructed (Morris et al. 2016).

Inside, a spiral stair provides access to the upper levels of the habitat. All the rooms have curved forms, which makes small spaces seem bigger. The room program includes food preparation room, crew quarters, laboratory, medical room, work rooms and hygiene units. There are also radiation-safe inflatable windows, which are filled with hydrogen. A vertical hydroponic greenhouse supplies habitants with oxygen. Different light effects benefit the crew's psychological and mental well-being (Morris et al. 2016).

Despite the long history of using ice as a construction material, the method of 3D-printing is novel and needs further testing on earth and in space. Because of the ice qualities explained in paragraph 3.2.2. the process of 3D-printing with ice is very complicated and difficult to test on earth. Due to this fact the use of ice was restricted further in the competition. Nevertheless, this concept is fascinating and at the time it nudged the designers towards more sophisticated and human-centered proposals of Martian habitat.

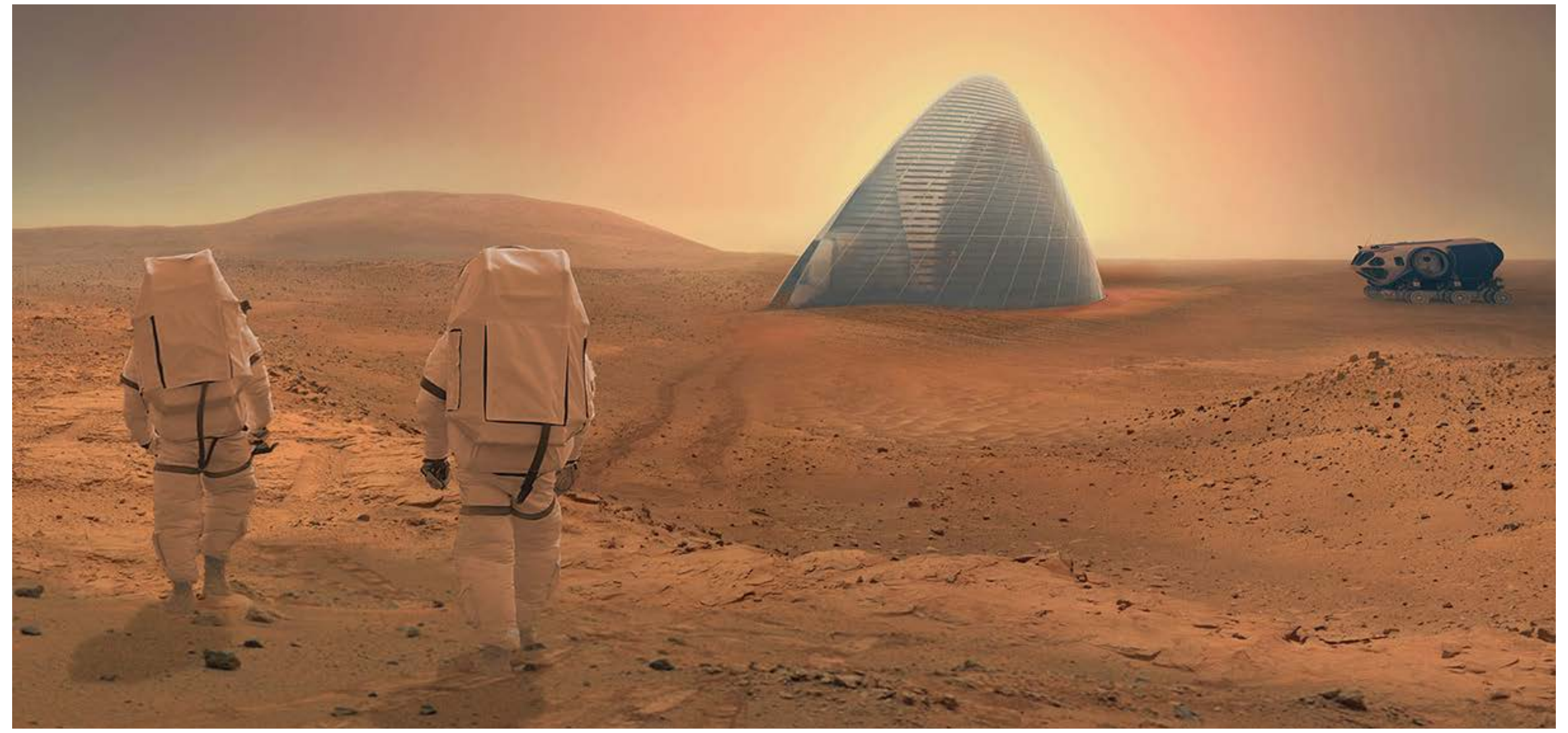


Figure 23. Mars Ice House / SEArch + Clouds AO (2015)

+ ONE PRINTING ROBOT
+ TRANSPARENT STRUCTURE
+ RADIATION SHIELDING

- DIFFICULT TO TEST
- COMPLICATED MATERIAL
- ICE WILL CONSTANTLY MELT
- ICE IS BRITLLE, MIGHT CRACK

3.3.3. 3D-PRINTED HABITAT / Hassel Studio

The project was done for NASA's Centennial challenge and was pre-selected as one of the top ten proposals. The goal was to design a habitat for the first astronauts on Mars. The requirement stated that pressurized volume must be 3D-printed. Because of the difficulties that occur during large-scale 3D-printing projects, architects proposed a double system, that consist of 3D-printed shell structure and pop-up tents, which are manufactured on Earth. The shell structures are 3D-printed using regolith and protects from gamma radiation. The shell protects from direct sunlight, but still brings indirect light trough the „courtyard" which is in the center of the structure. Spaces in the pop-up tents include research laboratory, greenhouse, workshop, sleeping quarters with gym facilities and a virtual-reality platform (Hassel 2018).

The concept of the habitat relies on wheeled robots that excavate and collect regolith for processing into 3D-printing material. Although, the result complements the surrounding environment, it is difficult to control this kind of robotic system from Earth. Also, to gather and process the regolith, and build this big of a structure, many heavy-duty robots are needed. They will be extremely costly to transport from earth and with this kind of complicated process there is a lot of room for errors.

Figure 24. 3D-printed habitat / Hassel Studio (2018)

+ PROTECTS FROM RADIATION	- HEAVY-DUTY ROBOTS NEEDED
+ ALLOWS LIGHT AND VIEWS	- A LOT OF ROOM FOR ERRORS
+ HUMAN-CENTERED DESIGN	- THIN INFLATABLE TENTS DO NOT PROTECT FROM EXTREME TEMPRETURES

Figure 25. Marsha / AI Space Factory (2018)

+ PROTECTS FROM RADIATION	- COMPLICATED PRINTING PROCESS
+ STRONG MATERIAL	- A LOT OF ROOM FOR ERRORS
+ ALLOWS LIGHT AND VIEWS	- COMPLICATED MATERIAL TO PRINT WITH AND PRODUCE LOCALLY

3.3.4. MARSHA / AI Space Factory

The project was the 1st place winner of NASA's Centennial challenge. The competition required the use of Martian regolith and mission-recycled materials; the design and development of an automated printing system; and the necessary logistics to deploy the system (Walsh 2018).

A habitat is a vertically 3D-printed cylinder. This shape increases usable floor area and reduces structural stresses of the habitat. Also it is an easy shape for a 3D-printer, because it does not have any sharp corners. The interior of the habitat is pressurized. To reduce the structural stresses at the ends of a shape, the diameters were made smaller at those spots. The result was an egg-like shape. The natural light is indirectly let inside the habitat through large water-filled skylight and intermittent windows. Function-based rooms are spread over the levels, each level has at least one window.

The chosen material for the habitat was basalt fiber-reinforced polylactic acid (PLA), a thermoplastic which has a lot of advantages: it does not require water, it can be remelted and reused, it is strong, it shields radiation, and it is non-toxic. It is produced by mixing basalt fiber extracted from Martian rock and bioplastic processed from plants grown on Mars (AI SpaceFactory, n.d.).

At the final stage of the competition, teams were given 30 hours to print a 1:3 scale habitat. Although, teams were able to make small changes and supervise the whole process, the robot still failed to install the skylight on the top of the structure, and it fell on the ground. The autonomous printing process is very complicated, and it will be even harder on Mars, when people will not have any chance of making small changes and adjustments.

In conclusion, the project proposes a lot of innovative solutions, like the vertical construction for maximum use of space, intermittent windows, and a strong construction material, which is reusable and radiation shielding. This proposal also has its weak points. It will be extremely complicated to produce such material autonomously. This kind of thermoplastic needs to be manufactured on Mars in big quantities to build with it, and it would mean mining on Mars. Also, there is a need for greenhouses to grow plants and to produce bioplastic. This process is far too energy-demanding for the early stages of the mission.

4 CONCLUSIONS

4. CONCLUSION: DESIGN

Many conclusions can be drawn based on the theoretical-analytical part of this study.

Martian environment is harsh: high radiation, no oxygen, extreme cold and low atmospheric pressure. Due to Martian thin atmosphere, it is difficult to land heavy objects[1]. It also influences the cost of transportation; thus, it is important to minimize payload to mission-critical equipment that cannot be produced on Mars. Habitats brought entirely from Earth will result in greater risk and economic imbalance.

The more lightweight payload is, the better. Yet, to protect habitants from Martian harsh environment the mass is needed. As it is impractical to bring from Earth, using in-situ materials is crucial to sustainable Mars mission. Local materials such as regolith and ice water can be used as building materials – they are both good for radiation protection however, regolith contains perchlorates which can be harmful for human health, and both regolith and ice require large and multifunctional machinery for building (van Ellen 2018).

First habitats will be autonomously constructed prior to the arrival of the crew. The challenge is to make the process as much independent from Earth as possible. All the machines (rovers, airbags, solar panels, 3D-printers) will need to handle the occurring problems independently. Therefore, it is important to choose a construction method which is manageable and leaves less room for errors.

The first step of designing a habitat on Mars is to define the location of the base. It is decided to build on one of the five Martian sites selected by SpaceX: Erebus Montes. This area is known to have plentiful near-surface ice-water deposits based on data collected from orbit (Hibbard et al. 2021). Erebus Montes not very far from the equator, so the seasonal temperature flux is lesser. The region locates on the lower elevation and thus the atmosphere there is thicker. Consequently, and due also to the flat area, the landing will be safer, and the habitat will be better protected from the harsh environment.

The reference study shows that most of the recently proposed habitats for Mars are composed of two structures: a pressurized living unit and external protective shell. The unit provides the right conditions for human comfort: higher pressure, temperature and livable spaces, while external shell protects from radiation, thermal flux and dust. The construction method of this external shell is what defines the design of the habitat. It is the most complicated part, because the main purpose of the shell is to protect, while leaving a visual connection with the outside world, which is a must for providing psychological comfort for the inhabitants. The 3D-printing method allows you to provide for both of those needs simultaneously but makes the process extremely complicated.

The myco-architecture concept allows the construction process to be easier by having the protection implemented to the living unit itself. Few robots and folded prefabricated units will be needed to assemble the base. The big advantage of this method is that the whole base constructs itself using the process of mycelium growth. The base layer of the habitat can be supplemented with translucent skylights and thus allows natural light to flow through the structure without needing structural cuts. This construction method also requires significantly less energy to produce (Rothschild and Maurer 2018).

The mycelial-based construction is selected within the framework of the architecture project. This material is chosen because mycelia could grow and expand to provide structural mass against radiation but still allow light to go through the structure. This concept complies to many necessities that are set for the Martian habitat. However, while several prototypes were grown by NASA research team, they still have not confirmed on optimal fungi, enhancements, growth conditions, packing, shipping, growth at destination or post-processing (Rothschild and Maurer 2018). Nevertheless, this concept is very promising.

Psychological comfort is mission critical, therefore room program should offer diverse spaces and allow visual connection to exterior. Room program should include communal spaces, like gym and kitchen.

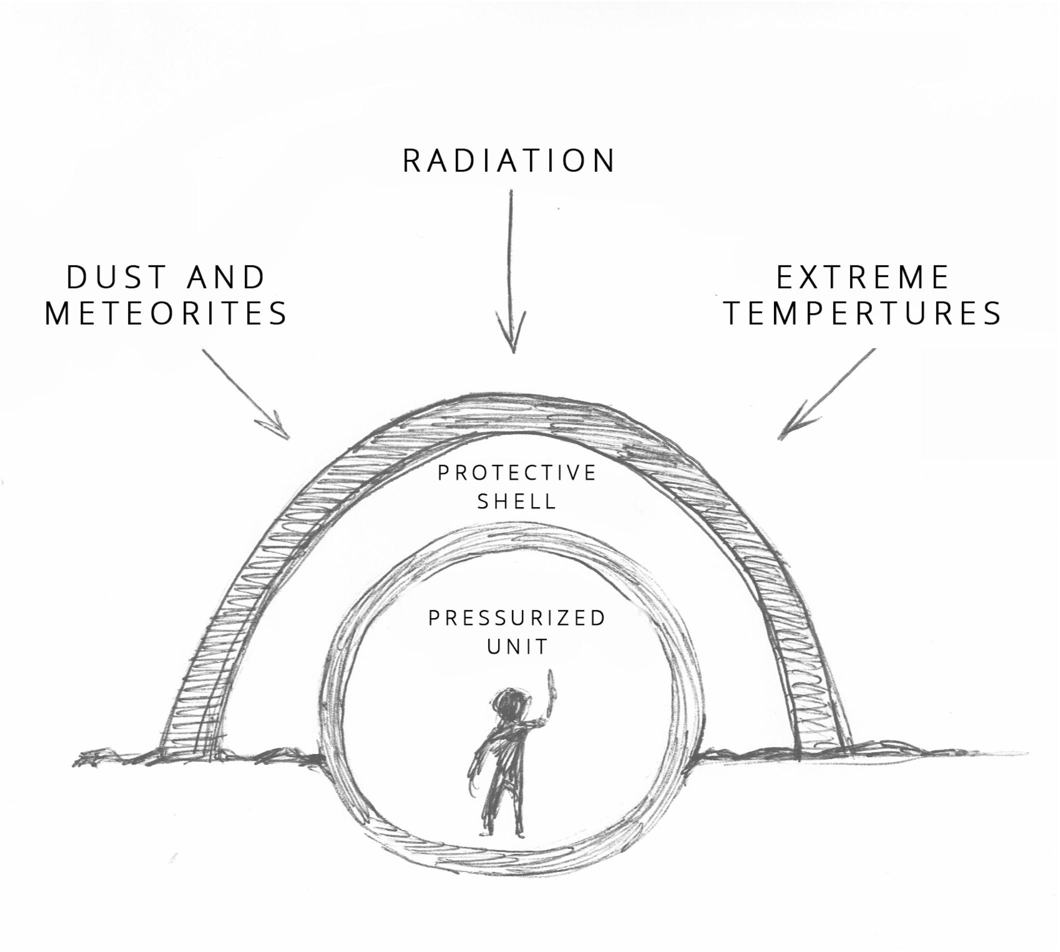
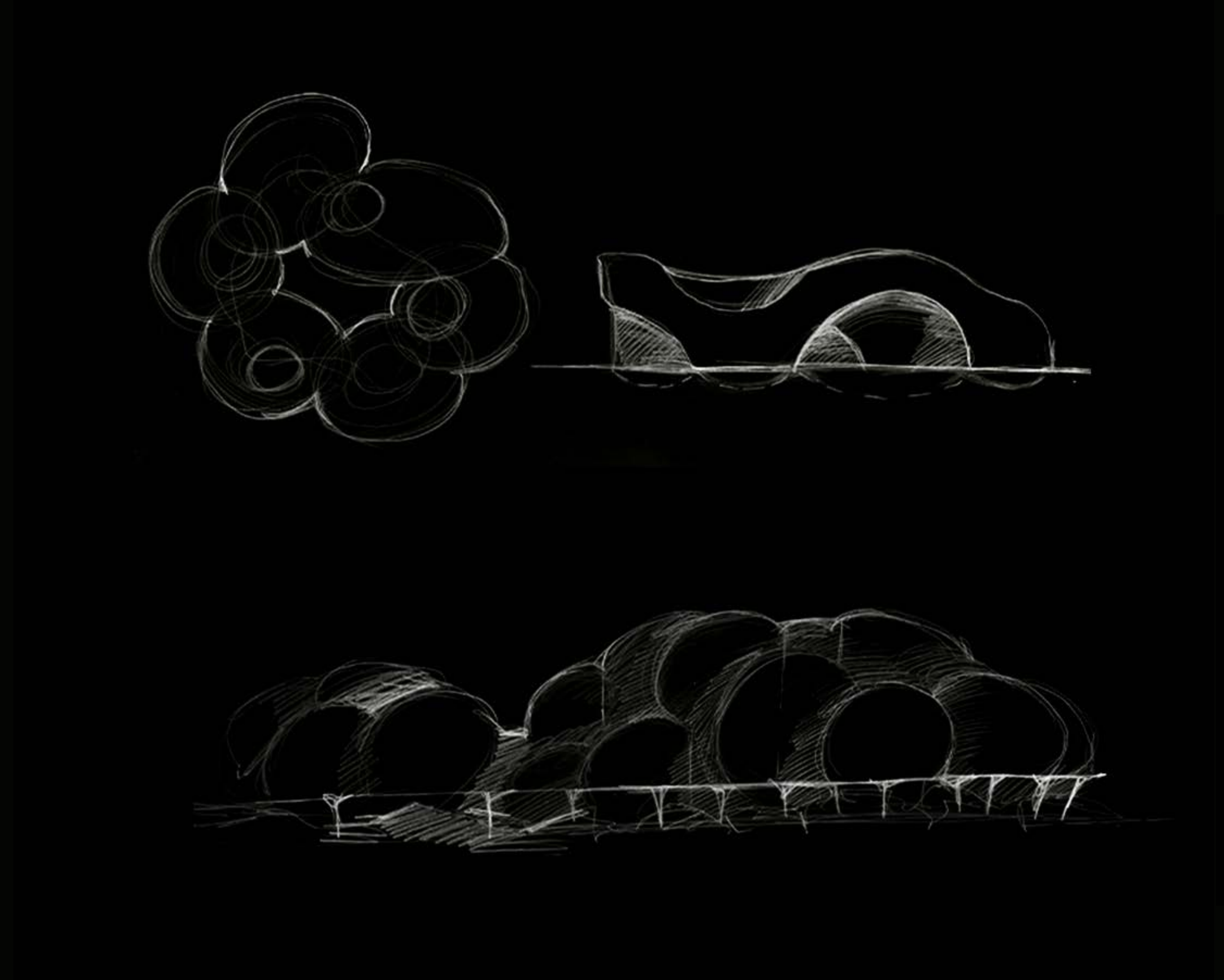
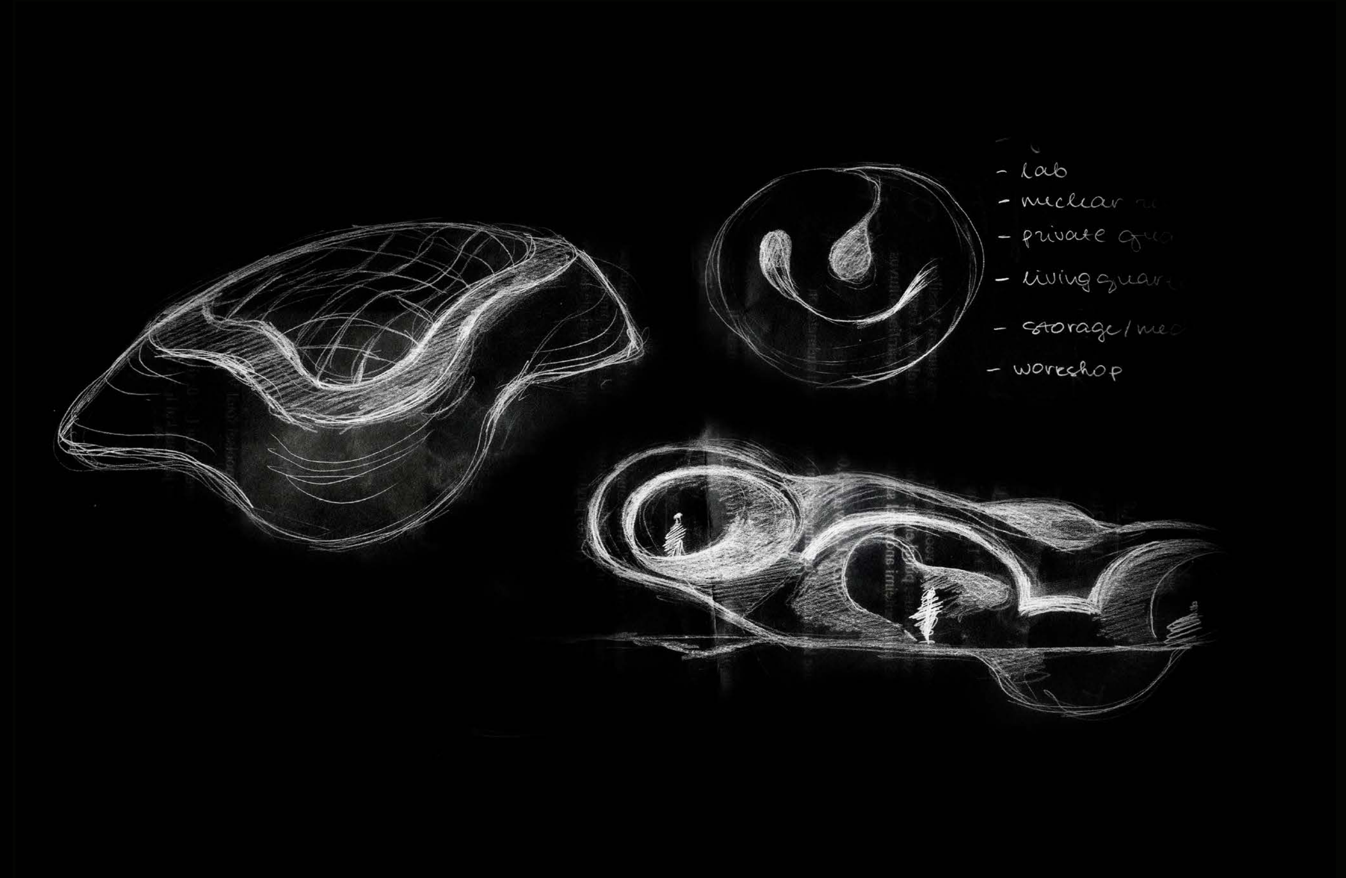


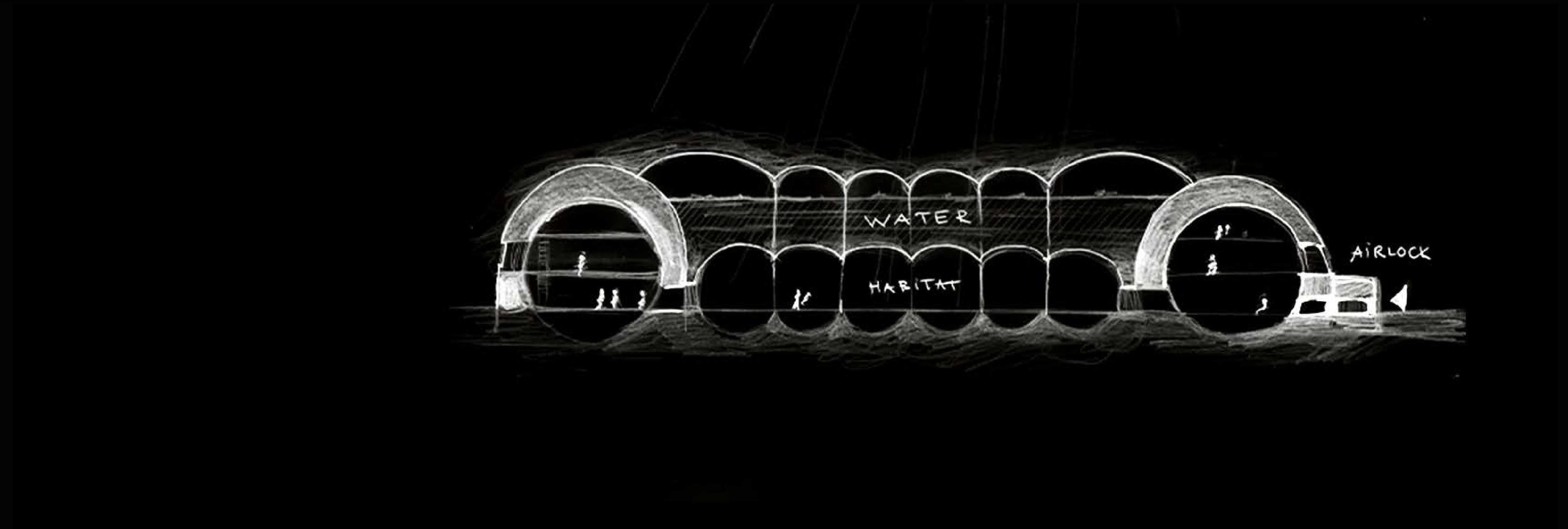
Figure 26. Concept of the habitat based on reference study

1 Phases of entry and landing are explained in chapter 2.3.1

5 ARCHITECTURAL PROJECT







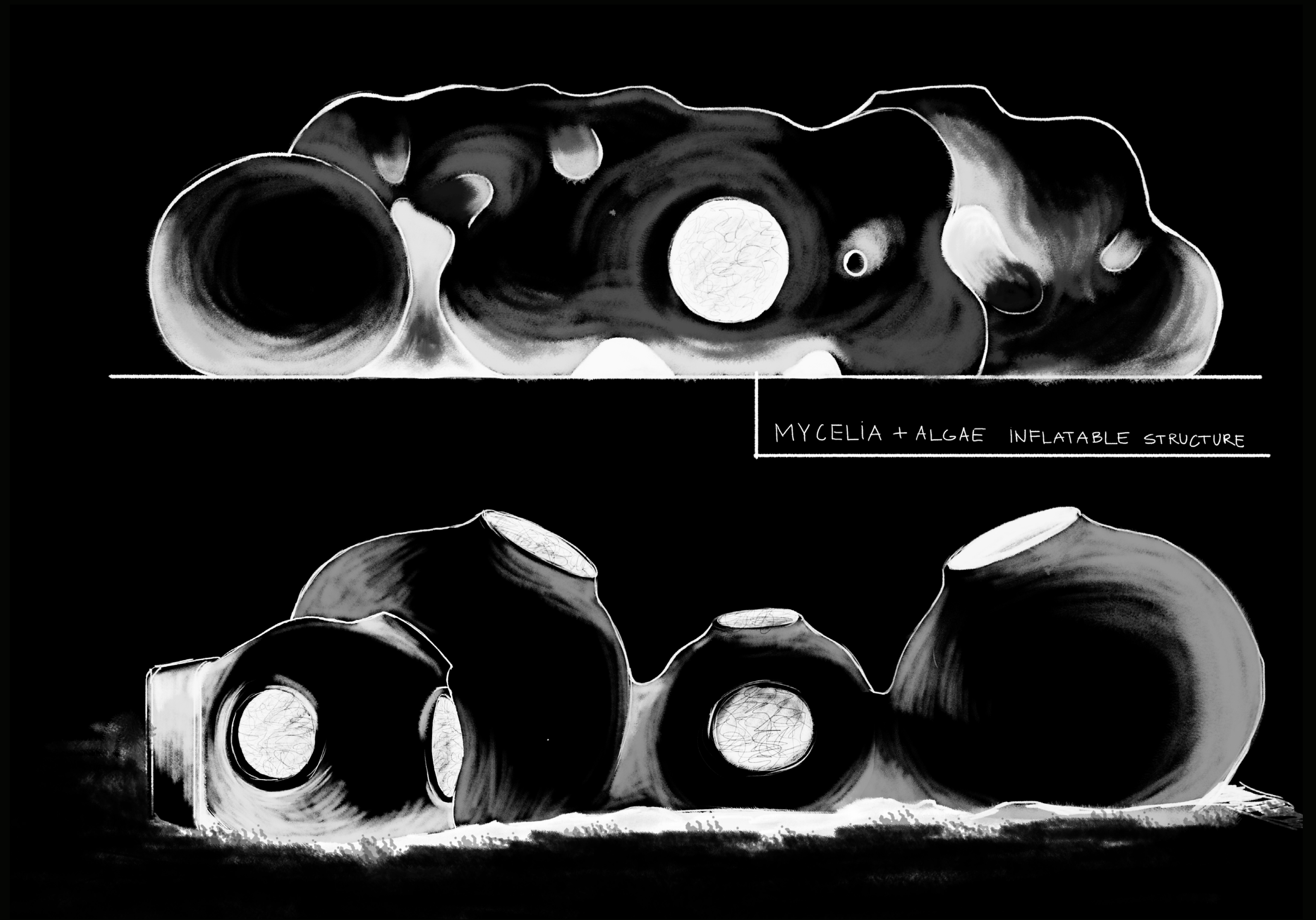
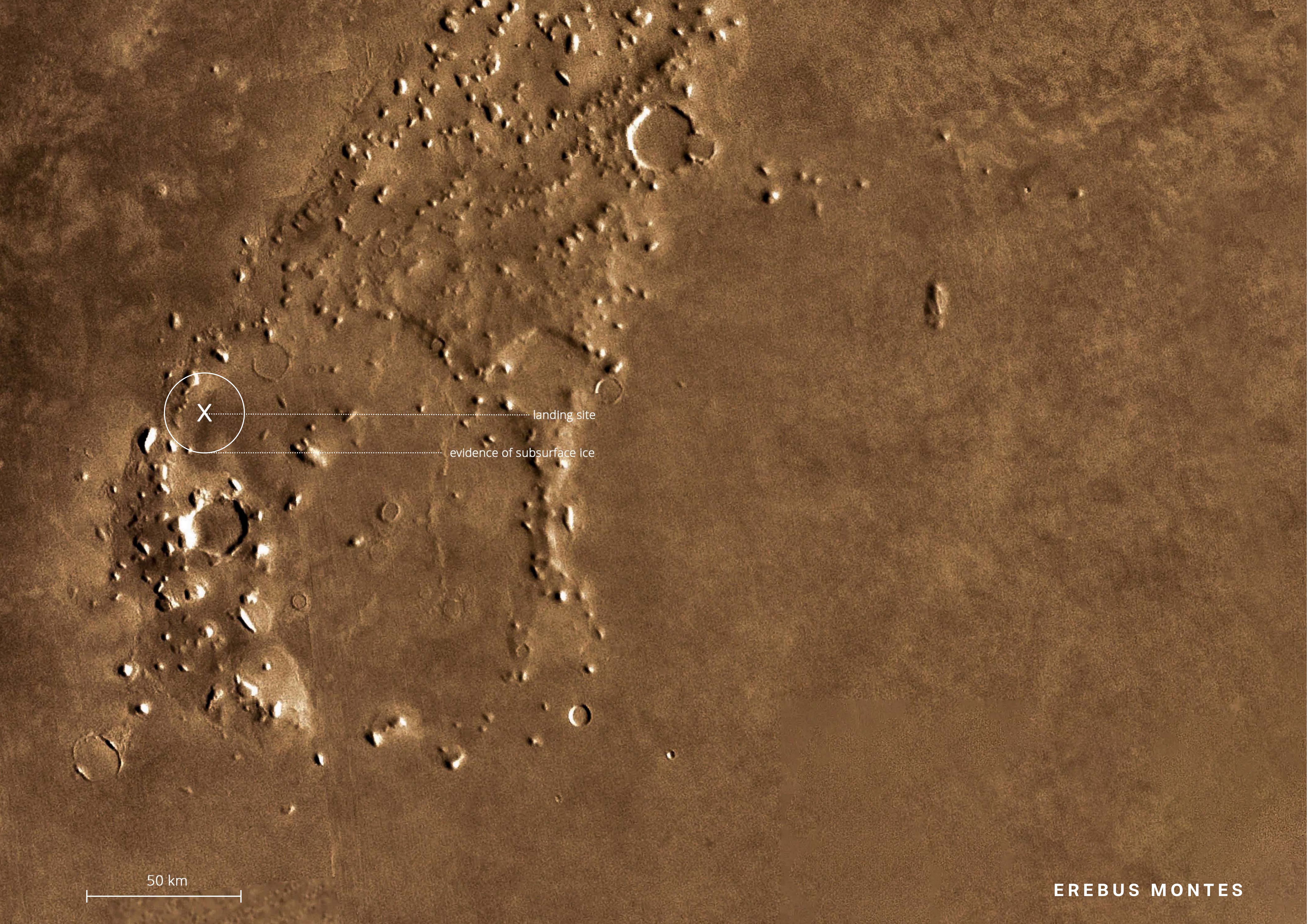


Figure 27. Early design stages. Searching for the concept.



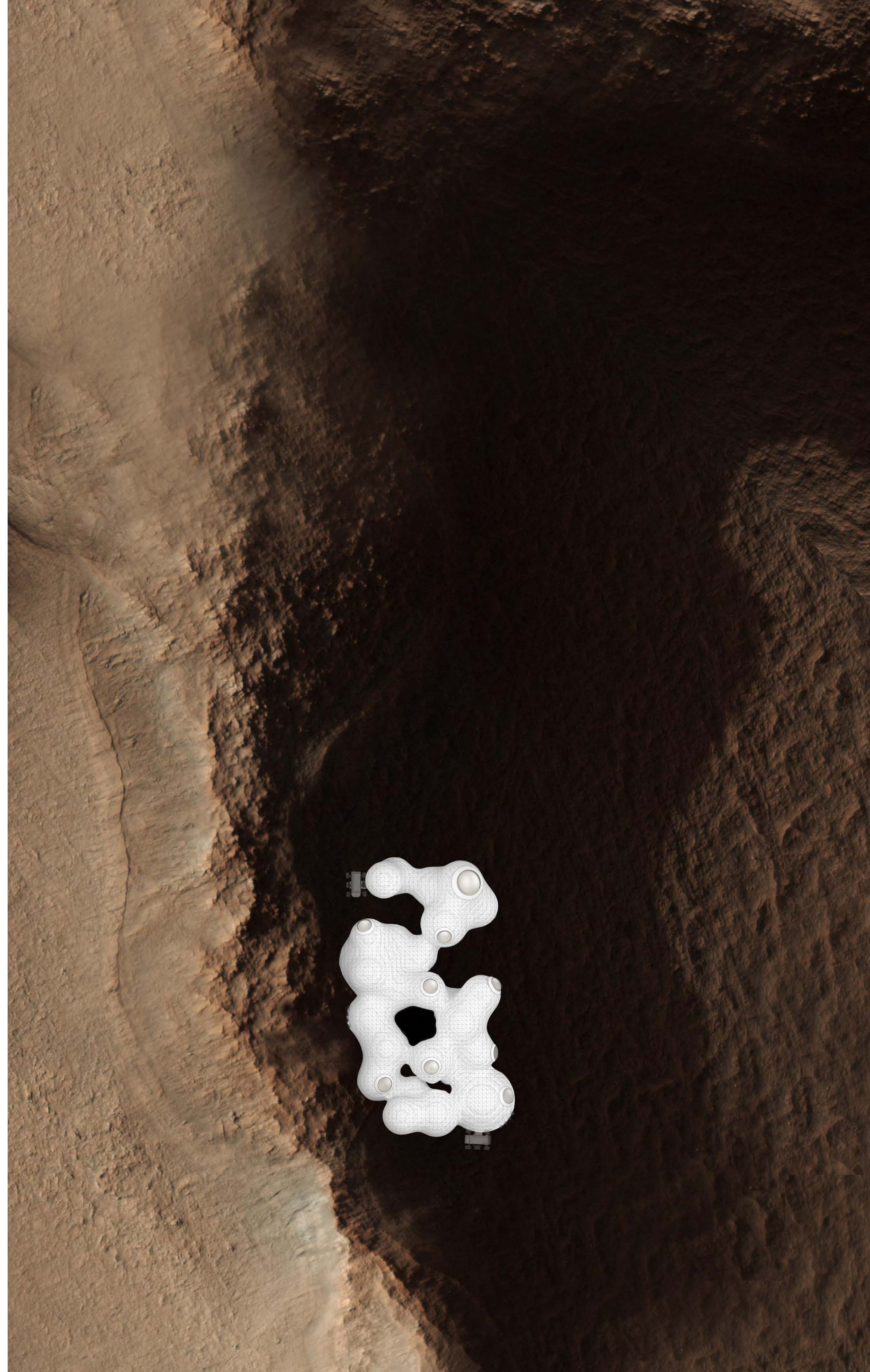
5. ARCHITECTURAL PROJECT

5.1. Site plan

Erebus Montes is chosen as a landing site. The area is located on lower elevation where the atmospheric pressure is higher, and it has relatively flat surface, consequently providing for the safer landing for a heavy spaceship. The location was also chosen due to the fact of having ice water right below the surface, as water will be an important resource for not only return fuel but also for habitat construction.

5.2. Masterplan

As Mars is not inhabited yet, the design process of the first habitat basically starts with a blank canvas. Though, the design flow does not have a lot of freedom- it should be mostly construction driven. Because of the need for having a pressurized environment inside, the habitat is composed of units that are smoothly fused together. The visual connection with the exterior is provided through three-layered water filled windows, that allow natural light but also protect from radiation. The construction site is located on the safe distance from the landing area.



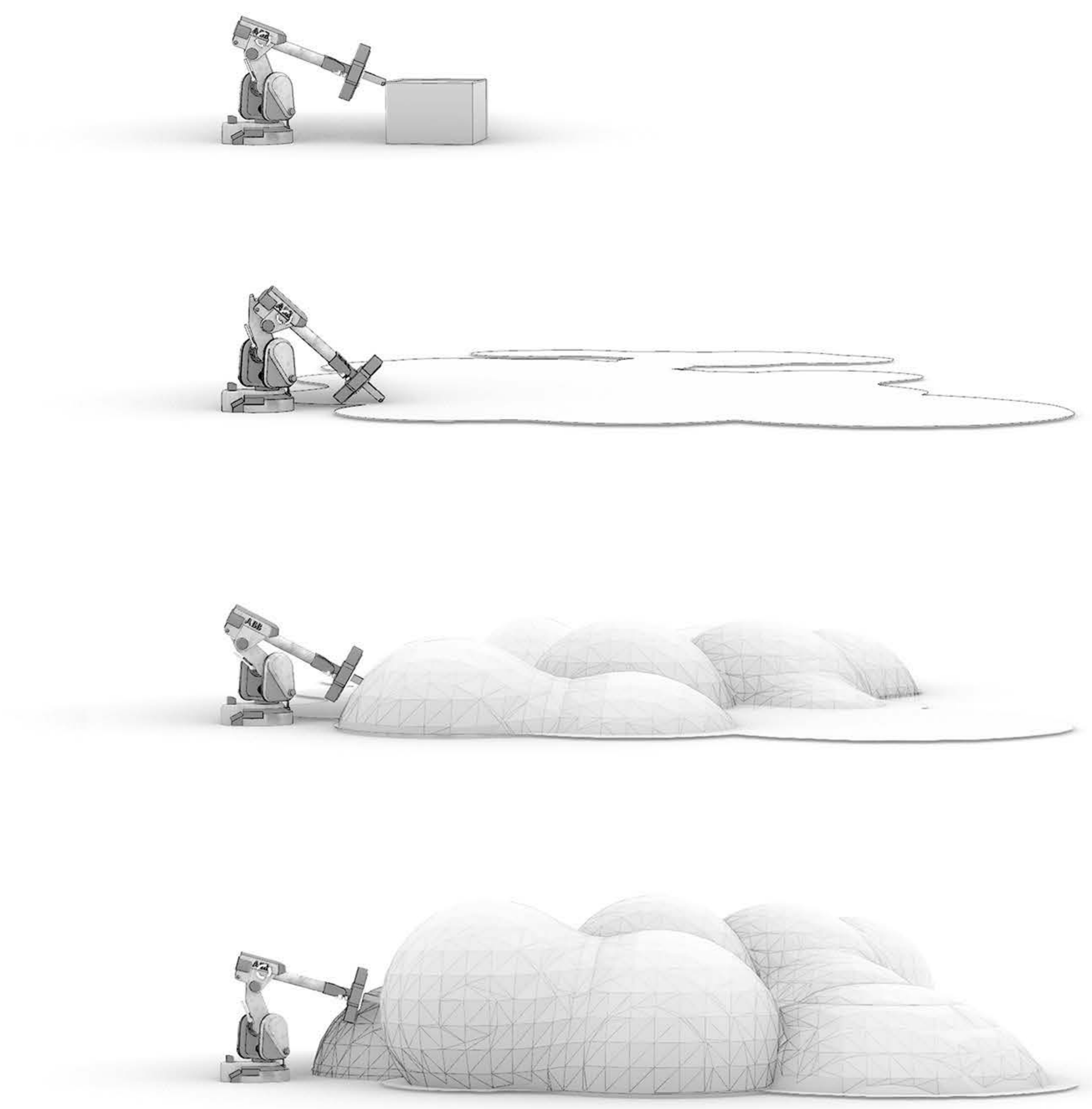


Figure 28. Concept of assembling the habitation units

5.3. Construction

The habitation pods are produced on Earth prior to the mission. They are transported to Mars in a deflated state, with mycelia and feedstock (cyanobacteria) placed inside. When the first cargo ships arrive on Mars, the robots and rovers, powered by solar energy, deploy the pods to the construction site. Robots collect Martian water from the surface and CO_2 from the atmosphere and fill the pods while also adding heat. This process activates mycelium growth and expands the pod. Mycelia will consume the feedstock and grows into light and strong structure. According to the NASA research, the 900 mm thick wall is enough to provide every protection needed. If additions or repairs are needed, additional water, heat and feedstock can reactivate growth. The window partition is produced without mycelia, but filled with water simultaneously along with the construction process. Additional layers are separately filled with hydrogen for additional protection against radiation.

The whole base constructs itself autonomously, without a need for light or large energy consumption. Growth stops when all of the feedstock consumed and heat reduced. The myco-structure provides required mass against radiation, but still allows light to go through.

The structure is ready to use approximately in one year and as the new launch window opens, astronauts arrive to live in ready-to-use habitation system.

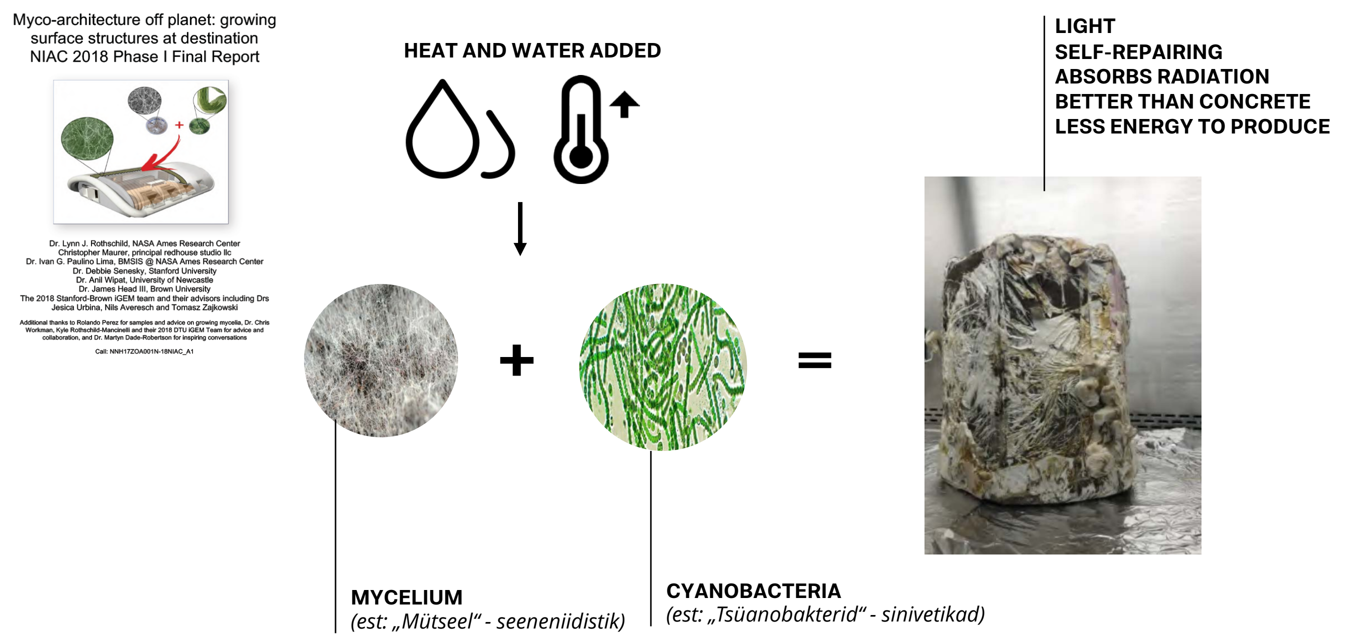


Figure 29. Concept of mycrete

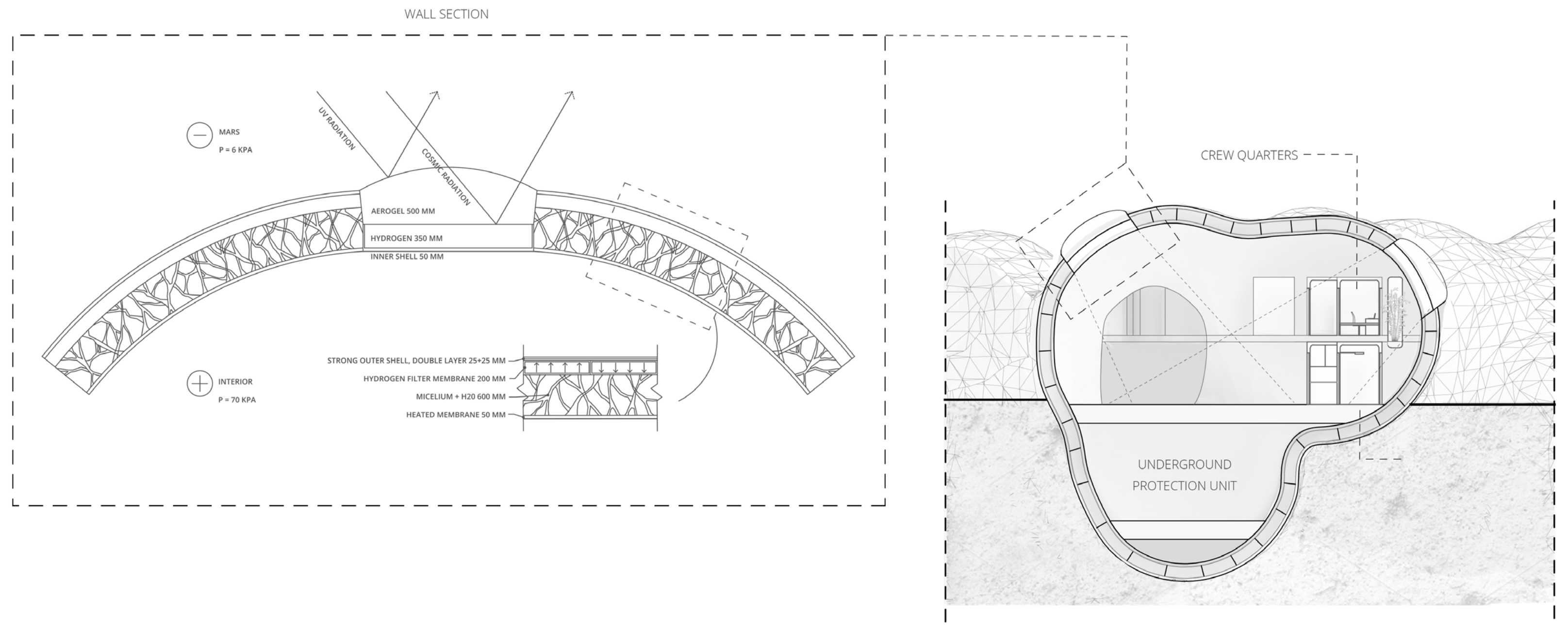
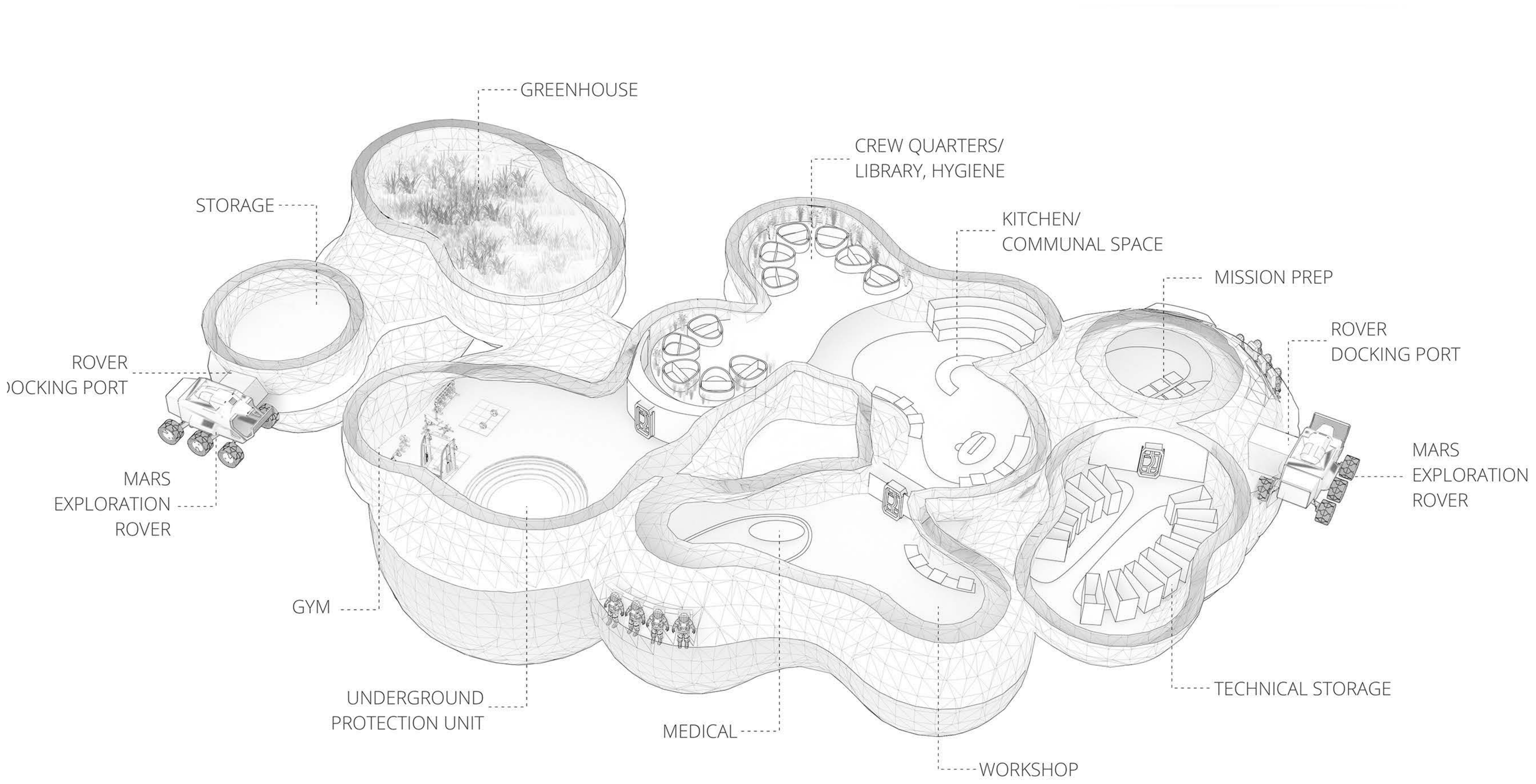


Figure 30. Section



5.4. Room plan

The room program is put together on the basis of previous architectural contests that were held by NASA. This habitation system is designed for the crew of 12 people. It includes, greenhouse, communal spaces, workshop, mission preparation room, underground protection unit for occasional solar flares.

All of the units are linked through connector modules, in which various life support systems are placed. They deliver essential services such as data, electricity, water and oxygen to all of the units. The habitat is remotely powered by two nuclear kylo-power reactors, located a safe distance from the habitat.

5.5. Interior

When the astronauts arrive, they will install additional structures needed for interior, like furniture and leveling platforms. Because the gravity on Mars is only 1/3 of Earth's people will be able to jump much higher, so no stairs are needed, only support trusses.

There are multiple levels with unique and diverse interior. Skylights provide natural light to all levels. As mental health is critical for successful mission, design offers different communal rooms like gym, workshop and kitchen communal space, so members of the crew can have different experiences and less monotone existance.

Each level has at least 1 window. Indirect natural light from the windows allows sunlight through while still keeping the crew safe from harmful solar and cosmic radiation.

In the project, the original idea is realized and novel construction applied. A habitat has been designed to fulfill all the required needs. One of the main objectives was to implement is designing for human needs. So, human-centric design. And not just kind of systems engineering processes that you might find in a traditional aerospace workflow.

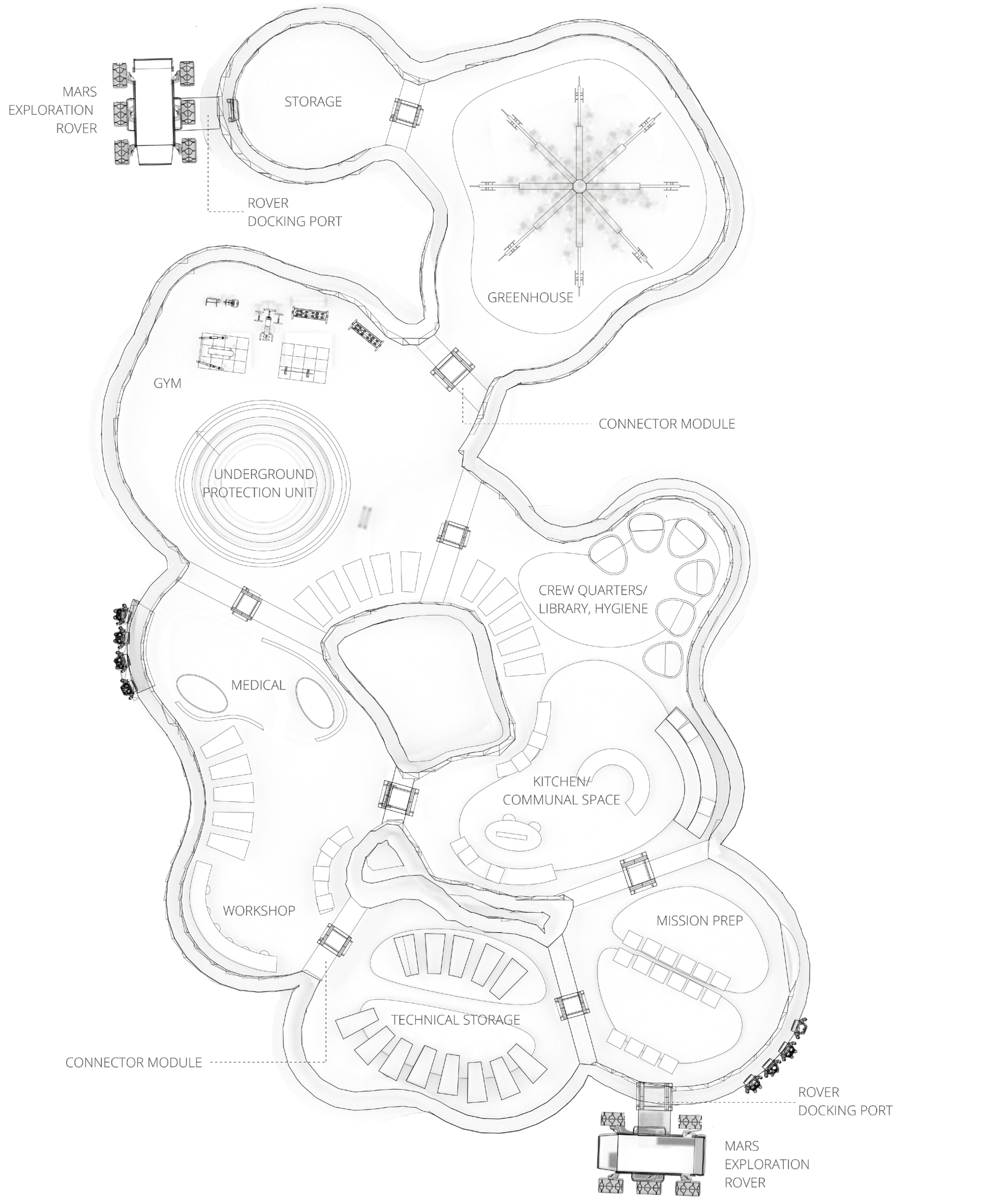


Figure 31. Floor plan


SUMMARY

The main objective of this master thesis was to explore the methods of building an autonomous habitat on Mars and propose the architectural solution for the habitat, which not only protects the inhabitants from Martian extreme environment, but also considers human comfort.

The available construction materials and methods were defined. Through careful analysis, a mycelial-based construction method was found to be the most compliable to most necessities that are set for the Martian habitat. The main challenges for the development of the living environment were explained and human-centered criteria were established with extensive reference study.

Finally, technical knowledge and space quality standards were applied when proposing a vision of a Martian habitat.

Although Mars is inhospitable, it still has much to offer in the scientific field. Developing a viable architectural solution for the Martian habitat is a challenge because of the extreme conditions. Existing design proposals may work in theory, but they are largely untested in harsh environments. The proposed new design idea helps in finding new solutions as innovation happens when looking at things from different angles.

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