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NEW HOME

Martian Habitat

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A First Martian Habitat

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ABSTRACT

We are living in an era where interplanetary travel, most significantly to Mars, is widely discussed in both science and popular culture. However, considerably less attention is placed on the quality of living spaces provided for the mission crew even though it will have significant impacts on both the design of the journey and the overall success of the mission. That is why our project of a Martian habitat firstly seeks to identify the crucial technical and human-centered architectural challenges of a long-duration stay in seclusion and confinement in the hostile Martian environment. Secondly, through systematic analyses and case studies it investigates necessary theory to tackle these challenges and, lastly, through integrated interdisciplinary design, it seeks to translate the gathered theory into a comprehensive design for a permanent Martian habitat that will support the physiological and psychological well-being of the six-member crew.

CONTENTS

PROLOGUE

motivation / synopsis
TMIDP / technical approach

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What, why and how are the main questions answered within this section. In the following four chapters, we describe why the design of a Martian habitat is currently pressing and what formed our point of departure for its scale, location and particular design considerations. Later, we portray what design methodologies were followed in order to address these considerations in an efficient and structured manner and we summarize our approach to the main technical challenges.

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MOTIVATION

Exploration

Since the dawn of time, mankind has been captivated by exploration of its surroundings and all unknown regions, looking for new possibilities and knowledge. After the Space Race to the Moon, the next giant leap for mankind is the next closest astronomical body, Mars. Currently, a few of both public and private organizations, such as NASA, SpaceX or Mars One, just to name a few, have already started planning manned missions to Mars. Based on the information from their websites, NASA's current goal is to send a manned mission to Mars in the 30's. SpaceX believes to be equipped to send the first humans to Mars by 2024 and Mars One plans to land the first four humans in 2032.

Themes

Unlike any previous mission to the Moon, a manned mission to Mars poses a significant architectural challenge. Due to the mission's logistics, the crew will be required to stay on the planet for approximately 1.5 years (NASA, 2017), requiring a completely different approach to space habitats from how they are understood today. In order to ensure a successful mission, it is crucial to provide the future crew with physiological and psychological welfare. Such consideration makes architects a critical part of the design team as we are specialists in intercorrelations between the built environment and human well-being. Therefore, this will form the central focus of our project.

Such a broad theme of human welfare can be understood from many different perspectives. Some are highly complementary to those on Earth, mostly connected to the human body, which are universal and will inform our design despite its nature. However, some perspectives, especially the psychological and functional, are rudimentarily different than the current themes in residential architecture and will need to be examined further. We investigate both perspectives in detail and seek for an architectural response through the chapter Home.

In addition to a strongly anthropological piece of architecture, such a project is also a highly technical one due to the very specific environmental conditions and the currently unmatched nature of the mission, closely inspected through the chapter Mars. Many observed challenges are fundamentally different from the standard themes of building engineering on Earth and will, therefore, require many innovative solutions contemplated in the chapter Engineering. In this project, both the anthropological and technical approaches are strongly reciprocal and need to be considered thus, as one will not exist without the other.

Relevance

We hope to start a discussion on how architects can understand or possibly even redefine the notion of home in spaces fundamentally unfit for life. We also ask ourselves what the architectural essentials to human welfare are and what the architectural core input in space travel will be. Such a discussion will be crucial if we are ever to become interplanetary species which might potentially be paramount in ensuring human survival.

We argue that now is the time to start developing architectural concepts for the future habitats as their design will also largely influence the design of the journey in relation to the transportation payload and the deployment of the structure.

Human exploration

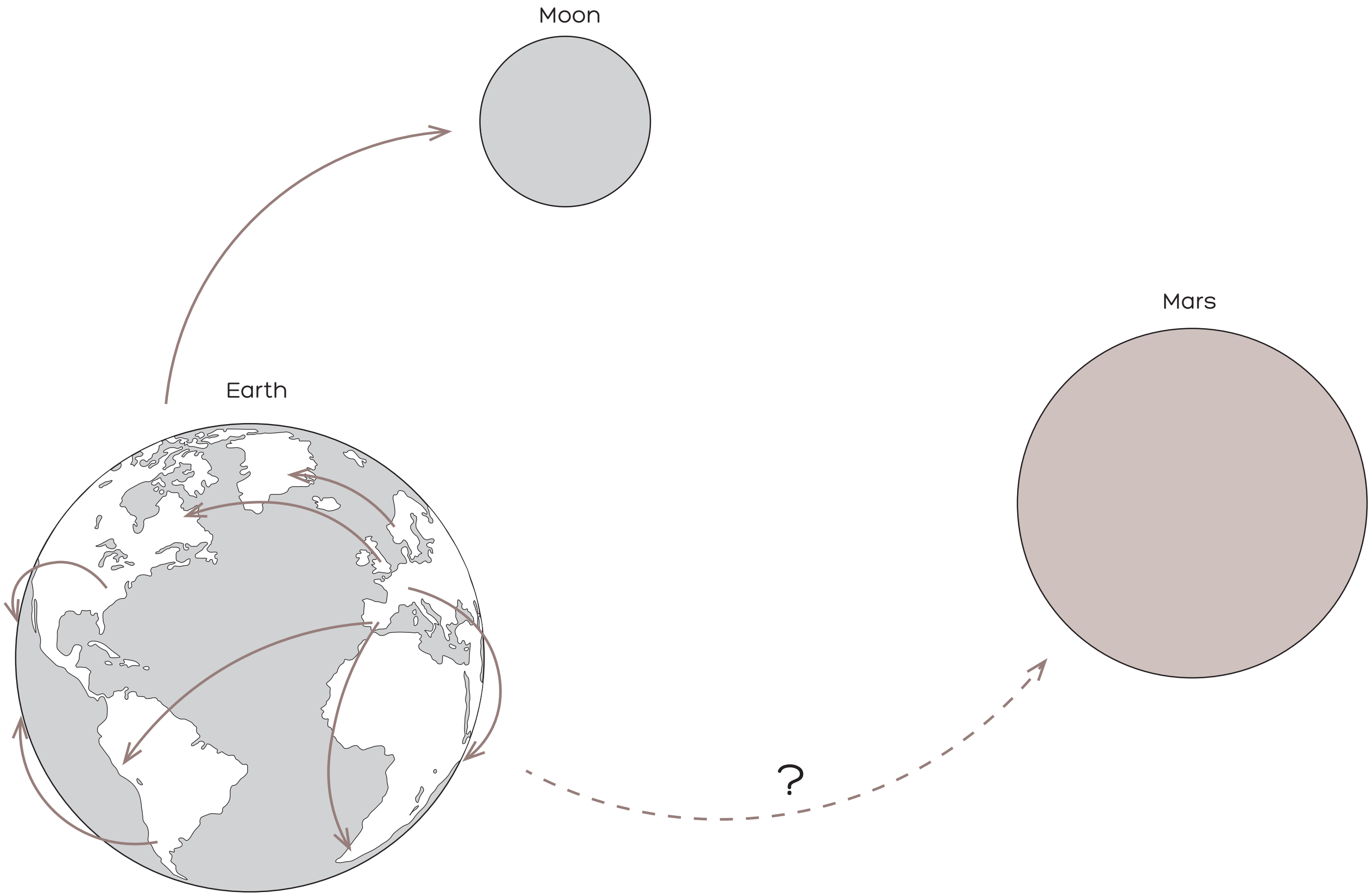

Illustration 1.: Human exploration

SYNOPSIS

Task

Our primary task was to design a first Martian habitat that combines the anthropological aspects of an ideal home and work and the technical aspects of structure, construction and self-sufficiency of the potential manned mission to Mars in an architecturally sound design. This NEW HOME will serve the combined function of a space base, dwelling and a highly-specialized place of work. The overall design will be informed by thorough investigations of the affiliated social patterns of the user group, the specialized functionality and technical challenges of each element. The habitat will be a permanent structure, mostly prefabricated and transported from Earth and deployed on the surface of Mars and finalized by utilizing local resources. It is presumed that said structure will support the crew for a 1.5-year period before a return journey is feasible and the current occupants replaced with a new mission.

Scale

Said habitat will host six people, building on the most up-to-date NASA Mars reference missions from 2009 where such crew is considered ideal and will, therefore, be our point of departure for the occupants of a single habitat. The particular volume and floor surface of the habitat and all its components will be determined through detailed investigation of all the defined anthropological and technical challenges, through the affiliated case studies and the consequential design process.

Location

No landing sites have yet been established by the space agencies and, therefore, the choice for a habitat site was fully under our advisement. As seen in the chapter Geography, due to the Martian environment, lower altitudes in the tropical zones exhibit most favorable conditions for inhabitability and seem as the ideal starting point for our design. One specific location is illustrated in the chapter Mars. However, such extensive project requires an open mind in many aspects of the design process and we, therefore, used our particular habitat design as a parameter that informed the choice of the site and vice versa to assure the ideal conditions for our particular solutions at a later stage of the process.

Focuses

Even though there are numerous challenges and unknowns within such an immense task, we pursued what we believe to be the core approaches to architecture and also the most relevant themes for such a project - the anthropological approach, where the human mind and the body are the centerpieces of any modern architectural design and the technical approach, as a means of reaching the anthropological goals in an architecturally sound, valuable and meaningful solution. The closer themes of said approaches can be seen in illustration 2.

Anthropological Approach

What are the environmental physiological dangers to the human body on Mars?

What are the psychological challenges bound with a potential manned Mars mission?

What does the term “home” mean from a phenomenological perspective and how can this finding help us in architecturally answering the psychological challenges?

How is the term “home” understood from the architectural perspectives and how can the lessons learnt from Earth application help us in an extraterrestrial dwelling design?

What does the history, phenomenological definition and home architecture theory teach us about the combination of dwelling and office functionality under a comprehensive concept of home?

What existing example of space dwelling and working can help us answer our humanistic challenges? How can we use the previously acquired knowledge to analyze it and use the acquired knowledge to inform our design?

Technical Approach

What are the structural implications of pressurized systems? What lessons can we learn from the mechanical design of pressure vessels on Earth? Do the daily pressure fluctuations within and without the habitat affect its design?

How can we use the learnt knowledge to select structures that can sustain the inhabitable pressure and be economical in its transportation weight and assembly system?

What are the possibilities for building the construction in unhostile Martian conditions and what are crucial parameters for construction of the design?

How do we secure indoor comfort for physical and psychological well-being of inhabitants?

How can we ensure sufficient amount of oxygen, water, food and energy for long term mission without supplies needed to be brought from Earth?

How do we design a solution to all the aforementioned challenges while minimizing the dependency on Earth’s resources?

Illustration 2.: Approach

TMIDP

Introduction

IDP as described in 2003 by Knudstrup is a strong tool in managing the design process, however, is only concerned with the design phase itself. It doesn't describe a project as a whole and its connection to a given timeframe. Virtually, it is a never-ending circle of iterations without any rules on how to structure one's creative work within a certain timeframe.

Description

Due to the complexity of our project, we need an expanded system that would help us structure our work in order to use the given timeframe as efficiently as possible and to move forward at all times. That is why we have developed a new expanded methodology that builds on the current IDP – "Time Management Integrated Design Process" (TMIDP). It divides the project into three main phases: The Kickoff Phase which is an initial phase serving to deepen the understanding of the task and its challenges, the Design Phase where the project is advancing towards a solution and the Acceptance when submission is imminent and no time to advance remains.

The three main phases are further divided into seven different stages represented by circles. The surrounding surface represents the unaddressed complexity of the project in each particular stage. Task is the first stage where program is being developed or design brief being understood. At the very beginning, a certain complexity already exists due to unfamiliarity with the project. Throughout the progress within this stage, minor questions are answered and other minor questions arise. The second stage is Aggregation which formulates the challenges and focuses that need to be addressed through the design; and develops the consequential analysis used to provide oneself with the means of answering them. This stage represents the largest growth of complexity of unanswered questions. Problem or Idea / Investigation / Sketching / Synthesis / Presentation is the slightly revised IDP, originally by Knudstrup (2003). Through these iterative stages, complexity is being addressed. Design advances with the exception of minor issues arising, due to their unpredictability within the Analysis stage.

Relevance

a / Task stage must be done thoroughly so it doesn't need to be revisited in later stages. Such a setback would throw the entire process off balance and considerably decelerate the progress. b / During the Task stage, one should recognize only the crucial facts as lingering in formalities decelerates the progress and does not inform the project to become stronger. c / Analysis should be as strong as possible to fully understand any relevant challenges so they can't arise later on and the new issue spikes in the design phase are not larger than the previous advances. d / In the Analysis stage, it is important to prioritize the challenges so the complexity of the project doesn't cross the Line of Overambition from where it is no longer possible to solve all said challenges within the timeframe. e / However, it is crucial to attempt to approach the Line of Overambition in order to assure a strong project within the given timeframe. f / It is crucial to stretch the design phase over a majority of the timeframe in order to be able to afford more iterations. g / The speed of progress and level of complexity during the design phase should be continuously adjusted so the unaddressed complexity ends in a spike at the Line of Acceptance (Illustration 3).

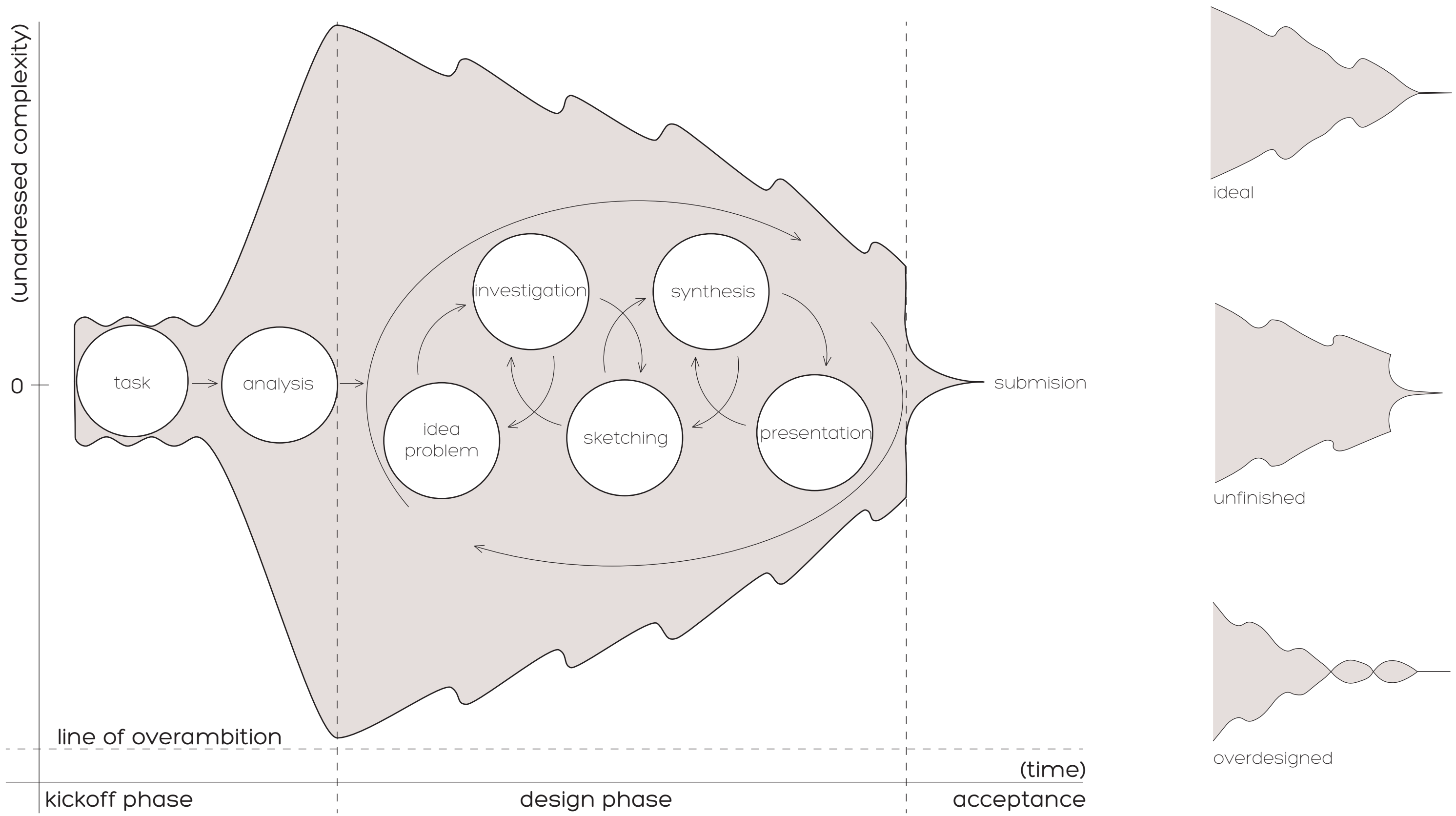

Illustration 3.: TMIDP diagram

TECHNICAL APPROACH

Introduction

In this chapter, we describe how we structured our work to efficiently address all the selected technical challenges (see Engineering analysis). The theoretical knowledge and calculation methods behind the selected technical approaches will be helpful in creating informed decisions from early phase of the project.

Approach

Through theoretical analysis of climate, geography and physiological threats to humans (see Mars analysis), we determined the technical issues related to the design. Awareness of climate and geographical limitations on the red planet was crucial for further technical development. Given the constrains of atmospheric pressure, it was necessary to understand mechanical forces of pressure vessel (see Pressure Vessel analysis) on the building envelope through different studies of geometries and empirical calculations. Based on the knowledge of pressure vessel, different types of structures possible in Martian environment were explored.

The consideration of the transportation impact on design brought another technical challenge. Limited weight and volume influenced the construction method (see Construction analysis). In close relation to transport was self-sufficiency (see Self-sufficiency) of the habitat. Together with indoor climate (see Indoor climate), they were approached conceptually, without detailed calculations or simulations.

Choosing the most appropriate structure and construction method based on all the selected technical approaches required further understanding of correlations between pressure forces induced by the pressure vessel and the geometry of its container and exploration of possibilities for form-finding through experimentation. In order to find an ideal composition of the selected structure in relation to optimization of its structural performance in accordance to the pressure vessel, optimization of the deployment, reduction of the Earth-bound material and in relation to its ability to allow for all anthropological approaches (see Home analysis) usage of TMIDP (see TMIDP) phase methodology was important.

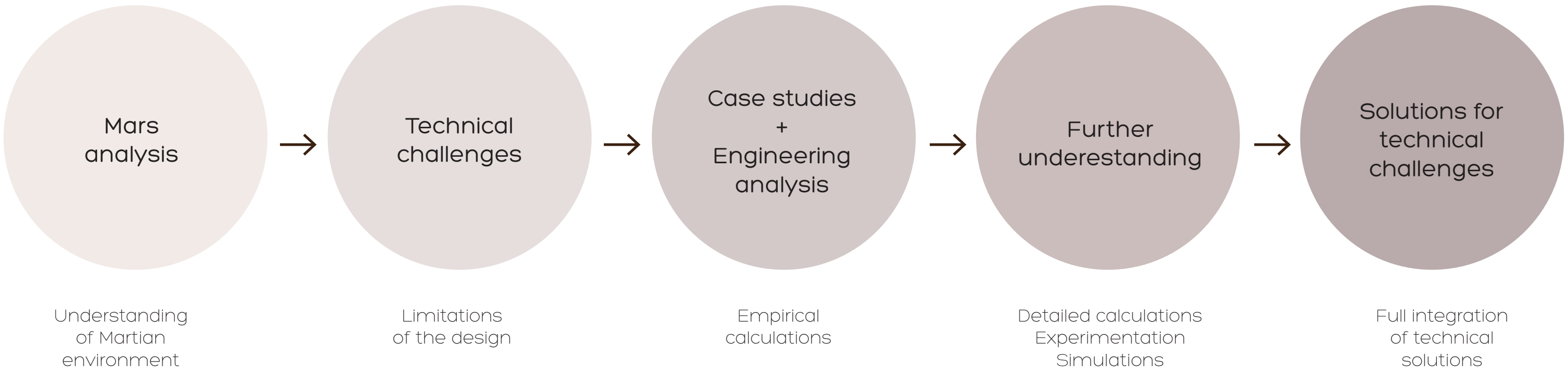

Illustration 4.: Technical approach diagram

MARS

geography / climate / physiological threats
psychological threats

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Within this section, we attempt to gather and understand specific issues and challenges, in relation to the focuses set in the previous chapter, coming from the specificities of the Martian environment and the mission in general. In particular, we investigate the overall geography and climate of the planet to determine all possible environmental challenges in relation to the theme of physiological welfare and all the technical considerations. Secondly, we investigate the general nature of the six-man mission to determine the psychological challenges.

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GEOGRAPHY

Introduction

Mars is the fourth planet of our Solar system from Sun. Its radius is only half of Earth`s, although in Solar system, planet Mars is the most similar to Earth. With its axial tilt not even 2° higher, there are four seasons during a year, much like on Earth. One year consists of 668,5 days which are only 41 minutes longer than those on Earth. Due to considerably smaller radius of the planet, the gravity reaches only 0,38 of the Earth`s gravity (NASA, 2017). As a fraction of Earths gravity, martian gravity will have significant impact on the further design.
Martian gravity:
$g_{MARS} = g_{EARTH} * 0,38 = 9,81 * 0,38 = 3,73 m/s^2$

Martian surface is noticeably "rougher" than Earth`s surface, the highest and lowest point difference is three times larger. As a result of many previous collisions with asteroids or meteors, Mars has many impact craters. On the other hand, the north hemisphere has mostly flat surface of darker, brown colour. Both Martian poles are covered with desublimated carbon dioxide creating ice caps of white colour. In general, the top of Mars surface is mostly iron/rich basaltic rock covered with sharp shaped stones and dust of reddish colour.

Water

Under Martian surface is frozen water, especially colder locations of Mars and some craters have ice supply within several centimeters under the top. (Illustration 5) Besides that, Martian soil consist of many mineral ores, for instance aluminium, iron, magnesium, sulfur etc. Identical to Earth, due to hot core inside the planet, there is a possibility of geothermal energy supply, called areothermal on the red planet.

Low dense atmosphere of Mars does not block cosmic radiation effectively. The cosmic radiation could be defined as charged particles fast moving from the Sun. On Earth, it is shielded with strong magnetic field, which is absent on Mars. Different locations have diverse radiation, lower altitudes are exposed to radiation in smaller amounts because of thicker atmosphere and the opposite. Long-term exposure could be harmful and thus, it is necessary to provide shielding (NASA, 2017).

Water concentration in upper surface

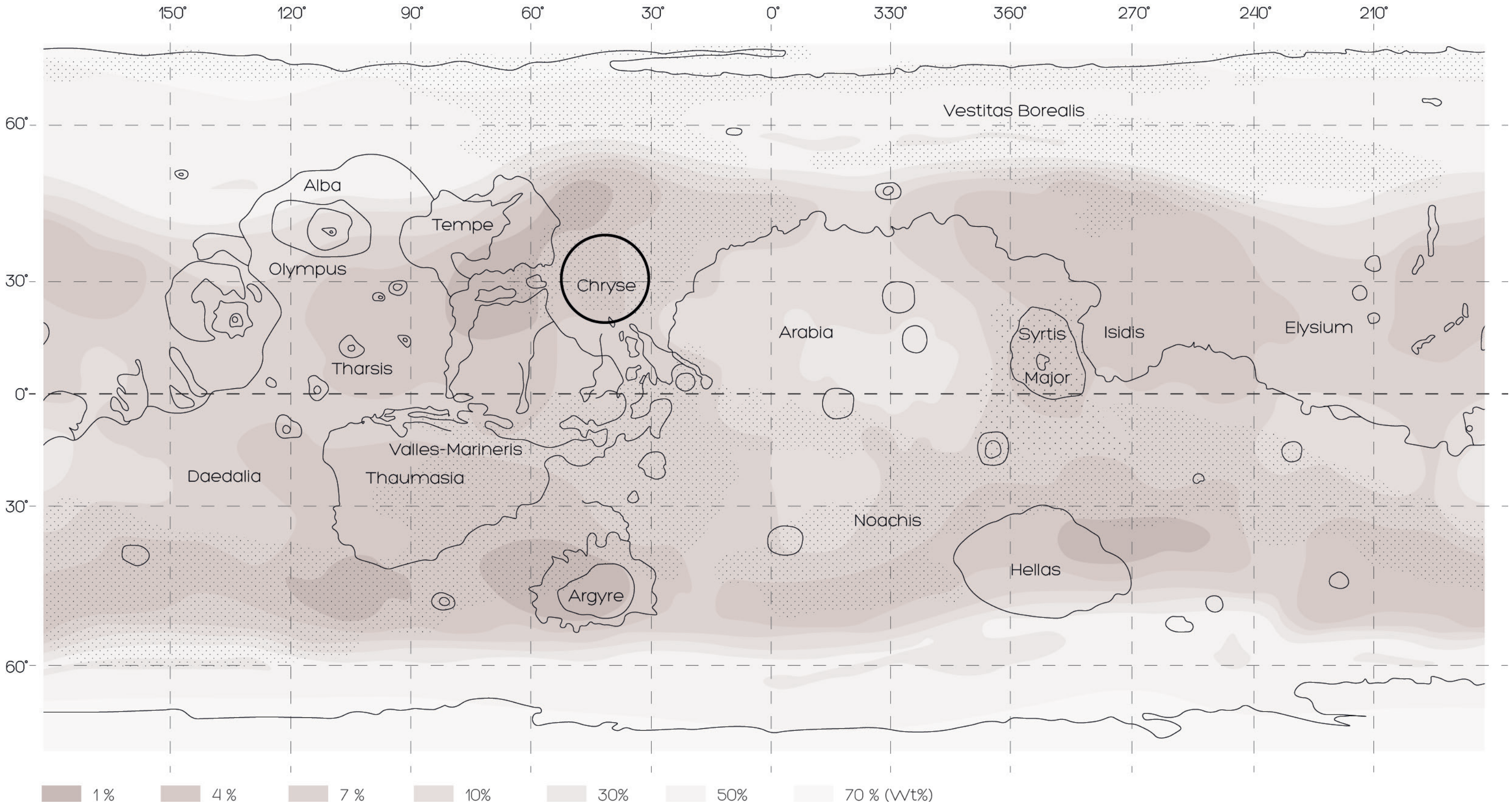

Illustration 5.: Water concentration in upper surface

CLIMATE

Atmosphere

The atmosphere of the planet Mars mainly consists of carbon dioxide (95,9%), argon (2%), nitrogen (2%), water vapor and other trace gases with a fraction of oxygen. Martian atmosphere has a low pressure of 0,6kPa, which is not even 1% of Earth's atmosphere Low atmospheric density causes enormous temperature fluctuations between days and nights. The average atmosphere`s temperature (in height relative to surface) reaches about -63°C (Illustration 6). However, the maximum temperature reaches up to 30°C and the minimum temperature up to -120°C close to poles, depending on weather seasons.

Together with extreme temperature differences, the atmosphere is very dry. Even though low atmospheric pressure and temperature leads to desublimation of any ice on the Martian surface, the atmosphere is very dry and clear, almost without any clouds. The clouds of CO_2 are appearing only close to polar cabs in spring due to the desublimation of dry ice (NASA, 2017). Martian surface is not exposed to rain, neither snow.

Weather

Weather has repetitive patterns. Events that occur at a particular time one year are most likely to happen next year at almost the same day at the same location. The weather on Mars is rather calm with several dust storms over year, mostly at southern hemisphere. The wind speed during the storm can hit 30-50m/s. Although it is considered to be hurricane on Earth, due to low dense atmosphere "the maximum wind speed on Mars is roughly equivalent to a 3,3 to 5,5 m/s wind on Earth" (National Research Council, 2002). Overall, the average wind speed on the red planet is 9-13m/s is comparable to 1m/s on Earth. The wind loads, significantly smaller than on Earth due to the low air pressure, will, therefore, not be considered in further calculations.

Dust storms lower overall amount of solar energy that reaches the Martian surface. The regular solar constant on Mars is only 50% of what reaches the Earth's surface, depending on the location.

Temperature during equinox

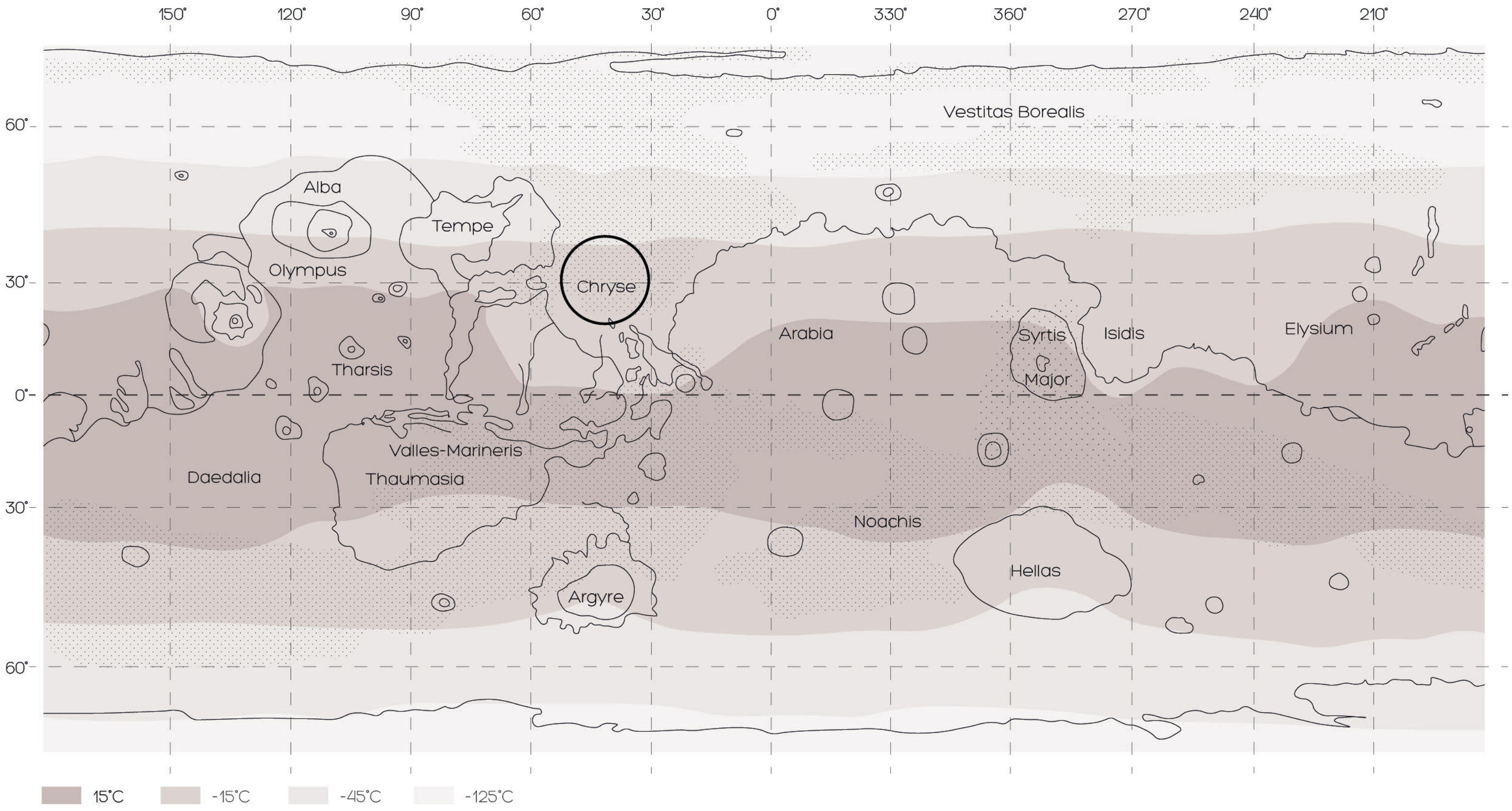

Illustration 6.: Temperature during equinox

PHYSIOLOGICAL THREATS

CO_2

In Martian extreme environment, humans are exposed to many threats that could possibly cause harm or even death. Atmosphere of the red planet represents several of these hazards. One of them is its low pressure (see Climate analysis) that could lead to decompression sickness due to moving through different pressure areas. Second hazard is the toxic composition of the air, mainly consisting of CO_2, that is poisonous for humans. Low concentration of O_2 in air could result in replacement by CO_2 in blood and thus, lead to death. Other hazard for human life is temperature and thus, “astronauts require temperature-controlled and pressurized dwellings and workspaces” (Kading, B., Straub, J., 2015).

Low gravity

Another hazard could be Martian low gravity. Although there is a lot of research on microgravity, it is not known what effect would have 0,38 gravity on humans. Microgravity causes osteoporosis, loss of mussels and other medical problems. Therefore, to some extent, similar effects could be prevented by exercise and pharmaceuticals.

Radiation

Coming from the Geography analysis, potential threat to people could be also raised by cosmic radiation. High radiation levels have delayed effects on humans, such as cancer, skin damage, genetic damage, suppression of immune function and others (National Research Council, 2002). The radiation on Mars is lower than in Space, but still considerably strong with average of 10rems/year in lowest altitudes to more than 20rems/year on highest points of the planet (Illustration). According to United States Nuclear Regulatory Commission, 2015, the maximum allowed radiation for humans is 5rems annually, which would be exceeded in 2-5 months. On the other hand, NASA allows exposure for astronauts up to 50 rems per year and such the 1.5-year long stay is well within the NASA standards and, therefore, does not represent a challenge. However, the occasional sudden solar flares, powerful blasts of radiation, portray a large threat that must be accounted for in the design.

Location

To lower the impact of radiation on the crew, the location of the habitat should be in lower altitudes, preferably crater. Moreover, lower altitudes provide ice (see Climate analysis) and smaller temperature fluctuations. In order to avoid long lasting dust storms, the habitat should be placed in Northern hemisphere. Analyzing the maps (Illustrations 5,6,7), the most beneficial location for New Home, combining minimal radiation, presence of water and acceptable weather conditions, would be Chryse, indicated by black circle.

Radiation

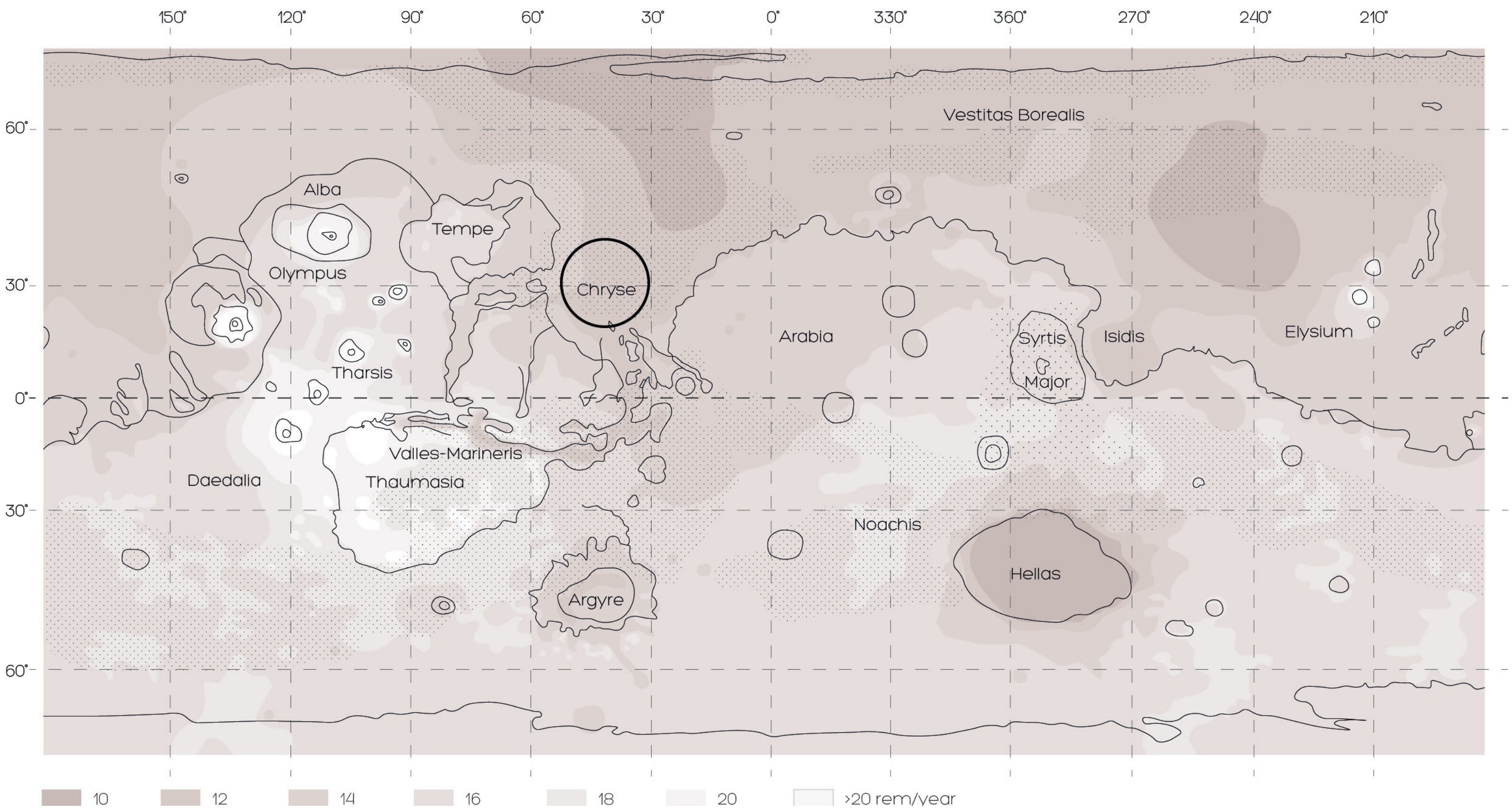

Illustration 7.: Radiation

PSYCHOLOGICAL THREATS

Importance

As contemplated in the motivation, the nature of a Mars mission will be far from anything mankind has ever experienced and the demand on the well-being of the crew will be an essential aspect for a successful mission. Here, we analyze the most crucial challenges on psychological well-being during the extended stay on Mars and offer a hypothetical solution.

Behavioral psychologists have a deep understanding of the effects of long expeditions on the mental state of a small crew, gathering knowledge from both the polar expeditions of the old and the ISS missions of the new. Their knowledge can help us in estimating the psychological challenges of the future, more demanding, Mars mission. This greater demand is summarized by Stuster, a leading NASA behavioral psychologist, in an interview: “Going to Mars and having Earth so far away for two or three years would be a challenge to even the most experienced astronaut.” (2016)

Challenges

Building on the experiences learnt from polar expeditions and the ISS missions, the largest psychological threat is isolation and confinement. (Stuster, 2010, 2011) They result in the main challenges such as sustained, close personal contact, where there is no escape and large emphasis is placed upon healthy social connections. (Palinkas, 2001, Stuster, 2011) The lack of broader social structures closely relates to the former but results in the feeling of seclusion, rather than frustration with team members. (Palinkas, 2001) Lastly, two other crucial challenges of isolation and confinement are boredom and homesickness. (Stuster, 2011)

In addition to isolation and confinement, the largest stressor on the crew will be an ever-present threat of death. Such danger is also present on the ISS; however, the nature of the much extended and distant Mars mission will handicap any possibility for an escape or a rescue mission. (Palinkas, 2001)

Conclusion

We believe that good design can positively affect the mental state of the user and this particular theme of architecture will be crucial for this mission as the future habitat will be the only thing separating the crew from death. They will have to put all their trust in the habitat and fully rely on it. This hypothesis is also supported by Stuster: “…need to be careful in the design of habitats, equipment, and procedures…” (2011)

In an interview, Struster said: “We know ISS but Mars will be very different and more pressing. You can’t see your home.” (2016) which gave us an idea. What if we bring home with us? Could that be, at least partially, the architectural answer to these challenges? Does home invoke the feeling of safety, reliability and strong social structures? Should we, as our first beacon of hope for mankind’s new home, design an actual first extraterrestrial home? A NEW HOME?

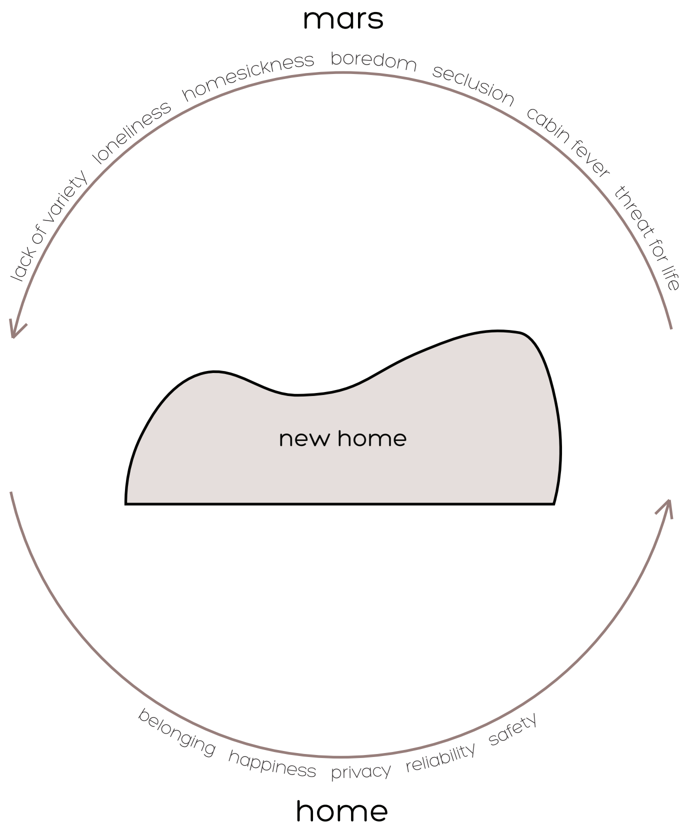

Illustration 8.: Psychological threats

HOME

phenomenon / dwelling
greenery / work / iss

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What is home? Is it a place, a feeling or a social structure? Throughout this chapter, we investigate the meaning from the phenomenological perspective of an ideal home and from the architectural perspective of an ideal dwelling, through which we seek the architectural answers to the psychological threats of the mission. Later, we examine the effects of time, greenery and inclusion of work on the observed qualities of home. Lastly, we investigate the crew's potential social patterns and the implications of the closest existing example to inform our design.

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PHENOMENON

Importance

Within this chapter, we try to tackle the questions stated above, whether a “home” can generally counter the psychological threats of such mission. In order to find the answer, we first need to analyse what the term “home” implies. Above all, it signifies an odd, subjective merger between the phenomenon and the physical matter. This merger is supported by Mallet (2011) in the introduction to her research by asking: “Is home (a) place(s), (a) space(s), feeling(s), practices, and/or an active state of being in the world?” In her research, she goes even further in describing the perspective on definition of this term and sums up, that most architectural research on this topic is highly dominated by the complete unification of terms home, dwelling, housing, residence or habitat.

However, from a multidisciplinary point of view, it is impossible to clearly define the term. As Mallet (2011) concludes: “It can be a dwelling place or a lived space of interaction between people, places, things; or perhaps both. The boundaries of home can be permeable and/or impermeable. Home can be singular and/or plural, alienable and/or inalienable, fixed and stable and/or mobile and changing. It can be associated with feelings of comfort, ease, intimacy, relaxation and security…” Due to such complexity of considerations in the search for a definition, we look into the general phenomena and qualities associated with the term “home”.

Phenomena

In her phenomenological research, Sixsmith (1986) also begins by defining the term in a very vague sense as one or number of places that are often identifiable through personal and social characteristics underlying any physical structure involved, and through their extent to which they are able to fulfil the person’s requirements, their changing objectives and circumstances. She then tries to closer specify the phenomena invoked by the term “home” though a representative sample of respondents and defines most crucial terms such as: Belonging, Self-expression, Extent of Services, Happiness, Spatiality (in order).

In her analyses of the data, she divides all the phenomena into three groups of qualities of home. The personal home refers to a reference point in one’s life that is encapsulated by the feelings of safety, security, happiness and belonging and the expression of self-identity. The social home is built around one’s most valued social networks and relationships in relation to their common emotions, actions or habitats. Lastly, the physical home is understood as the physical entity that embraces not only the structural elements and style or architecture but also the human space available that affords opportunities for personally highly valued actions. However, it is essential to understand that these qualities are closely interrelated between various meanings from a personally meaningful network of experience through which “home” is felt. (Sixsmith, 1986)

Conclusion

In our reflection upon this analysis, we are confident to summarize the phenomenon of home as: one’s significant place/s, created, maintained and experienced through a series of strong positive emotions and feelings in relation to physiological, psychological and social aspects of safety, belonging and happiness. These emotions would be highly valued and strong means in battling the aforementioned challenges of isolation and confinement. In addition, through this analysis, we haven’t found a contradictory aspect to our cause that might convince us of the impossibility of such endeavour. However, one large question still remains: What are the correlations between the phenomena and physical entities?

Illustration 9.: Phenomenon

DWELLING

Introduction

In the following text, we tackle the question of home from a more architectural perspective as described in the previous chapter; where home, dwelling, housing and many other similar terms become one and the same in an interrelated physical and phenomenological manner. Closer understanding of such a merger of terms provides us with a deeper insight into the appropriate design processes behind the design of an ultimate home and hopefully provide a few examples of physical architectural element examples of such home, helping us out in our ambitious endeavor to successfully design a Martian habitat that the occupants can call home, a NEW HOME.

Comfort

Our conclusion of the broader phenomenon of home is surprisingly close to how architecture perceive such phenomenon that is signified by general positive emotion connected to a place; such as Rybczynski (1987) states that domestic well-being is a fundamental human need that is deeply rooted in us and must be satisfied. However, in addition to the aforementioned physical merger of terms, there is a slight but critical divergence in the qualities used to describe a home. Safety and belonging are no longer the primary terms describing a home but a shift exists towards qualities such as comfort, convenience or privacy, described by Evans (1997), which are social constructs starting to emerge in the 17th century. Similarly, Rybczynski (1987) emphasizes comfort as the essentiality of any home, above any other aspect, and convenience and privacy are simply contributors to the quality of comfort.

However, such a realization raises as many questions as it answers. What is comfort? Is it something objectively physical, rational and quantifiable or something subjective, unquantifiable and poetically emotional? Rybczynski (1987) states that both perspectives are equally correct and examples of both perspectives exist. Building on his work, we argue that a clear division between the two perspectives is impossible, as many parameters exist in numerous dimensions. We go even further to argue that for a sound comfort one cannot exist without the other and they need to be considered on a multidimensional level.

Social Patterns

The rational and quantifiable qualities of comfort are self-explanatory as they are strictly tied to physiological well-being. That is not the case for the poetic side of comfort and therefore, in his further quest of defining this aspect, Rybczynski (1987) focuses mainly on questioning the stylistic and behavioral aspects of space. He argues that décor or style are insignificant aspects of space and that it is the behavior that the space evokes is the main element of comfort. He describes the necessity of studying the evolving social traditions and patterns in order to define comfort, rather than studying the décor as it is relatively a short-lived phenomenon in comparison to social patterns: “Changes in fashion occur more frequently than changes in behavior.”

Rybczynski (1987) supports his theory by using a case of a décor that attempts to recapture the comfort of the past through its use of the exact visual qualities of a certain era. He refers back to his theory and claims that such elements miss the essential ingredient of comfort as the sentiment of comfort was a result of large cultural condition that developed into a certain expression and not the other way around. He continues by describing the example of a Colonial house which was a comfortable entity for the Colonial era but is merely an image of a time gone by.

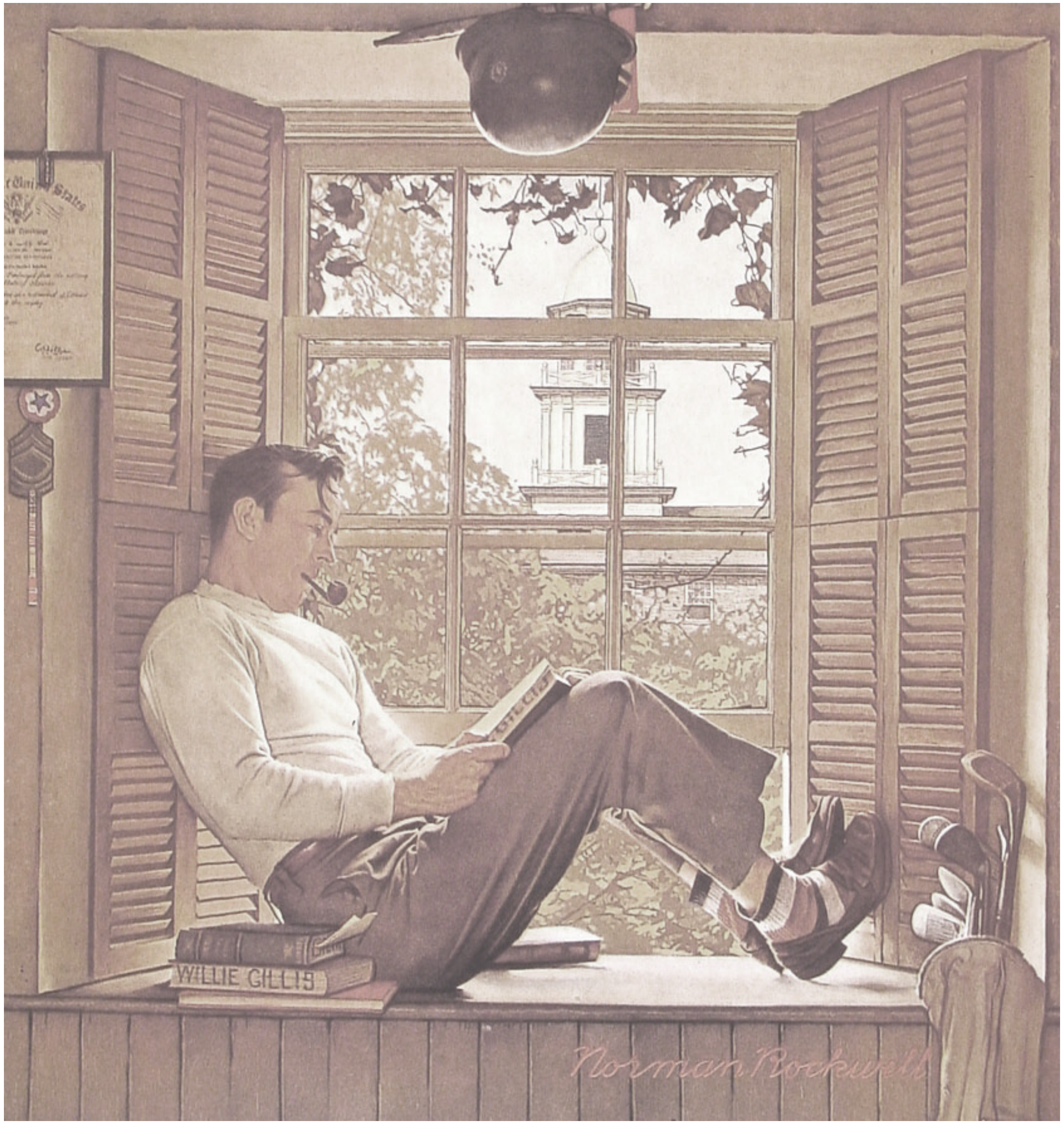

Illustration 10.: Willie Gillis: A College (Norman Rockwell, 1945)

Examples

In order to better understand both the rational quantification of comfort and the poetic ineffability of comfort resulting from different social patterns of certain ages and their frequent multidimensionality, we have chosen numerous significant examples of these constructs, better clarifying their nature.

Starting with one of the most crucial social shifts resulting in an extremely significant architectural innovation was the need to separate occupants of a house from their servants. Up to this social pattern shift, rooms were positioned enfilade, next to each other with a door in the middle of the partition wall. However, as a consequence of this social shift, the architectural element of hallways emerged and over time became a crucial aspect of architectural design as described by Evans. (1997) In the modern world without servants, we can again sense yet another strong social change. Due to modern technology, the rise of leisure activities outside the residence and in some cases tourism, we have started being alienated in our social relations within our own home. This social shift results in a continuous transformation of hallways into multi-purpose social constructs that promote interaction and, in many cases, vanish completely. (personal observation)

Yet another paramount example is concerned with the self-expression and self-realization through one's home, using the observations by Sparke (2008) and Stone (2015). During the industrialization in the 19th century, a large social shift occurs as the man of the house is required to leave for most of the week in order to work. This resulted in home being a strongly private place, somewhere for the man to retreat to from the rigors of industrial life and for the woman it became the extension of her own self, her personality. After the social shift from the previously strong social division, both members of the couple are required to leave the house and thus the home becomes the extension of the entire family, its way of interacting and passing time.

The previous two examples explained mainly the effects of the social pattern change on the home in its convenience and general sentiment of comfort. Within this paragraph, we will simply summarize the other developing aspect of comfort, the physiological human well-being, without any further explanation we don't believe to be necessary. Firstly, architectural history shows a continuous growth of minimal spatial demands for an individual. Secondly, the demand on the indoor comfort from the perspective of temperature, natural light or ventilation has been significantly rising the past two hundred years, all in connection to physiological and mental well-being.

Conclusion

Even with the slight change in phenomenological and architectural descriptions of home, after the revision of Rybczynski's work, we can state with confidence they are, in fact, one and the same, only with a certain divergence caused by time. Terms, such as safety or belonging, do not appear in architectural definitions of home anymore. Perhaps, they are considered to be obvious in todays architecture and are, therefore, no longer discussed. However, these elementary values of the phenomenon cannot be forgotten, especially in our conditions, where architecture must refelect back on its primordial and elementary values that are the aforementioned safety and shelter.

Nevertheless, we have learnt that a home is a construct of comfort, through its aspects of convenience, privacy and physiological well-being that are the results of human demands and current and relevant social patterns within the occupants of such home that all need to be used within their multidimensionality. It is, therefore, apparent that, in order to create the sensation of home as architects, we need to clearly specify the social patterns of astronauts, our user group, and use the acquired knowledge to inform our design.

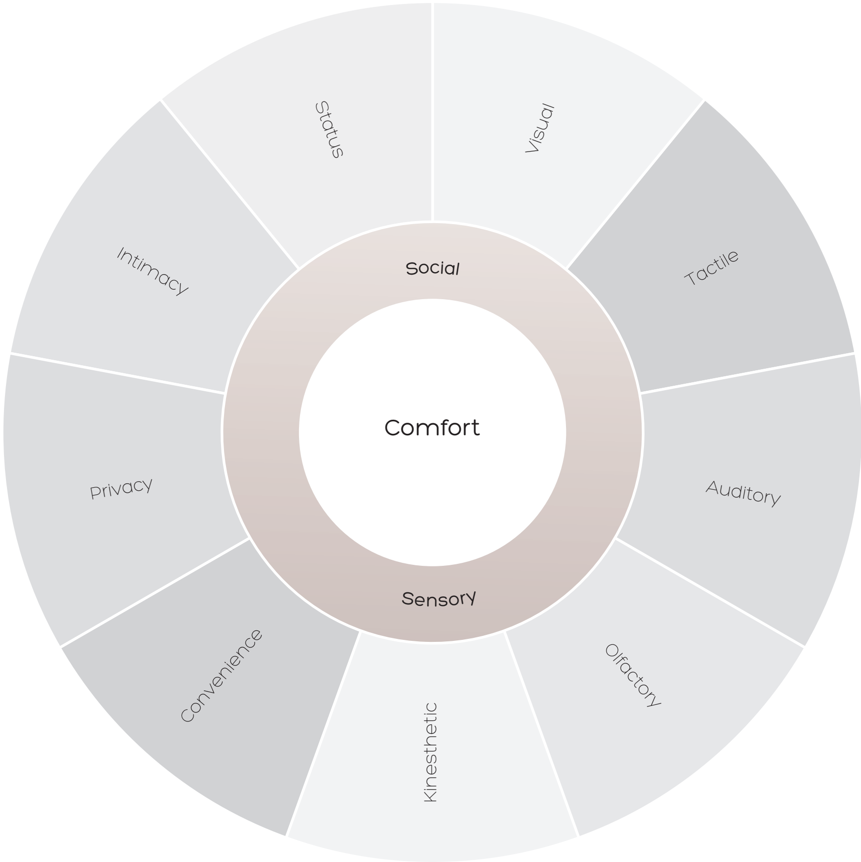

Illustration 11.: Dwelling diagram

GREENERY

Introduction

Within the previous few chapters, we have investigated the phenomenon and architectural implications of the concept of home. However, we haven't considered the physical scales yet. What if we took a large step back to inspect the bigger picture? It is Earth that is one large home of all of us and is very different from Mars, the place that we are trying to create a NEW HOME for the mission crew. One of the biggest differences that makes Earth our home and that we can't imagine living without is greenery. Thus, within this chapter, we ask ourselves, what is greenery's place in a home on a smaller scale? Does it somehow relate to the phenomenon of home or qualities of dwelling retrospectively?

Benefits

Throughout our analyses, we have found extensive strong evidence of positive psychological and sentimental implications of humans' proximity to greenery and its maintenance that directly or indirectly correlate to many of the definitions of home. As described by Kaplan (1973) and Brook (2010), nature and close relation to greenery will lead to the sensation of belonging and attachment to particular places and environments and supportive behavior, both closely relating to the phenomenon of home. In addition, based on the works of Elings (2006), the active participation in gardening results in "positive social and psychological outcomes … such as increased self-esteem, improved health, sense of community, accomplishment and pride."

In addition, greenery poses other psychological benefits that could help tackle some of the other psychological challenges faced. As described by many researchers: "Gardening can be a possible coping strategy for stressful life experiences and can be beneficial for the physical, emotional, social and spiritual well-being". (Elings, 2006) "… indoor plants can significantly change the anxiety level" (Chen-yen, C., and Ping-Kun, C. 2005). "[greenery] … may promote health, well-being and social safety through three mechanisms: enhanced physical activities, reduced stress and improved social cohesion". (Elings, 2006)

Mars

However, the question arises: Are we capable of growing plants on Mars? It turns out that many botanists and academics have been concerned with this issue for years now. The results of these studies are not fully comprehensive and provable but most scientists believe it to be possible with a few alterations. Firstly, a recurring issue is the biological content of soil, necessary for growth, which is absent from the Martian regolith. This could be solved by adding the necessary nutrients and partially by using wastewater, a view supported by NASA (2015).

Modernfarmer (2015,2016), a botany newspaper, describes challenges regarding the toxicity of the potential produced crops. There are two potential threats, heavy metals found on Mars and perchlorates. However, scientists have used soil of similar composition to test the harvest and they have found no unsafe levels. Perchlorates would be a larger toxicity issue but can be simply rinsed out from the regolith before nutrients are added. Alternatively, all crops can be grown hydroponically, which is a method of producing crops in special water solutions without soil.

Conclusion

Within this analysis, we have found greenery to have many psychological benefits to both individuals and social structures, and some of the sensations experienced through gardening or simply by the proximity to greenery correlate directly to the phenomenon of home and might pose an additional means of reaching these sensations. In addition, we have found many scientific experiments, dealing with producing crops on Mars that state growing plants should be feasible in the Martian regolith or it could be grown hydroponically.

Illustration 12.: Outoor greenery

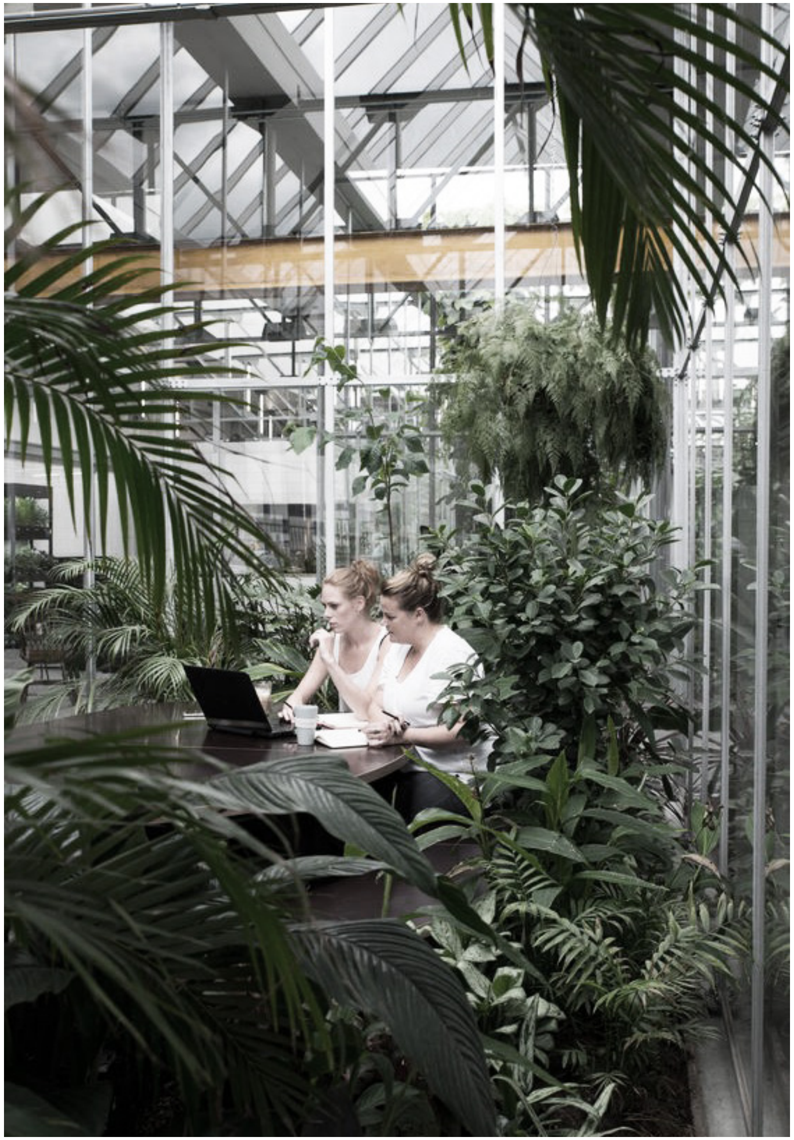

Illustration 13.: Indoor greenery

WORK

Introduction

The endeavor of understanding the social patterns of the potential crew needs to be driven by two different perspectives. In this chapter, we employ the theoretical perspective of analyzing the future social patterns that will develop on the potential Martian manned mission. It is absolutely crucial to emphasize that such a mission will not be an exciting form of tourism but a highly scientific and professional mission with enormous responsibility and ambition. However, we then need to ask ourselves how this parameter affects our concept of home. What effects does it have on the ultimate home of comfort? Here, we try to investigate the answers.

Divergence

Throughout the past centuries, social pattern shifts have occurred that completely changed the perspectives upon the reciprocity of a home and a place of work and largely influenced the ways in which they are occupied and, consequently, their architecture. Building on the writings of Benjamin (2002), Sparke (2008) and Stone (2015), prior to the eighteenth century, home and a place of work were, in most cases, completely merged and no differentiation existed. The most significant social pattern shift has been caused by the industrialization era when factories are on the rise and require their employees commute for the first time. This social separation has largely influenced both the functionality and the phenomenological character of a home for both genders.

At the beginning of the 21st century, we can observe many deviating shifts in both the domestic social patterns and the working pattern. Building on the observations by Stone (2015), the ultimate office and home have very divergent qualities. Office is a place designed with the intention to support and stimulate concentrated work for a fixed amount of time without causing harm. Contrarily, the ultimate home must be adaptable for a number of different activities and situations connected to the occupants. However, she argues that the strict barriers between home and work have been eroded due to the rise of technology and demands on the employees: “The home is now a place where the boundaries between private and public, work and leisure have been eroded.” She points out that dwelling architecture is yet to respond to these changes.

Conclusion

Both Stone (2015) and Turkle (2011) describe the negative effects of the merger between the home and work on the life of an individual due to the tendency of a teleworker to overwork as there is no need to distinguish between work and one’s family and other commitments. The home phenomenon is becoming spoiled with the rigors of work. Building on our findings both functionalities are designed for comfort and should, therefore, be easily combinable. However, as we learnt before, comfort is not a universal phenomenon but rather is a construct of the particular social patterns and both home and work exhibit uniformly detrimental social patterns.

However, the astronauts’ overall social patterns will be fundamentally different from any Earth’s social structure, due to their training and the nature of the mission. Within this highly specific case, why should we understand home as an equal counterpart to work, as considered on Earth? Divergently, we will employ our previously gathered theory of home phenomenology and comfort and further gained knowledge to design a partial designation of the habitat to the leisure activities and work under a comprehensive concept of home, a NEW HOME.

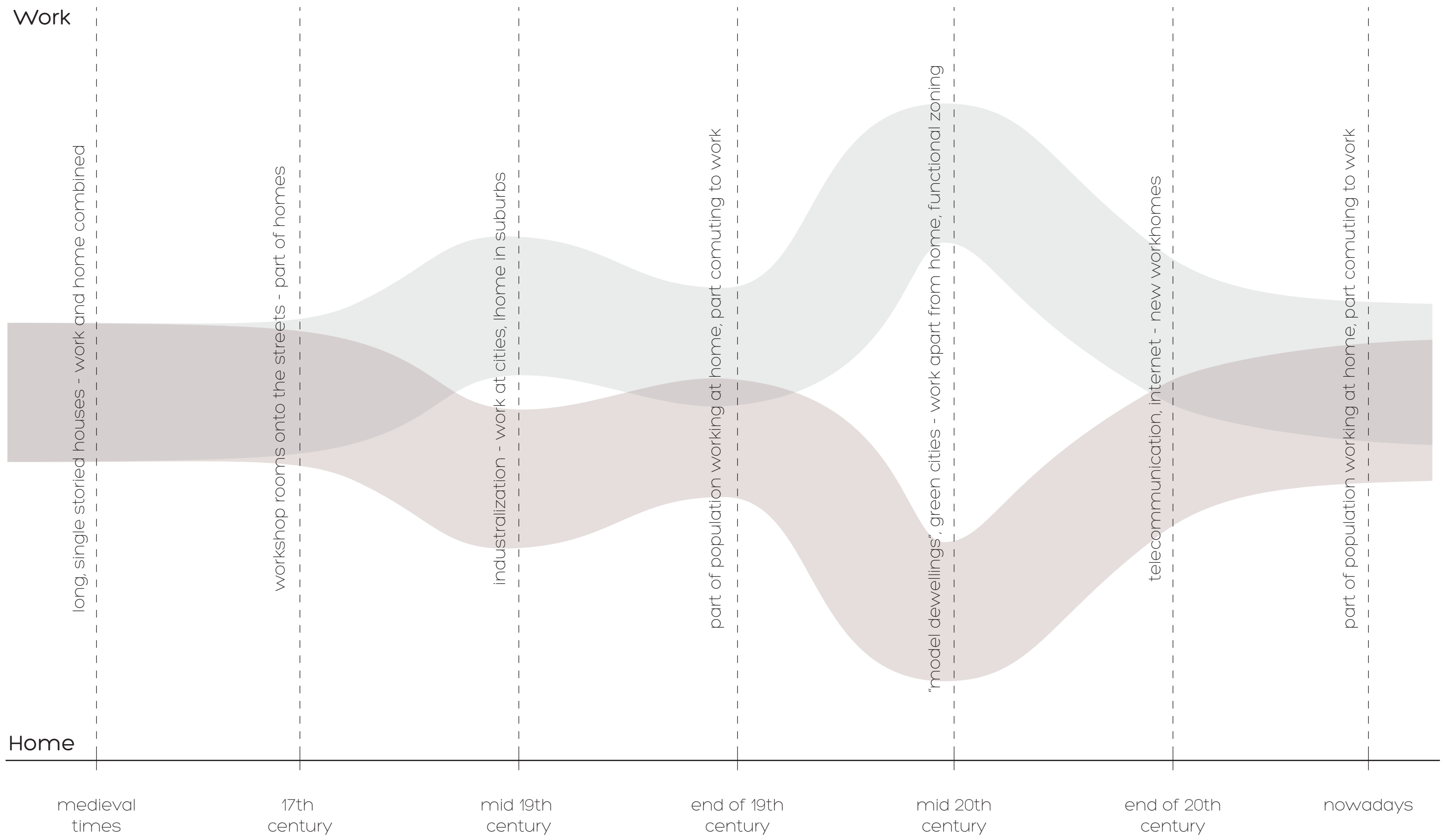

Illustration 14.: Work diagram

ISS

Introduction

Within this chapter, we build upon the previous theoretical studies and use the knowledge acquired to carry out an empirical study of the ISS, the most similar existing example to our particular case, to investigate the possible social patterns of the potential crew, in relation to their work and leisure activities. These patterns will be investigated through the factual daily, highly standardized, routine of the ISS crew, building upon the knowledge acquired through numerous NASA and ESA articles and the crew's blogs and journals, and the consequential behavioral psychology research on the behavior and mental state alterations of the crew by Stuster (2010).

Work

The most crucial aspects of the crew's work routine, that needs to be understood, is the permanent and ever-present scheduling, controlling the member's each minute of the ten working hours per day. In addition to the strict time schedule, each working task is standardized by draconian procedures and are continuously monitored by the mission control removing any sense of independency or privacy, closely tied to the phenomenon of home as described above. All of these patterns act as the main stressor on the entire crew but are necessary to avoid any possible failures that could result in fatal errors for the crew and, in addition, according to Stuster (2016) are the superior alternatives to possible boredom.

Other important working social patterns, developed on/for the ISS missions include relative professional independency of the crew members, as it consists of specialists from different scientific fields who all have different research tasks and barely cooperate. Secondly, it is necessary to point out that all members are subjects to daily exercise and medical inspections to assure physiological well-being. Lastly, it is necessary to express that unlike onboard the ISS, the future Mars crew will be mainly tasked with exploration and sample analyses.

Leisure

Due to the tight schedule and all the psychological challenges of such mission, the leisure activities play a crucial part in sustaining the mental well-being of the crew. The most important developed leisure social pattern is common cooking and eating, where the entire crew gathers and enjoys a break from the daily rigors. However, private leisure activities play an equally crucial part in ensuring the mental comfort, as it allows to escape the cumulative stress of isolated community. These activities include small group activities such as music or board games or strictly private activities and projects, such as photography or reading or education in the private quarters: "…private quarters designed to mitigate the cumulative stress that results from the unrelenting proximity of one's comrades." (Stuster, 2011)

Conclusion

The observed social patterns help us to inform our design to achieve convenience and privacy to construct the ultimate comfort in the divided two main social pattern zones, home and work, as described in the previous chapter. Most of our findings of this entire chapter, the need for both the physiological well-being of the body and the spiritual comfort of the particular social patterns, are very closely summarized by Leich (2014): "To create a perception of physical and emotional comfort, the individuals should be given personal freedom, creating different interaction zones within the habitat. Another big concern is a sensory deprivation, "it is impossible to go out to 'breath some fresh air' - environmental control (temperature, humidity, pressure, illumination, olfactory), communication, audio systems and food are all employed as stimulating countermeasures to this."

Illustration 15.: Social patterns diagram

ENGINEERING

pressure vessel / structure / construction
indoor comfort / self-sufficiency

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Within this technical section, we seek answers to all our main themes within the technical approach, as described in the Synopsis, from both theoretical and design perspectives. We investigate the implications of the difference between the indoor and ambient pressures on the structure and their possible design solutions. We analyze possible materials and methods of construction, demands and corresponding technical solutions for the atmospheric comfort of the habitat and strategies for minimizing Earth-dependency.

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PRESSURE VESSEL

Introduction

Based on the knowledge learnt through the Mars analysis and the Physiological threats analysis, in order to sustain standards for human life, it is necessary to keep the indoor pressure at 101kPa. Earth's atmospheric pressure at sea level (101kPa) is also used as a standard at International Space Station (NASA, 2015). Therefore, any space habitat needs to work as a container that holds extensively higher pressures from the ambient pressure, also referred to as gauge pressure. Such a container is called a pressure vessel.

Geometric design

Pressure is always a normal vector to vessel surface. Therefore, the most efficient geometric design for pressure vessel is a sphere where the stresses are distributed evenly (Illustration 16). Less effective, yet easier to construct are sections of spheres, for instance cylinders or cones. The thickness of pressure vessel proportionally depends on gauge pressure and its volume.

Angular Vessel

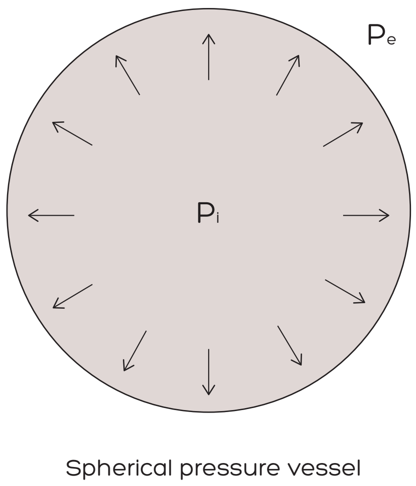
Constructing a corner in the pressure vessel would lead to a bending moment (Illustration 17). Normal forces push walls outside direction from pressure vessel, which creates an enormous stress concentration in the corners. As spherical pressure vessel carries only tension force, added bending moment in corners would require extensive use of material and thus, the structure would become more massive.

Gay-Lussac's Law

Gay-Lussac's law is thermodynamic law that describes the relation between pressure and temperature with a constant volume. This law is relevant to the design because the hourly fluctuation of temperatures within the habitat (due to heat losses, passive solar heat gains, room use schedules et. al.) could therefore affect the gauge pressure. Due to large volume of the habitat, this could significantly affect the inside pressure and thus, endanger the functioning of the habitat.

Other Features

In order to prevent any collapse of pressure vessel, it is necessary to control the limit of pressure in the system by PRV – Pressure Relief Valve.



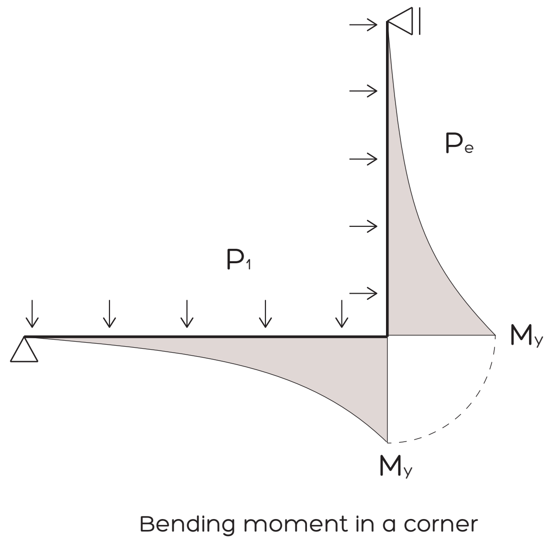


Illustration 16.: Spherical pressure vessel

Illustration 17.: Bending moment in a corner

STRUCTURE

Introduction

Structure on Mars is exposed to different loads than on Earth. Like stated in Climate and Geography analysis, there is no snow, the gravity is markedly lower and wind loads are insignificant. The biggest load (as mentioned in Pressure vessel) is the pressure inside the building. Another important parameter for choosing the structural system is its transport to Mars. Thus, in order to create a feasible structure on the red planet, we have investigated what kinds of structure are possible to use.

Options

One of the potential structures for the red planet is geodesic (Illuatration 18). It is 3D curved structure made of linear elements and planes in between them, often made of triangles or hexagons. This rigid structure is type of thin shell structures which carries both, compression and tension. It is often used as a greenhouse, what could be beneficial in Martian cold environment.

To carry the inside pressure, an additional weight could be added on the top of the structure. Heavy weight structure leads to a compression from outside. On Mars, weigh element can be made of regolith.

In order to minimize the space demand for transportation on Mars, the structure could be deployable. Their advantage is the possibility to change shape and size of the structure (Illustration 19). There are two types of deployable structures: rigid component deployables and deformable component structures (Adrover, 2015).

A kind of deformable deployable structures are pneumatic. They are entirely tensile, lightweight with minimal storage volume and translucent. Air supported pneumatic structures are single membrane enclosing the inside environment. They require higher inside than outside pressure which is essential for Martian habitat. The simplest air inflated structure is made of one material, which could demand a bigger thickness of material (Illustration 20). To create larger spans, cable reinforcement can be applied. In that case, cables create another tensile element, taking part of the loads and therefore, allow thinner membrane. Membrane can be also hold by a net (cable net or rigid net) that is using the same principal as cable reinforcement. This additional structure creates desired shape, enabling both concave and convex shape (Illustration 21). Other group of pneumatic structures are inflated, high pressure structures which are supported by inflated elements and interior and exterior pressure remains the same (Illustration 22).

A type of rigid component deployable systems is, for instance, structures inspired by origami shape (Illustration 23). Its form provides flexibility and stiffness. Scissor structure is also a rigid component folding system that could allow easy transport to Mars.

A combination of rigid and deformable component deployable system is a tensegrity structure. This spatial structure has compression components inside and tension ones outside which together create a stable structure.


Illustration 18.: Roskilde Geodesic Dome


Illustration 19.: Pantograph (Studio Florian - Jan Tuma)


Illustration 20.: Medusa at RDS Showcase


Illustration 21.: Botanic garden in Aarhus


Illustration 22.: Bouncing Bridge

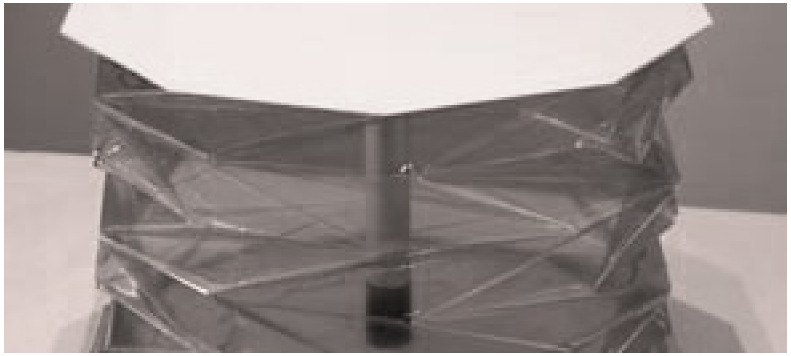


Illustration 23.: Origami deployable structure

CONSTRUCTION

Introduction

The construction method relies upon many factors which are significantly different in comparison to Earth. Transportation, speed of erection, usage of in-situ materials, a type of structure, a need of pressurized space are just a few that are addressed in construction analysis.

Speed

In the first place, the construction method depends on the speed of erection. Fast buildable construction allows humans to arrive with the earliest spacecraft. On the other hand, it is rather time consuming (astronauts could be working on a research instead) and it brings a risk of failure while building the habitat. In other case, first spacecraft can be unmanned. “This preparation mission would be sent to build the requisite infrastructure required to support human life. With this infrastructure deployed and validated, a second mission would then be readied for launch. This second mission would carry multiple astronauts to Mars to inhabit the structures built by the robotic assembly vehicles from the first mission” (National Research Council, 2002). Fully robotic mission is safer for humans as any defects would be known before their arrival. Construction of habitat offers two possible extremes: prefabrication on Earth or robotic in-situ construction.

Weight

For transportation reasons, it is necessary to minimize the amount of material that needs to be shipped to Mars. The requirement is not only the minimum volume but also the weight. Previous studies of manned missions on Mars counted mostly with 96 to 114 tons of total mass for transportation, with the lowest weight of 83 tons. It is possible to land with total mass of 20-80 tons and thus, more missions are needed for transportation (National Research council, 2002). In order to decrease the necessary transportation space, the structure could be deployable (see Structure analysis).

Another consideration is usage of in-situ recourses for building the habitat by 3D printing. Available materials that allows the usage of such a construction technique are basalt, ice or sulfur. Basalt is abundant on Mars and its properties could even enable to build pressurized structure. Despite higher melting temperature, the structure could be used almost directly after 3D printing. The possibility of ice printing is shown in the case study (see Mars Ice House). Sulfur concrete 3D printable material is made of elemental sulfur and aggregate (regolith), without any use of water. The absence of water is replaced by heating the sulfur to its melting point 115°C, which is significantly low. Its compression strength after cooling down is much greater than typical concrete. All of these construction techniques can be also used for partition walls. However, use of in-situ materials brings a difficulty with doors and windows of the habitat as well as piping, electricity network and ventilation system.

Other Features

Other important parameter for construction is pressure inside of the habitat (as mentioned in Pressure vessel analysis). The transition space between pressure vessel and unpressurized, exterior environment is called airlock. It allows safe crossing to other environment, minimizing pressure and air loses. This small space has two airtight doors that cannot be opened at the same time. By equalizing the conditions of airlock to the next environment, it prevents humans from decompression sickness (see Physiological threats).

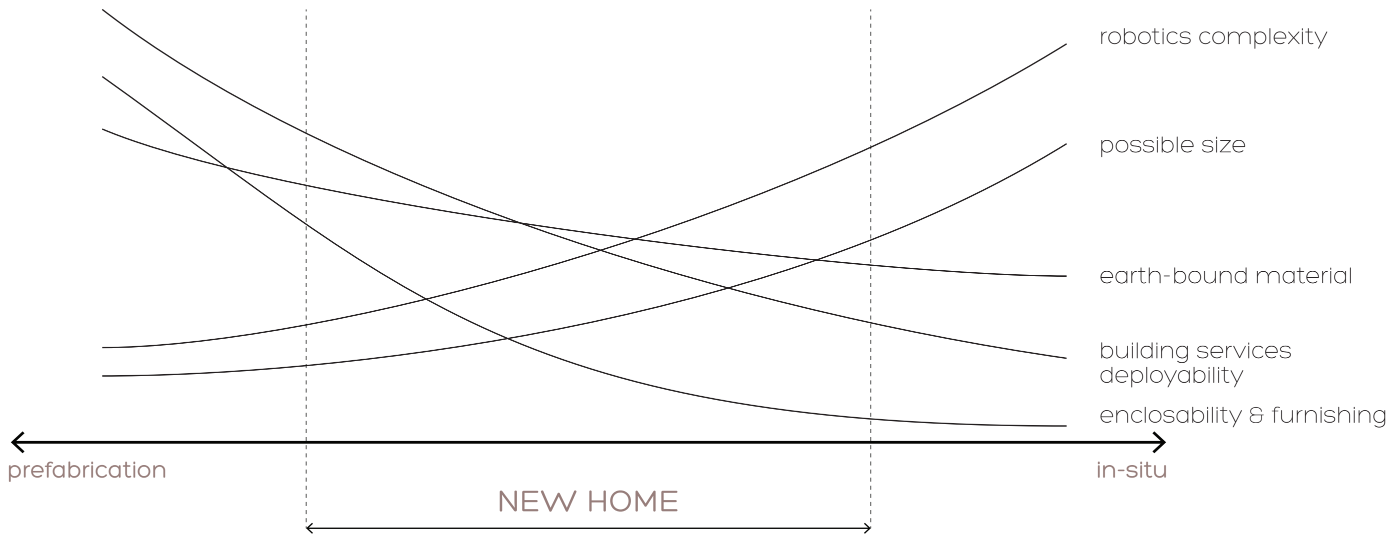


Illustration 24.: Construction diagram

INDOOR COMFORT

Introduction

Climate conditions on Mars are not detailed. Inaccurate data makes any precise calculations and simulations extremely difficult and, therefore, A New Home indoor comfort will be designed conceptually.

Unlike on Earth, part of indoor comfort contains also a protection against cosmic radiation (see Climate analysis). Even though the NASA`s annual upper radiation limit is not exceeded on Mars (see Physiological threats), the solar particle events still represents a potential biggest danger to humans. In the occasion of solar flares, the radiation could exceed the upper limit several times and thus, there is need of “storm shelters” (NASA, 2009). The warning system would inform humans and they could avoid the most intense radiation. These shelters can be created by building zones with different radiation shielding or making a specific room, where people can stay for several hours and avoid any medical damage.

Visual Comfort

One of the most important considerations for well-being of inhabitants is visual comfort. Both, visual connection to surroundings and efficient amount of daylight inside the building contribute to convenient environment. Therefore, windows or building envelope need to transmit enough visible light into interior. One of the last studies for spaceships recommends acrylic glass for windows with light transmittance up to 92%, good UV resistance and lower heat losses than typical glass. Moreover, its strength is appropriate for pressure vessel. (Darling, D., 2015). Another potential material with great strength is ETFE membrane that is available translucent and also highly transparent. Its benefit is also transmittance of UV required for photosynthesis of plants (see Self-sufficiency).

Thermal Comfort

The cold Martian atmosphere challenges the achievement of thermal comfort. Its low density, and thus, the heat transfer from interior to exterior is mainly through radiation. Convection and conduction are close to zero due to vacuum like exterior Martian environment. Therefore, to insulate the habitat against heat loss, it is important to shield infrared and long waves of electromagnetic spectrum. The solution is usage of much thinner layers of insulation. The most utilized thermal insulation in space engineering is a multi-layer insulation, or MLI. It comprises of a few very thin highly reflective sheets of material, similar to aluminum foils which reflect most of radiation heat back. These layers are then separated by thin net spacers to avoid conduction between the layers. Convection in the gaps between the reflective layers is zero as the entire MLI is situated in vacuum. These insulation systems of around 25mm are about five times more effective than 300mm insulation of mineral wool on Earth. Such insulation is used on the ISS.

In order to obtain considerably higher temperatures in interior compare to exterior, several approaches need to be combined. Heat gains can be achieved by use of greenhouse effect. Other concept leading to thermal comfort is zoning inside the habitat from the warmest to the coldest, exterior space.

Atmospheric Comfort

Atmospheric comfort in the habitat will be created according to International Space Station, where the composition of air is equal to air at the sea level on Earth. The air inside the habitat will be continuously monitored, assuring the right fractions of all gasses. The amount of oxygen, 21%, requires constant supply. Due to long stay on Mars, it is not possible to transport it from Earth. Therefore, all of the oxygen needs to be produced, using ISRU system. “The ISRU plant is designed to convert Mars atmosphere into oxygen for use as propellants and life support” (NASA, 2009).

Illustration 25.: Indoor comfort diagram

SELF-SUFFICIENCY

Introduction

Since the transportation limits does not allow to bring everything from Earth, long term mission on Mars demands high level of self-sufficiency. Life support systems, such as oxygen (see Indoor comfort analysis), water and food supply are crucial for human survival.

Resources

The water will be mostly recycled from waste water. The initially extracted amount of water needs to be constantly complemented to cover the losses from nonrecyclable waste water. All water will be extracted from soil, then heated to boiling point and evaporated, to obtain distillate water. The proposed daily need of water per astronaut according to Mars One mission (2015) is 50l per day.

Currently, there is no possibility to produce all necessary food for humans on Mars. However, a considerable amount of food are plants that can be grown inside the habitat. According to Febriera, B. (2017) these plants are multifunctional, resistant to colder temperatures, and do not require insects to pollinate them. The plants can be grown with use of Martian soil (NASA, Jordan, G., 2015) or hydroponically, by using water and nutrients brought from Earth as well as recycled from human waste. More information is provided in chapter Greenery.

Energy

To create and maintain adequate conditions for living, the production of energy is necessary. There are three options for generating the energy on Mars. The first is solar energy, which production is possible by solar panels. Disadvantage of this system is dust and low solar radiation on Martian surface which is only 715 watts/m^2. Dust storms can also significantly influence the efficiency. Altogether, these conditions might decrease the performance of energy production up to 60% in comparison to Earth. Most adequate solar system for Martian environment according to NASA (2014) are wide rolls of thin-film panels placed at latitude 0-40° north of the equator. The second option for energy production is a use of geothermal energy called aerothermal on Mars. The soil is less dense due to gravity and, therefore, it is easier to drill deeper. The energy would be generated from steam created from the water brought to the surface. Zubrin (1996) claims, that this will work even more efficiently on Mars than it does on Earth, because the low atmospheric pressure will allow the steam to be much more fully expanded before it is condensed. Last option for production of energy is nuclear power, as it has already been used for rovers on Mars. To increase its efficiency, radioisotope power system is still under the development. The main advantage of this system is that it does not relay on the environmental conditions of Mars.

Self-sufficient habitat is an independent dwelling, where everything necessary for life and its functioning is produced on site. Due to unhostile environment and lack of technology, the New Home will demand limited supply from Earth, especially a food. Energy, oxygen and water can be fully produced on Mars and thus, enable to create relatively self-sufficient habitat.

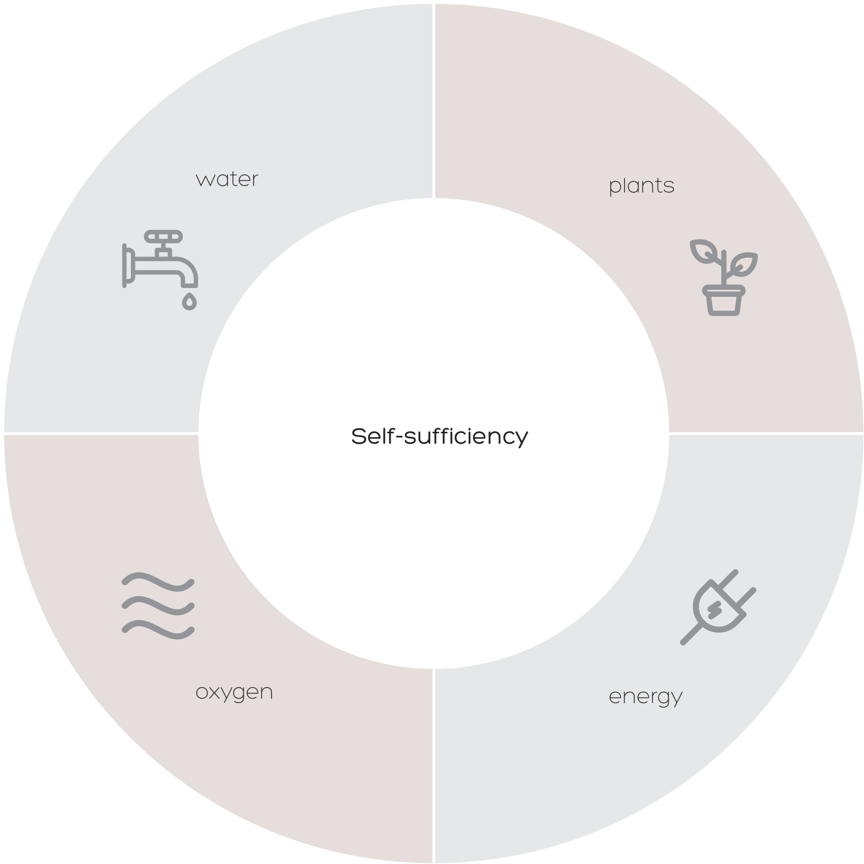


Illustration 26.: Self-sufficiency diagram

CASE STUDIES

mars ice house
house n

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In the next two chapters, we investigate one conceptual proposal for a Martian habitat and one existing example of dwelling architecture that both closely relate to our engineering and architectural challenges. The first case is the most similar to ours in its task, approach and design solutions and the second is an example of an ultimate home concept that offers many spatial solutions that later inform our design. In their analyses, we employ the theoretical and factual knowledge, gained through the previous chapters Home and Engineering, to extract new relevant knowledge and discover possible design concepts.

• • •

MARS ICE HOUSE

Introduction

During the analysis of environment on Mars, many questions arose about solving technical issues. The case study, Mars Ice House, addresses most of them, having possible solutions, options to solve them.

Description

The location, northern flanks of Alba Mons, is chosen in regard to highest solar exposure and presence of ice Mars Ice House is designed in order to minimize the total mass for transport. It is built inside of large inflated ETFE membrane structure reinforced with tensile textile, holding inside pressure of 70kPa. Interior structure is made of 3D printed ice. Water, or ice, is able to protect the crew against cosmic rays and at the same time, allows visible light spectrum to pass through the walls. The Ice structure itself is designed only for the gravity of Mars, creating relatively delicate structure. Thermal comfort is achieved by use of thermal insulation made of translucent aerogel with light transmittance 66%. Moreover, thermal insulation protects ice from melting. The entire construction of Mars Ice House will be finished before the arrival of inhabitants, assembled by robots.

Another step to improve the indoor comfort is zoning. It also divides the habitat into several zones with different radiation exposure. Two main zones differ functionally as well as thermally. The outer zone protects the inner one and gives the inhabitants the opportunity to experience outside without wearing the suit. The design aims for connection with surrounding likewise good daylight conditions. The inner zone is subdivided into several smaller zones according to functions.

Conclusion

Mars Ice Home involves many parameters into the design, especially adresses almost all of the technical difficulties to build on Mars, such as dealing with pressure, radiation, low temperatures, transportation to Mars and use of in-situ materials. However, the project only touches upon self-sufficiency. Unlike other space architecture projects, this case study includes to some extend also well-being of occupants. On the other hand, based on the Home analysis, we believe that to create a NEW HOME, requires much bigger focus on mental health of the crew and architectural aspects of the design.


Illustration 27.: Mars Ice House

HOUSE N

Introduction

Despite its different scale, motivation and even with its location on a different planet, the ingenious design of the House N by Sou Fujimoto closely relates to our particular considerations and focuses. In the following text, we use the challenges of our Anthropological and Technical approaches and the knowledge acquired through the chapter Home to critically assess the House N's concepts and design in search for possible design translations of these challenges and theory and in search of additional relevant concepts.

Relevance

Firstly, the architecture reflects the social patterns of the family based on their according need for privacy. All the spaces corresponding to these patterns are clustered based on the levels of their required intimacy. Through this zoning, the architect provides the family with the convenience for the family's social patterns which, as described in the chapter Dwelling, results in comfort, an important architectural element of a dwelling.

Furthermore, the design includes elements of greenery in its spaces which, as described in the chapter Greenery, creates a sense of belonging and results in a merger between the interior and the exterior where all strict boundaries have been completely eradicated and the previous standards of interior vs. exterior redefined. Through the ingenious layering and transparency, architecture, nature and the human become uniform. Fujimoto (2011) describes his thoughts behind the house: "A distinct boundary is nowhere to be found, except for a gradual change in the domain. One might say that an ideal architecture is an outdoor space that feels like the indoors and an indoor space that feels like the outdoors."

Conclusion

In relation to the phenomenology of home and the Rybczinsky's theory of a dwelling, investigated previously, this case study offers us with the option of using zoning of similar levels of privacy to create convenience for the occupants based on their social patterns. Furthermore, it demonstrates how greenery can be used as an integral part of an architectural concept. Despite the architect's very different motivation of strongly urban-driven considerations of the relationship between the domesticity and the city, it offers us a strong new insight and inspiration for the project's future development.

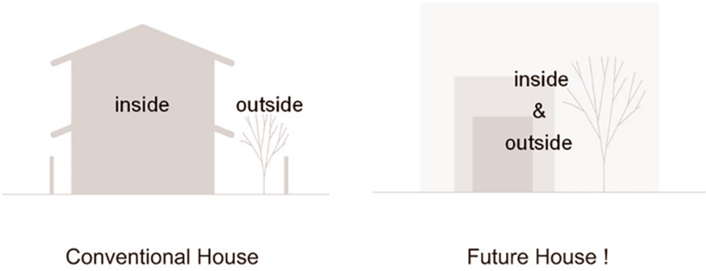

Illustration 28.: Conventional House vs. Future House

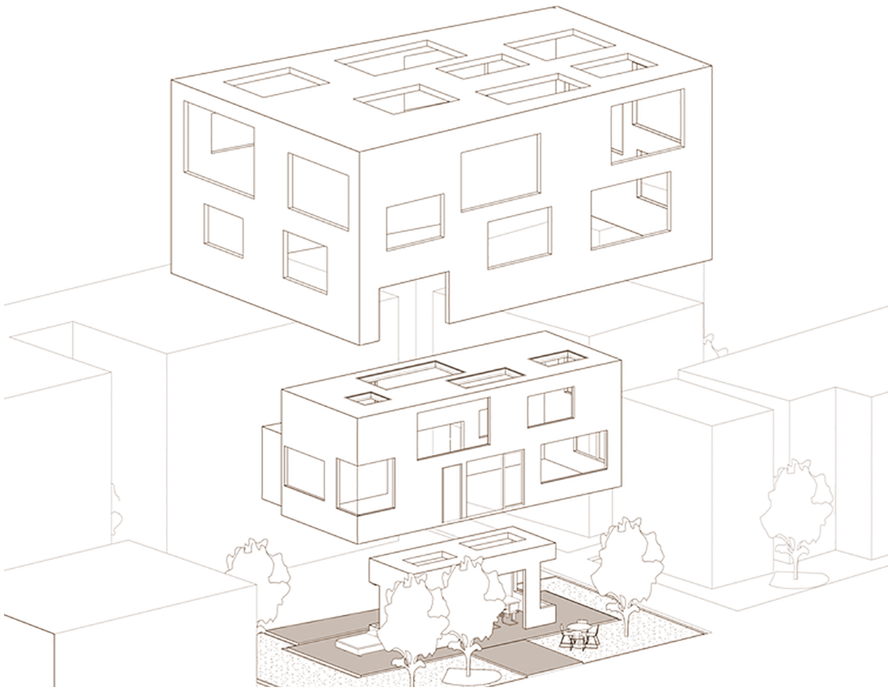
Illustration 29.: Spatial diagram


Illustration 30.: House N interior

DESIGN PARAMETERS

programming & zoning / social patterns
3-stage deployment / treehouse

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Through this section, acting as a design translation of the previous theoretical and factual analyses and case studies, we set a few core architectural design parameters that inform our design in response to the selected anthropological and technical challenges. Firstly, we present the assembled room program and its division. We introduce some of the spatial features that will help us in the pursuit of comfort and privacy, described in the chapter Home. We present a conceptual solution of the construction and, lastly, we propose an architectural concept for the experience of the space.

• • •

PROGRAMMING & ZONING

Introduction

This chapter lists all the required rooms and describes their overall functional connections and general zoning. All of our decisions within this section were informed through the theoretical and factual findings through chapters Home, Engineering and the Case Studies. Furthermore, we take into consideration our previous architectural experience with dwelling and office typologies and our personal empirical experience with both.

Zoning

Through chapter Home, we have learnt that convenience and privacy, based on the current social patterns, are the main constructs of comfort. We use the perspective of convenience in the general functional division of the habitat into Work and Leisure zones as they both relate to fundamentally divergent social patterns which are, in their nature, often contrastive. By the division, both main sections can be directly informed through their according expected social patterns in their corresponding convenience.

Building mostly on the knowledge gathered through the case of ISS and our previous experience, the perspective of privacy results in a further zoning of the different functional elements based on the social interaction or the privacy they should offer in relation to the social patterns they are associated with.

Last system of functional zoning is mainly affected by the chapter Engineering and is a response to all its findings in relation to our technical focuses. The Technical zoning is mainly developed in relation to different design pressures, temperatures and necessary location within the habitat, in relation to other zones, functions and the outdoor environment.

Rooms

The development of the list of rooms is based on general social patterns of home and work, building on our investigation of these phenomena, connected to the potential crew, through chapter Home and our personal architectural understanding of general dwelling and office typology patterns. Furthermore, it builds on the necessary technical functionality explored through chapters Engineering and on the chapter Case Studies, investigated from all observed perspectives.

Each room offers very different qualities based on the divergent associated social patterns. All rooms will require different levels of privacy and answer different patterns in their relevant convenience. These qualities of each room are observed through the theory lessons learnt from the chapter Home, understanding the technical essence of each function through the chapter Engineering and through the different case studies, investigated from all observed perspectives.

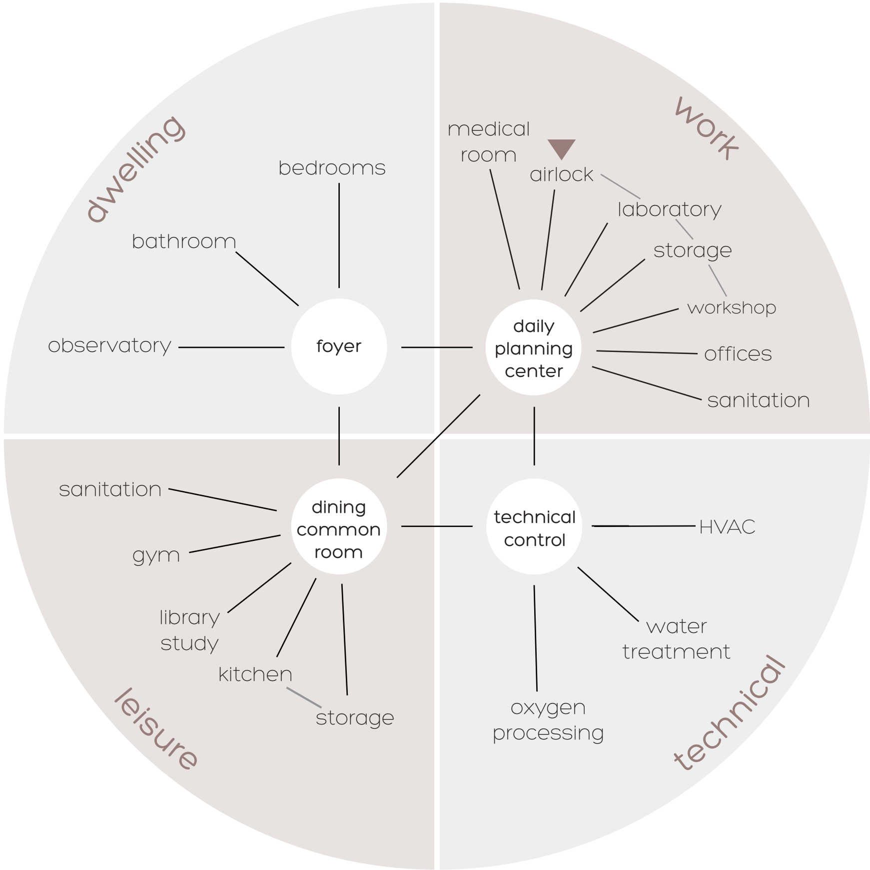


Illustration 31.: Room program

PATTERNS

Introduction

Through the theoretical chapter Home, we have learnt the importance of some of the experiences directly connected to the phenomenon of home and dwelling. To better understand the translation of these experiences into a physical form, we are building upon the investigations of Alexander in his work A Pattern Language (1977). We chose several out of 253 patterns described in the book, and created the combination essential to solving the problem by adapting the patterns.

Patterns

The main pattern of the habitat is intimacy gradient (Illustration 32 - Intimacy gradient), which brings a logical division between the spaces, from the public through semi-public to private. Without such an arrangement, rooms would have comparable degree of intimacy leading to social interaction decline.

The most public rooms, or common areas, should be placed tangentially to paths, so occupants naturally pass by on their way to another area (Illustration 32 - Placement of common area). If the common area would be placed directly on the way, it may be not comfortable to stay in. On the other hand, placement of the common room in the end of path requires lot of effort to enter and thus, it might not be used. By common area, we can understand rooms that are center of gravity in the building, for instance living room or dining room. These rooms should encourage people`s social interaction and provide the feeling of community. Another consideration for creating common room is its openness. Closed room with door causes difficulty for people to enter and completely opened space indicated only by different flooring is too exposed and vulnerable. Therefore, the balance between open and closed, half-open space (Illustration 32 - Half-open space), would create the best possibility to support occupant's interaction.

However, the private areas are equally important. Alexander in his book stated: "No one can be close to others, without also having frequent opportunities to be alone". For psychological well-being of inhabitants, it is necessary to provide them with their own, private room. The place of their own, with a desk, shelves and a chair. The intimacy of this room could be also enhanced by lowering the ceiling in comparison to common rooms (Illustration 32 - Height of the ceiling). The visual effect of the ceiling height can change the perception of how intimate the space is. The higher ceilings of communal areas virtually make the place more formal and the lower ceilings of private rooms supports the feeling of intimacy.

The intimacy/privacy levels are also influenced by the connection between rooms and their position. It is important to give to person freedom of choice, to give the opportunity to modify the situation. Thus, the most appropriate connection would be a loop, avoiding usage of passages or corridors. This spring connection always offers more than one way, allowing person to have freedom of choice.

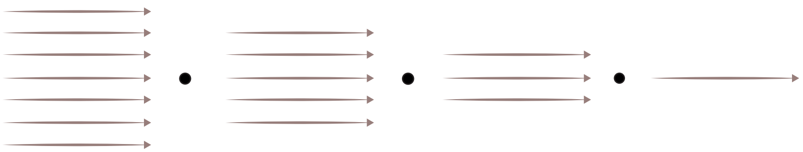
Another consideration chosen from patterns is a quiet place in the garden. A chair, or a bench placed in close relation to nature, a silent place for relaxation and recharging the energy. A place to get loose in own thoughts, to escape from everyday life, which could be important, especially for crew members on Mars.

Their schedules involve mainly work (see ISS analysis), putting an attention to a workplace. The offices should not be in closed room, providing connection to another area, using the concept of half-open room. The workplaces should be linked to common area, courtyard where people can sit and relax. Each office desk should be placed so the worker has visual connection to outside as well as other workers.

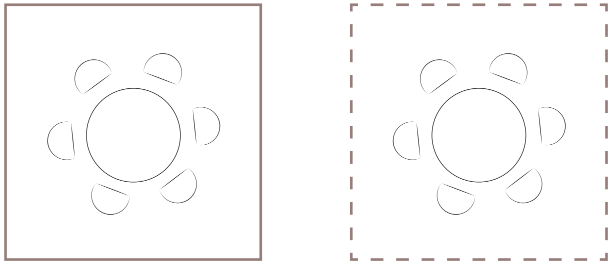
Conclusion

All above mentioned principles, patterns will be used as a guide to ensure the translation of convenience to spaces. Their application to our design will affect the social interaction on many levels and thus, benefit to the crew`s mental health and psychological comfort.

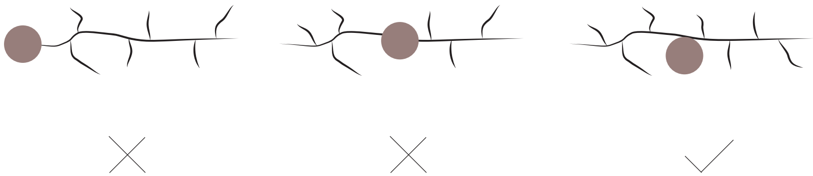
Intimacy gradient



Half-open space



Placement of common area



Height of the ceiling

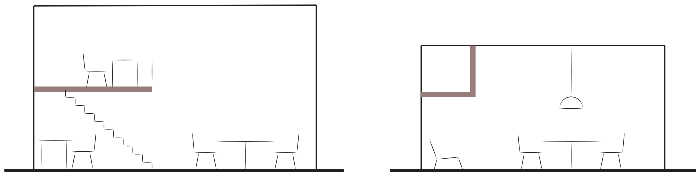


Illustration 32.: Patterns

3-STAGE DEPLOYMENT

Introduction

As mentioned in the chapter Construction, there are many limitations of building on Mars to achieve complex structures that is able to support life while lowering the chances of possible failures during the construction phase. In order to achieve these parameters, we have developed a construction concept that consists of three stages of deployment that will allow us to achieve a self-deployable habitat of sufficient spatiality, building on the phenomenology of home, while minimizing the need for earth-bound material. Through these three stages, we combine both prefabrication connected with deployment and utilization of in-situ construction.

Three Stages

1 / Core Stage

First, unmanned stage, where a "Core Structure" arrives in the form of a lander spacecraft. It comprises of all elements of the room program that require complex construction, building services and furnishings that are impossible to achieve robotically or too crucial to handle after arrival. The remaining interior spaces of the lander will be used to bring initial supplies and all necessary material and machinery for the next stage.

2 / Habitat Stage

This stage will comprise of all technical necessities and elements of the room program that are absolutely essential for sustaining human life. At the beginning of this stage, robots are deployed from the core and start sintering the Martian regolith to fill the small crater, left after the landing, and create a foundation for the habitat. Secondly, the robots deploy and attach a folded membrane to the foundations. It is then pressurized and thus forms the entire inhabitable part of the habitat. Lastly, smaller balconies are mechanically deployed from the core to further extend each story into the habitat.

3 / Home Stage

A second, now manned, ship from Earth delivers the crew along with additional supplies and other materials and tools necessary to transform the habitat into a home. The crew settles in and starts working on the luxury elements of the room program, that are not essential for sustaining life but form a home, the NEW HOME. Through these actions, they will be closely involved in the creation of their home and have a significant impact upon its functionality, resulting in the sensation of self-realization, an important factor of a home as described in the chapter Home.

Conclusion

Firstly, the necessity for these three stages results in yet another type of zoning for our habitat where we need to further divide the room program in accordance to these stages based on their particular technical needs and necessity for life sustainment. Secondly, this design parameter largely influences the possible geometries and technologies that we investigate through the design process.

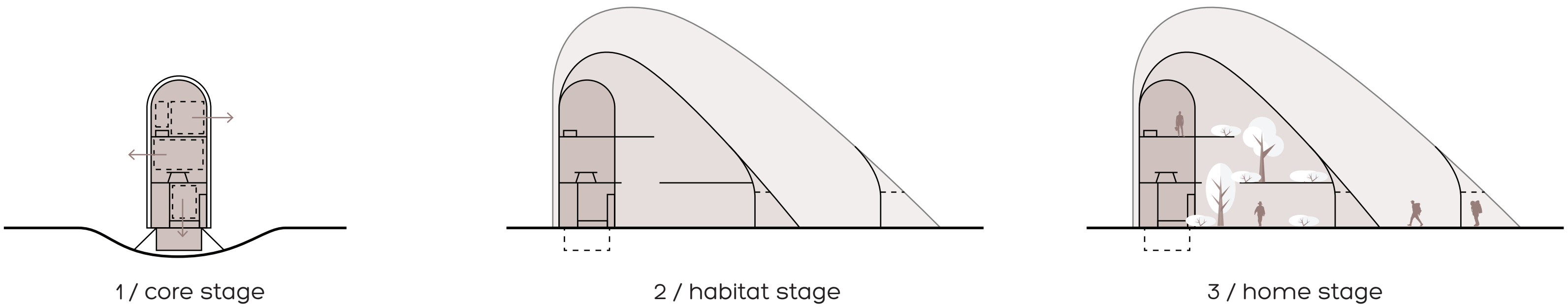


Illustration 33.: 3-stage deployment

TREEHOUSE

Introduction

Ever since the beginning of architecture, it has been evolving alongside Earth's nature, sometimes diverging, sometimes intertwining and sometimes not considering it at all. However, no matter the approach, both architecture and nature play a significant part of any beings' life, serve different functions and exhibit various spiritual experiences and motivations why they are pursued. No matter the particular reason, being it an escape from the highly planned and utterly unspontaneous to the ultimate freedom of nature or a human evolutionary urge to look for lush environments, or any other, architecture and nature are inseparable in any human's life.

Mars

Life on Mars will be very different. The hostility of the environment eliminates the possibility for the full experience of the planet in person. There will be no sitting on the grass on a summer evening, drinking wine and watching the sunset. And even further, the red aridity of the landscape strongly declares its hostility and uninhabitability that mankind has evolved to avoid.

However, a simple living on Mars does not make us Martians as we are not capable of anthropological revolution but evolve slowly, over time. Therefore, we must attempt to provide spaces and experiences of similar qualities that the occupants can relate to. For this endeavor, we have utilized the knowledge attained through the chapter HOME and match them with some of our other parameters.

Explanation

From the text above, it is clear we need a strongly natural archetype through the merger of the built with the greenery. Based on our 3-stage Deployment, we were in search of a vertical concept that would relate to the verticality of the core. And lastly, coming from our zoning parameter, we were looking for an archetype that divides different functionalities on different levels. That is where the archetype of a Treehouse comes in.

The vertically oriented central Core and its balconies form the treehouse that is not only a structure in nature, but is space that fully merges with its surroundings and builds upon its qualities; and rather than creating a solitary introverted function only extends their functionalities. In addition, its elevation above the ground divides the functions between the place of labor on the ground, for hunting, gathering and harvesting, and the elevation above these mundane activities and dangers of the world creates a sensation of safety, comfort and privacy, qualities described in the chapter Home to be the essentials of any home.

At the first glance, in our very hi-tech and even futuristic conditions, such a concept might seem contra-intuitive, very outdated and prehistoric. However, as observed in the conclusion of chapter Dwelling, our conditions are closely tied to elementary values of architecture and, therefore, "primordial" might be the best concept in relating the experiences in such difficult and diverse circumstances. Perhaps, revisiting a primeval architectural concept, that is treehouse, might help the occupants relate to some of the known experiences from Earth and help them connect to their habitat on the most elementary levels.

Illustration 34.: Treehouse

PRESENTATION

concept / habitat / dispositions / bamboo
interior / core / terrace / ETFE

• • •

The design proposal for the first Martian habitat, NEW HOME, is described in the following ten specialized chapters, contemplating different aspects of the design, as a response to the previously formulated anthropological and technical challenges. Firstly, a more general concept and overview of the project is presented, followed by a closer insight into the divisions and spatial qualities of the room program and its furnishings. Lastly, all the elements of the habitat are described from the engineering perspective and a solution for the operation of the habitat is offered.

• • •

CONCEPT

Context

What is the social history of Mars? What are the social patterns of the Martians inhabitants? What is the built environment on Mars? As far as we know, there are none. No matter what the first manned mission onto Mars will do, they will be the first to do it. Socially and historically, Mars is a place with no context for architecture and thus, it would seem we are not bound by any rules and are free in our design.

However, even with the lack of social context, architecture still reflects other contexts just as equally. In our case, especially the pragmatic contexts – environment, transportation or economy, just to name a few. Nevertheless, architecture is not only a pragmatic field but also a sentimental one and the aforementioned, mostly technical, context cannot be considered a full architectural one. No matter what, we are Earthlings and need a context from Earth that we can relate to. That is why we need to bring our own sentimental context – the Treehouse, as described above.

Explanation

In this sense, the Martian architecture, as we see it, eliminates the separation of many of the Earth's respected fields of urban planning, landscaping, interior design or product design and merges them all into one. By bringing a large part of our design's context, the traditional division of space into the interior and exterior is no longer relevant, there is only different spatial qualities of privacy or interaction, utilitarianism or freedom, and construction or nature, all in a single piece of architecture. The Martian architecture becomes everything – the design and planning, the science and engineering, the botany and craftsmanship. Before evolution takes its leap, we believe this approach to be the standard of interplanetary travel and journeying for the decades to come.

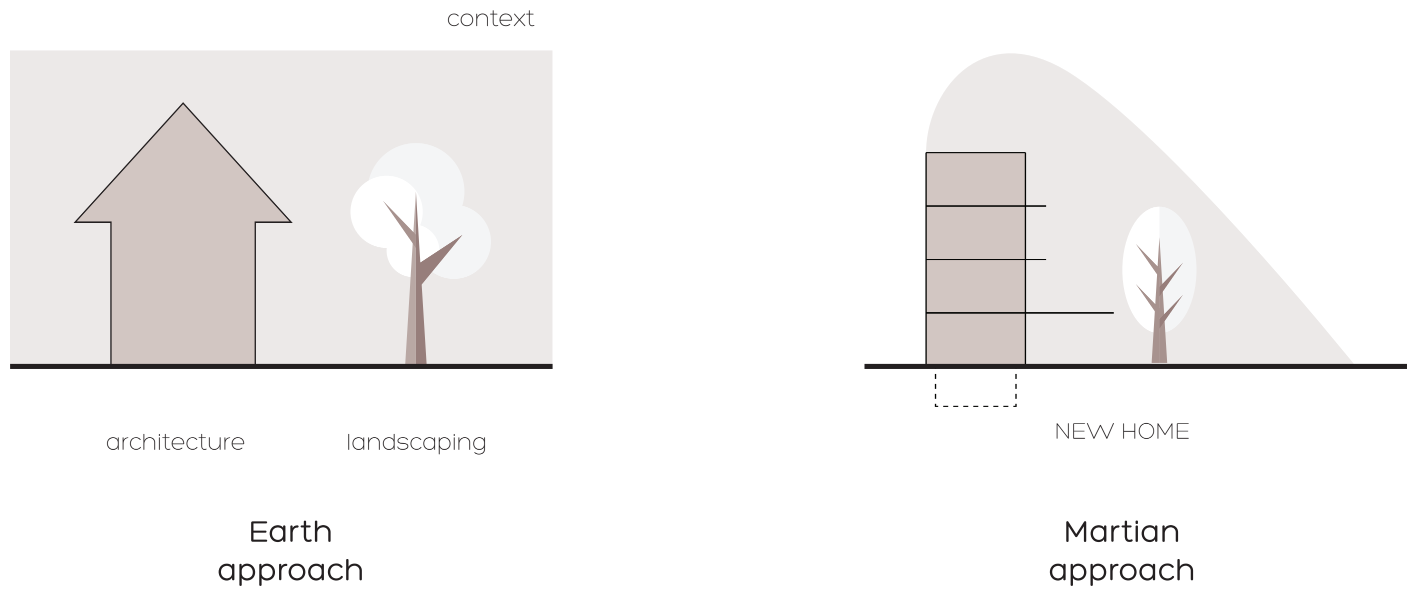


Illustration 35.: Concept

HABITAT

Introduction

The overall design of the NEW HOME comprises of three main structures that all create different spaces and serve different functionalities, the core, the terrace and balconies, and ETFE membrane. At the center of the design is a 6-storey fully prefabricated core that contains most of the room program. One terrace on the first floor and two balconies on the second and third floor will deploy out from within the core and will extend the usable space outside and merge it with the rest of the inhabitable space.

This extended space of the core and the deployable terrace and balconies contains all the inhabitable parts of the room program which are arranged into five stories. The ground floor is devoted to the crew's working tasks, estimated in the chapter ISS. The first floor contains all the leisure and luxury elements of the room program and creates space where the occupants will spend their free time socializing in large or smaller groups. The next two floors are dwelling units that will serve as the ultimate private retreat from the crew. Lastly, the fourth floor is an observatory, that is fully open to the habitat on one side and fully glazed to the Martian environment and where the crew can admire the arid landscape. In addition to the five stories, one underground story will consist of all the technical machinery.

ETFE

Two layers of transparent ETFE will be shipped attached to and folded around the core. After deployment, they will create the large extended inhabitable space. These two layers that are both connected to the middle of the core create two different zones. The inner space together with the core and terrace form the main occupied space where all everyday life takes place. A large part of the ground of the inner part forms small gardens that serve as the main food source with vegetables and bamboo, that both also divide the space. The outer ETFE environment encloses a natural forest that forms an extended part of the habitat that creates an ultimate natural escape from the habitat and the everyday perils. In addition, it is the main source of bamboo and contributes to the generation of O_2 for the inhabitants.

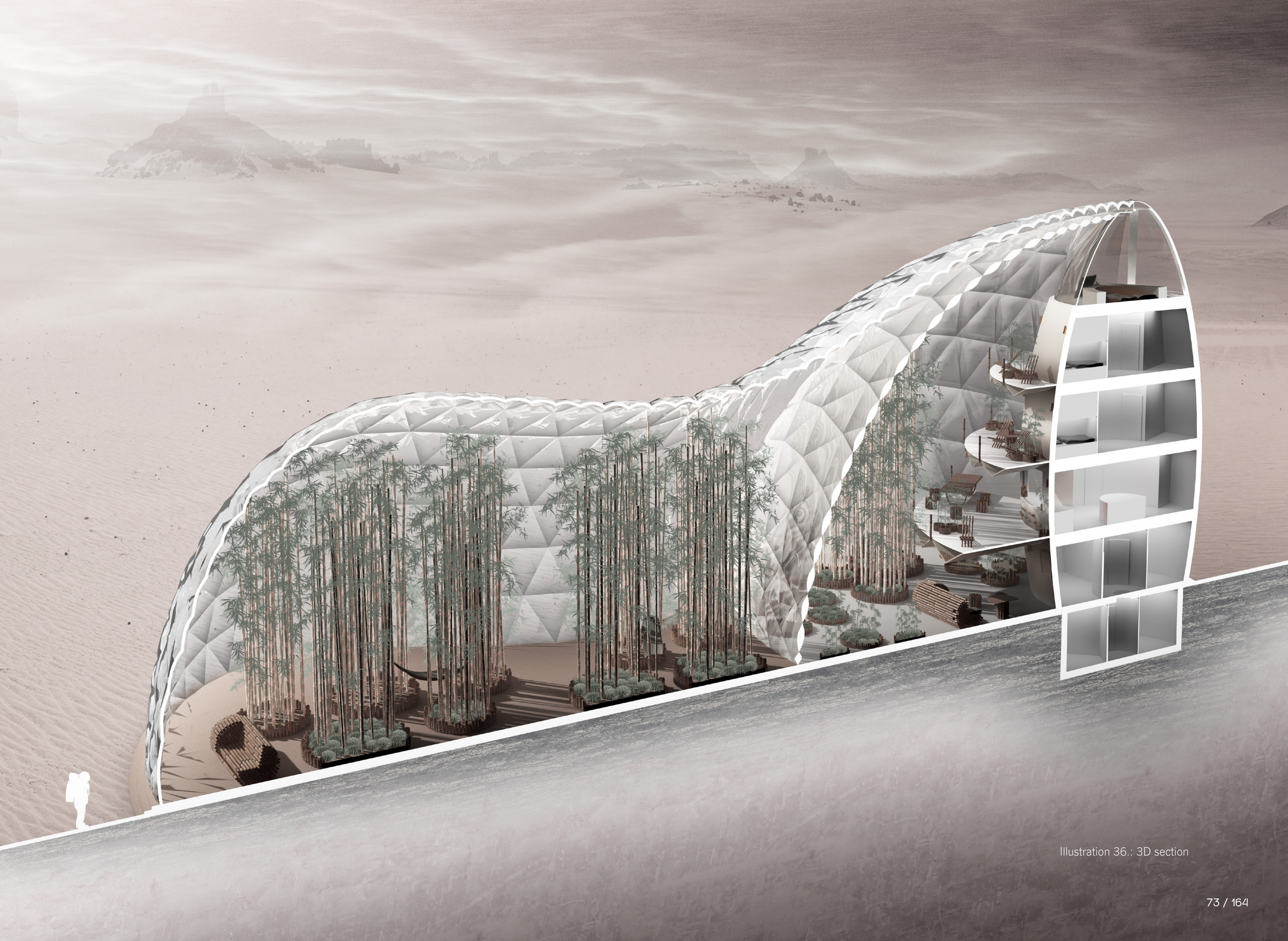


Illustration 36.: 3D section

DISPOSITIONS

Introduction

The habitat is divided according to zones based on the different privacy and social interaction levels. Furthermore, the technical requirements divide the spaces in accordance with different pressure and temperature zones, which relate to the zoning based on convenience of space. The division of rooms is based on programming (see Programming and zoning) and each of the rooms offers different qualities.

The entire habitat can be divided in two directions, horizontally and vertically, while not creating boundaries between them.

Horizontal division

The entire division creates three main spaces - the core, the habitat garden and the bamboo forest (Illustration 37). The habitat is connected to the exterior by airlock, forming the only entrance. It is also a transition between the bamboo forest and the habitat garden, as they represent different pressure zones. The airlock will be transported to Mars in the core and deployed in the habitat stage.

1./ Core

The core is defined by its prefabricated shape, functional and more closed. Its 6 floors contain the rooms which require technical equipment (piping), a higher privacy level or an enclosed space. On the other hand, it opens to the habitat garden, which creates very free and interconnected dispositions, resulting in a merger between the interior and the exterior.

2./ Habitat garden

The garden allows the crew members to grow own vegetables and bamboo in circular pots. Vegetables and bamboo represent the main food supply during the mission. The bamboo also provides glare control, forms division between rooms and creates the perception of a treehouse. Moreover, the gardening is beneficial to mental health (see Greenery analysis), partially helping to deal with sensory deprivation and sense of loneliness, and contributing to a feeling of belonging.

3./ Bamboo forest

Bamboo forest brings the Earth context like a natural retreat, which diverges from the planed and strict architecture of the habitat garden and the core. As mentioned in Patterns, it is necessary to provide such a place, that serves an “escape” from everyday life, for relaxation and recharging the energy.

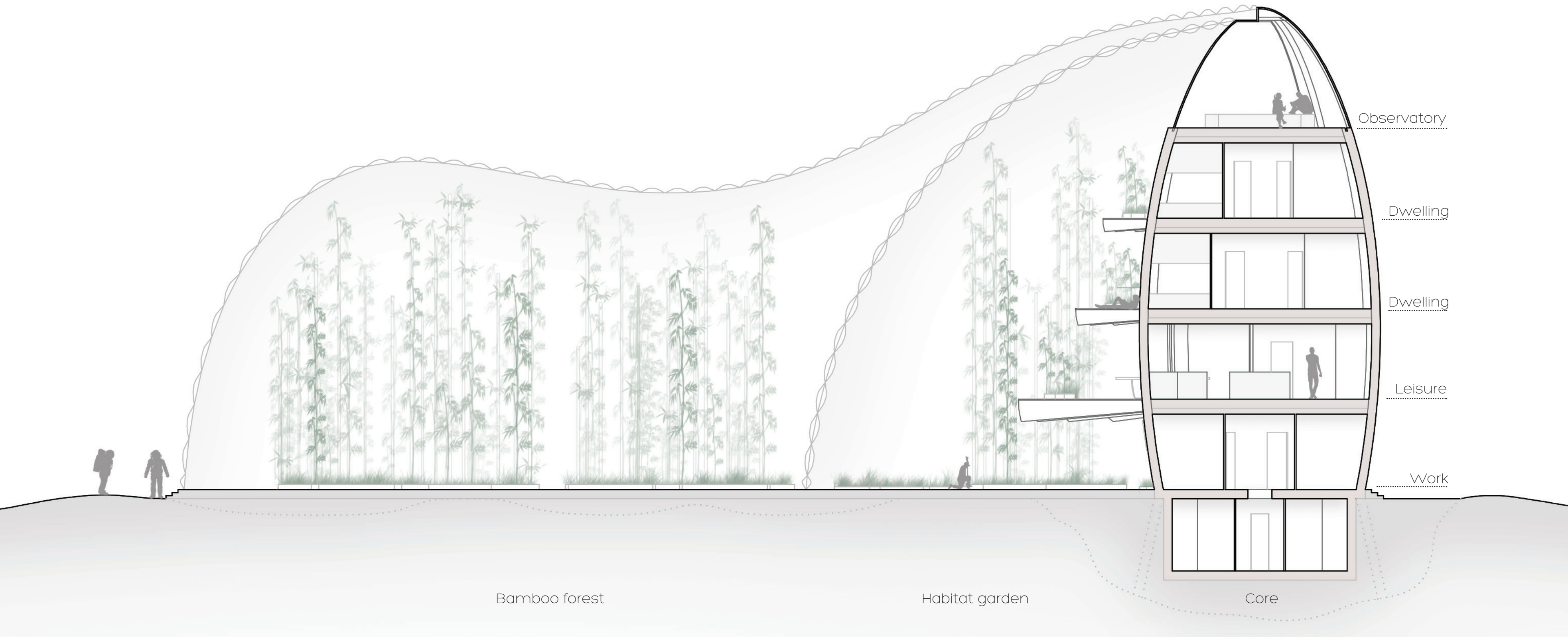


Illustration 37.: Longitudinal section 1:200

Vertical division

The habitat is vertically divided by floors, which serves different functions – work, leisure, dwelling, observatory and technical rooms. All of them are connected by a staircase curved around the wall, minimizing the use of corridors or passages. Using the theory of Patterns, the tangential placement of the rooms to the staircase gives the inhabitants a freedom of choice, whether they want to stay or not. The placement of the rooms also influences their different intimacy and privacy levels. The visual division of the elements of the room program outside the core is made by bamboo and its elements, that also gives the crew an opportunity to influence the space.

1./ Work

The function work, is located on the ground floor (Illustration 39). Medical room, laboratory and the sanitation require enclosed space, and thus, are placed in the core. The middle of the core provides changing room and entrance to the technical zone under it. Half-open rooms are placed in the habitat garden, with the center of social interaction between inhabitants represented by Daily planning center, where two daily briefings, with the ground control at Earth, will be held. The offices and workshop are separated by greenery, with visual connection to daily planning center and exterior. Moreover, the workshop is directly connected to the airlock.

2./ Leisure

The leisure part is designed as the main interaction zone and contains most of the relaxation functions (1st floor, Illustration 40). Its main functions are meal preparation, relaxation and exercise. The core includes sanitation, a storage and a kitchen which is visually opened to the terrace which contains dining room, study room and a gym, all separated by greenery.

3./ Dwelling – 2nd and 3rd floor

Dwelling consists of all 6 private rooms of crew members and two bathrooms, that are equally distributed to two floors (2nd and 3rd floor, Illustration 41). Individual rooms serve own, private space for retreat, outside communication and personal projects. The free space in each room extends from the center to the outside where it creates balconies that offer the ultimate incorporation in the atmosphere of the treehouse. Every room include build-in furniture walls – bed and table with storage spaces. In addition, the height of the ceiling is adjusted to gain more intimate feeling as well as add storages for inhabitants.

4./ Observatory

The top of the core (4th floor, Illustration 42) serves as another relaxation zone with a very specific experience as it offers the broadest visual connection with the surroundings. The Martian landscape, night sky and parts of the habitat all can be observed from the observatory.

5/ Technical rooms

All of the technical equipment, control and supply systems are placed on the underground floor of the core (Illustration 88).

Illustration 38.: Top view

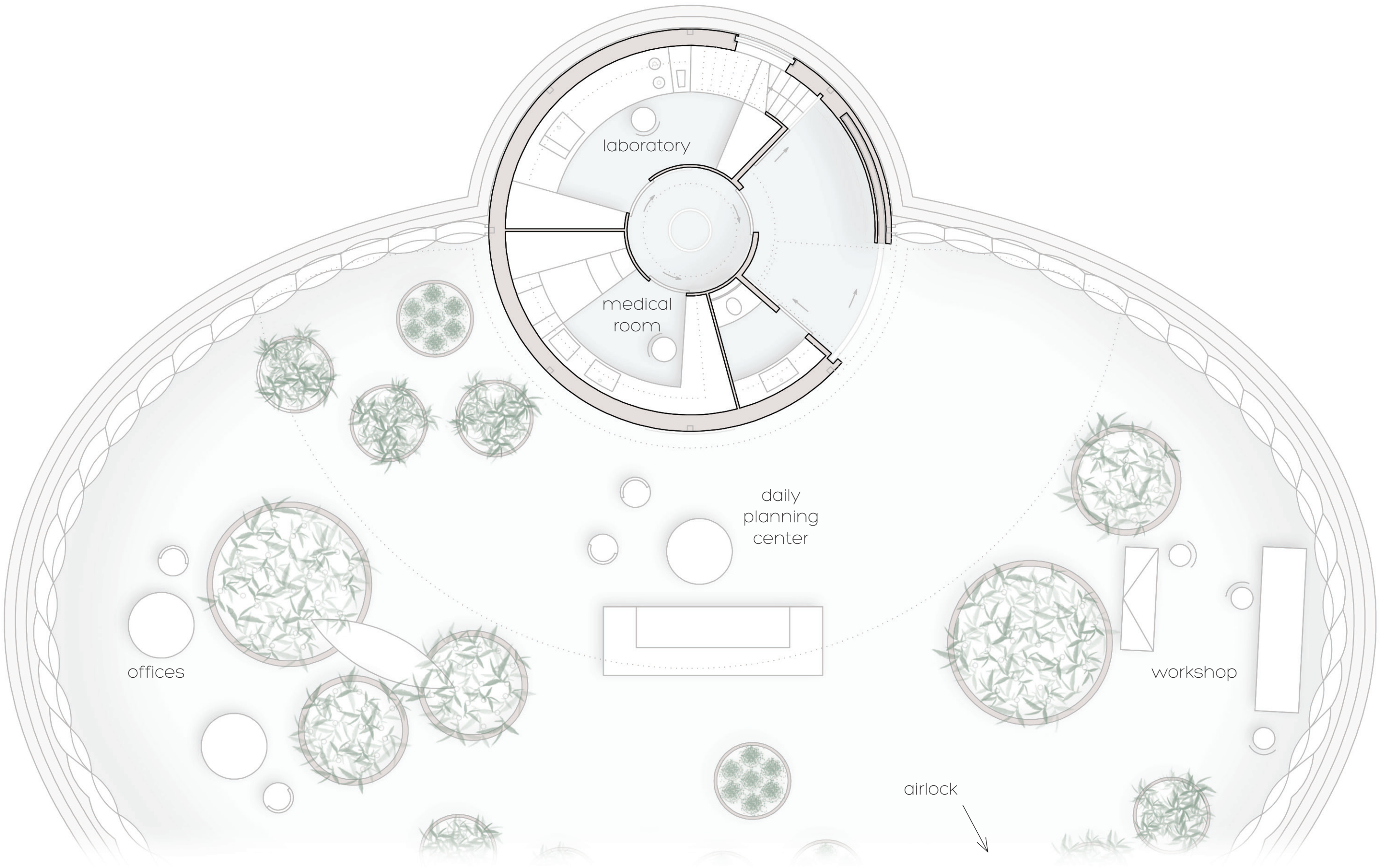


Illustration 39.: Plan 0 / Work 1:150

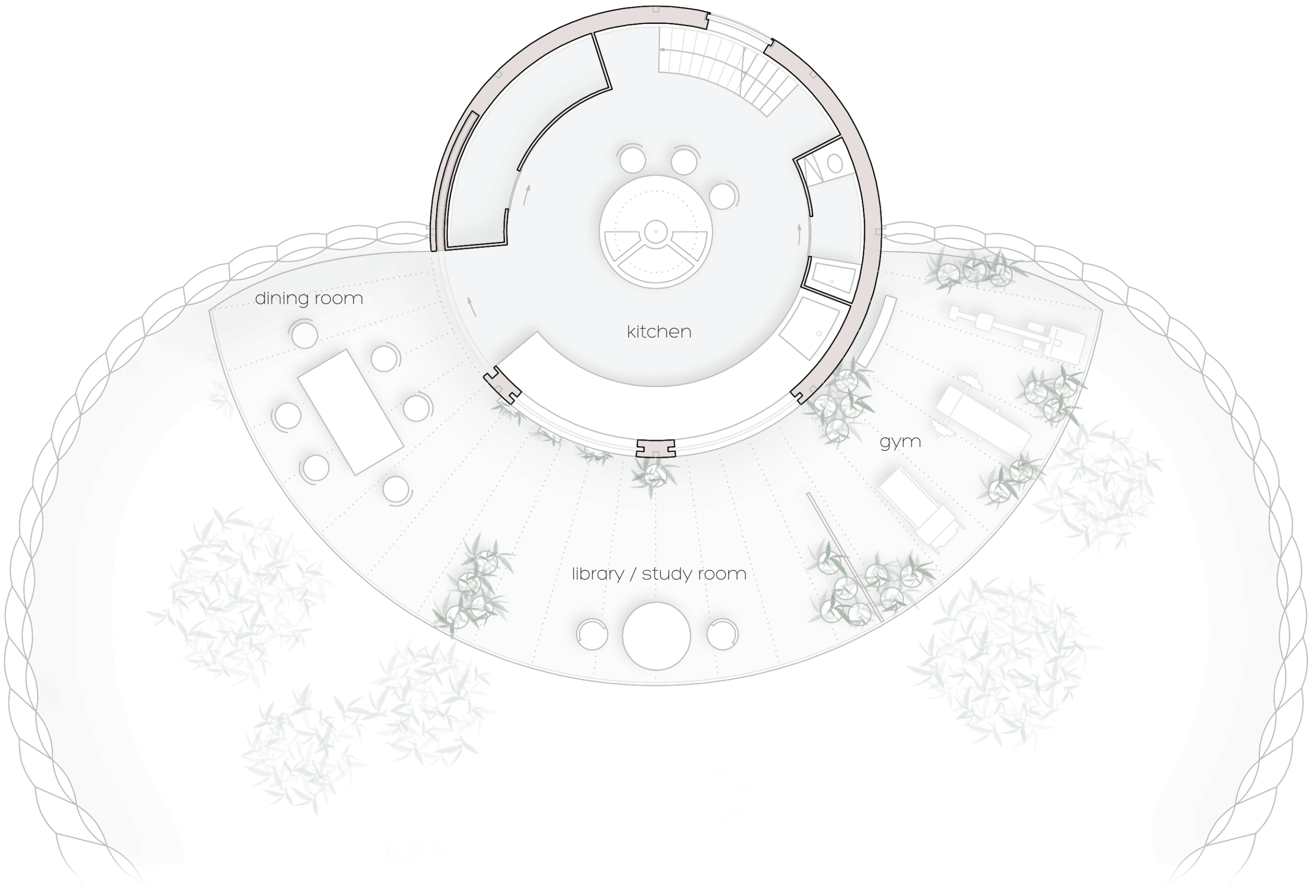


Illustration 40.: Plan +1 / Leisure 1:150

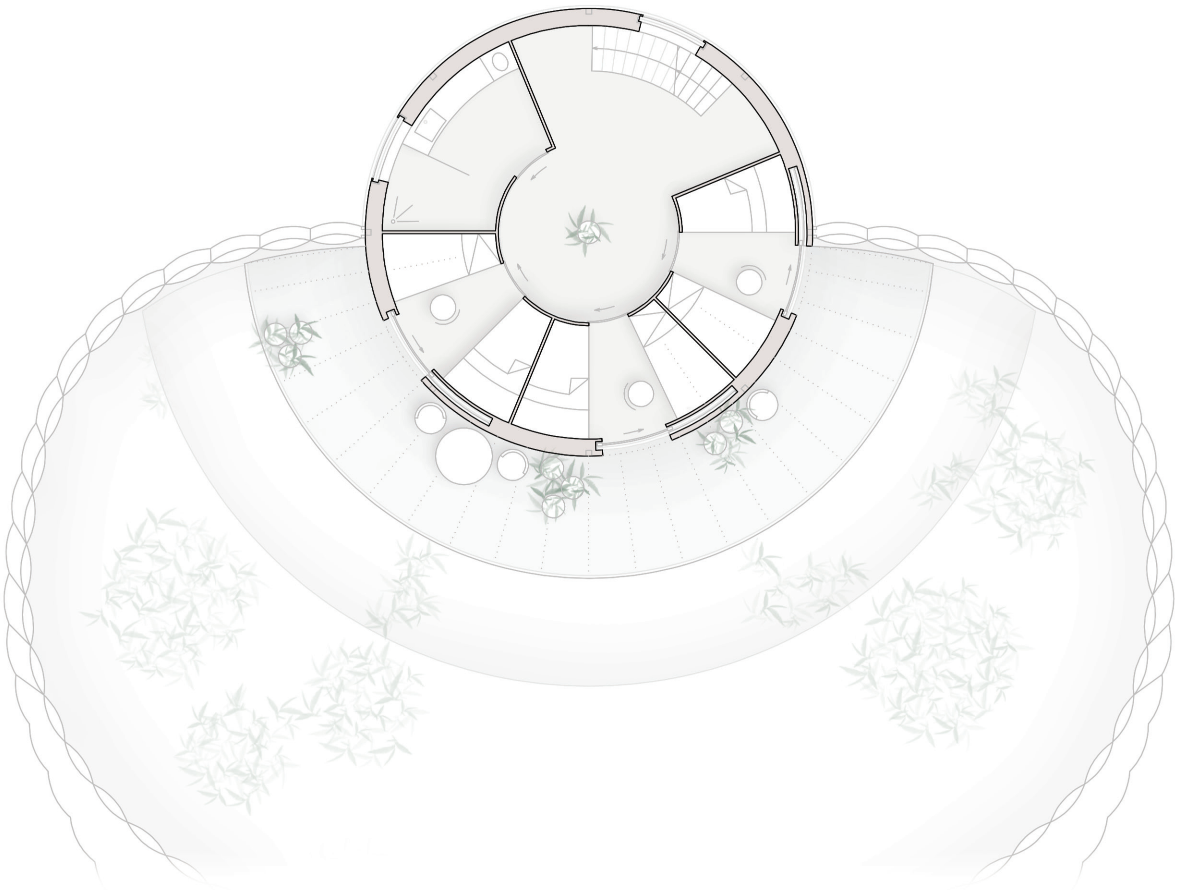


Illustration 41.: Plan +2 / Dwelling 1:150

Illustration 42.: Plan +4 / Observatory 1:150

BAMBOO

Introduction

As mentioned above, there are two main areas of the habitat with greenery, one being the gardens inside the inner ETFE, and a forest covering the entire area of the outer layer. This greenery is mostly represented by bamboo that serves multiple functions in the entire habitat. Firstly, it acts as a means of bringing a little bit of the known home Earth and creating a sensation of an architectural archetype of a rainforest treehouse, establishing experiences that the crew can relate to on the most basic levels.

Additionally, due to its superior physical properties and simple harvest, it can be used as resource for an extension in construction, furniture or tools, while minimizing the weight of transport of materials from Earth by in-situ production. It will provide the crew with the ability to directly affect their environment which has many positive implications upon their NEW HOME. Firstly, together with the very open dispositions of the terrace and the habitat garden, it allows for large flexibility through potential changes to the habitat as the needs of the occupants change over time. Furthermore, by the crew's self-realization and direct impact upon their environment they will develop a sense of belonging, a very important experience of any home.

Practical use

However, bamboo boasts many other practical benefits for the crew and the habitat. In the space of the habitat, it saves resources and labor by taking on the functionality of dividing space into a series of open dispositions and also forms a natural and simple means of glare control. Furthermore, it can lower the transportation weight of supplies as bamboo is edible and can be utilized in the kitchen in various ways. Lastly, through photosynthesis, all the bamboo in the gardens and the forest support the oxygen extraction systems and acts as the natural lungs of the habitat.

Not only is bamboo an ingenious material with very long tradition and craftsmanship, but it is also the ideal plant to grow in our conditions. By botanically identifying as grass, it is biologically very simple and exhibit very low requirements on the environment, being able to withstand extreme temperature fluctuations, and does not require pollinating to reproduce. It is also the fastest growing plants on Earth which makes it possible to be utilized for its purposes within months.

Other greenery

Besides bamboo, the NEW HOME also contains utility greenery, mostly vegetables, that will become a main supply of fresh food, lowering the needs for Earth-reliance. Due to the non-seasonability of the NEW HOME's indoor environment, this supply will be continuous, all year round. Together with the bamboo, through gardening and involvement, it will help the occupants forget about the danger of the mission and escape the draconian scheduling the astronauts are subjected to.

Illustration 43.: Bamboo furniture

INTERIOR

Introduction

The design of the interior, as a whole and in its elements, reflects upon the qualities of an ideal home in both its phenomenological and architectural meanings. Furthermore, it is a direct translation and continuation of the architectural concepts and experiences described above.

The open spatiality of the terrace and gardens using greenery and bamboo craftsmanship for space division results in some of the most important parameters of a home – spatiality, self-expression and flexibility. The lush greenery of these spaces also result in both auditory and olfactory comfort, where the greenery helps scatter any sound, that would typically resonate in the enclosed space. The natural smells of all the present greenery create a sense of nature, safety and home and helps in reaching a sensation of a treehouse.

Spatial qualities

Just as all the elements of the habitat are very different, they also exhibit very different spatial qualities. The central prefabricated Core is the least spatial but also the most intimate due to the clearly defined solid geometry that creates a sensation of safety and privacy. Contrarily, the terrace and balconies are very open in both their division and in their visual connections. The elevation above the ground and the concentration of leisure activities in this space offer a metaphorical distance from the perils of the world and results in a peaceful and relaxing atmosphere. Lastly, the spaces on the ground floor comprise mainly of greenery and thus create the context for the entire habitat and create the sensation of nature and prosperity.

Views

The use of the transparent ETFE membrane for the envelope results in a strong visual merger between the habitat and the environment. This strong connection is an important factor in eliminating the sensation of a capsule, positively affecting the psychological well-being of the occupants and serving as a means of reducing the stress caused by confinement of the crew. In addition, the concave shape of the ETFE membrane offers exterior views of the envelope and further minimizes the sensation of a capsule and helps the occupants create a bond with their home.

Next to the visual connection between the interior and exterior, large emphasis is also placed upon the visual connections within the habitat to help merge the elements of the habitat into one. The direct placement of the terrace and balconies above the gardens results in their direct inclusion in the space, as described above. Similarly, the kitchen boasts three large openings to the terrace that offer a wide view into the gardens and the forest.

Materiality

The interior materials are united in a white-wood color palette. White color in the form of interior wall claddings and core and terrace flooring help emphasize the sensation of spatiality due to its lightness. The use of natural wood in the furnishings, hanging ceilings and details provide warmth for the interior and help merge the primordial archetype of a treehouse and the crafted bamboo furniture with a modern, hi-tech piece of architecture. In addition, the color and texture of the wood helps in visually merging the interior of the habitat with the brown to red Martian environment.

Visual connections

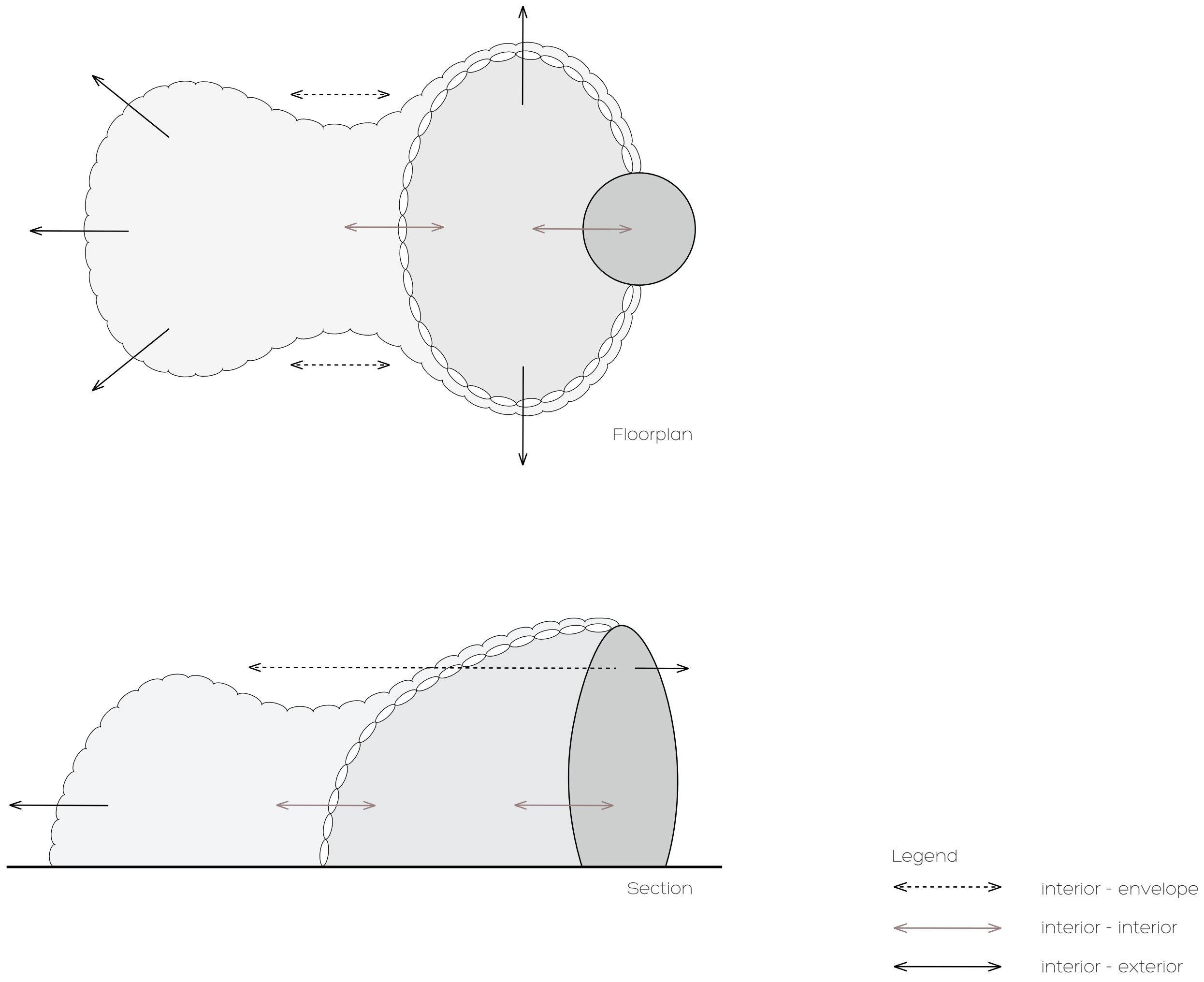


Illustration 44.: Visual connections

CORE

Geometry

As mentioned above, the core is the main and technically most complex structure in the habitat, including all life-sustaining technologies and appliances that are all prefabricated and inspected on Earth and shipped onto the surface of Mars. Its nose cone shape with a base of 7m and height of 16meters is designed to fit into a payload fairing for easiest transportation. The exact geometry of the core follows the required space demands for each floor function.

To reduce the weight of the core, it is fully constructed of aluminum as a skeletal system of eight curved columns that are connected on the top of the core. Each floor is then constructed by eight horizontal beams that meet in a circular beam in the middle. Small prefabricated aluminum plates are assembled on top of the beams in a radial composition and hold the acoustic insulation and final floor finishing.

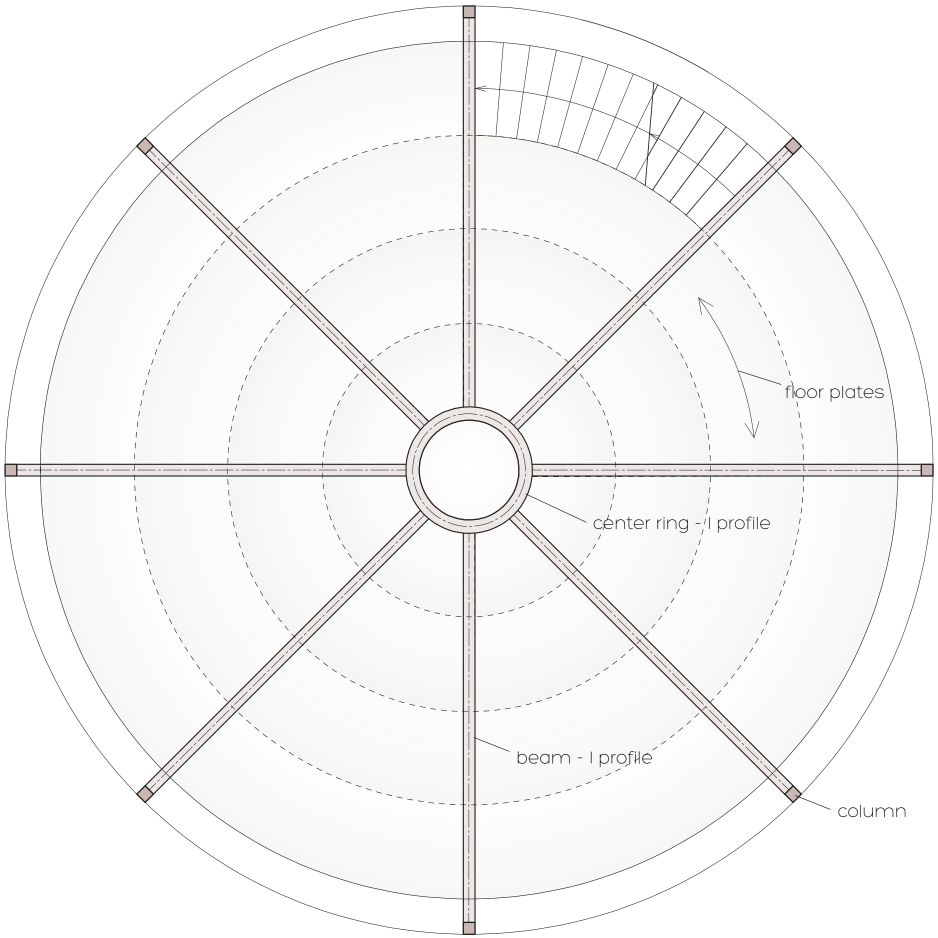
Pressure Vessel

In case of emergency, such as any damage to the ETFE envelope, the core can act as an independent pressure vessel, that can fully sustain the crew for the time of any necessary repairs or maintenance. To hold the indoor pressure independently of the ETFE membrane, the external layer of the core is constructed of welded sheets of aluminum and is supported by the structure, additional bracing and stiffeners. On the inside of these layers is spray-applied silica aerogel that creates the thermal insulation layer. The additional space between the outer layer and interior cladding is used for installations. Similarly, to protect the crew from the occasional solar flares, the core can house the crew for the time of the event and use its mass to block the strong radiation.

In order for the core to hold pressure, all openings can be closed by sliding pressure hatches that are stored in the wall cavities. In addition to the safety hatches, all dwellings feature additional balcony doors to create full visual as well as auditory privacy for the occupants.

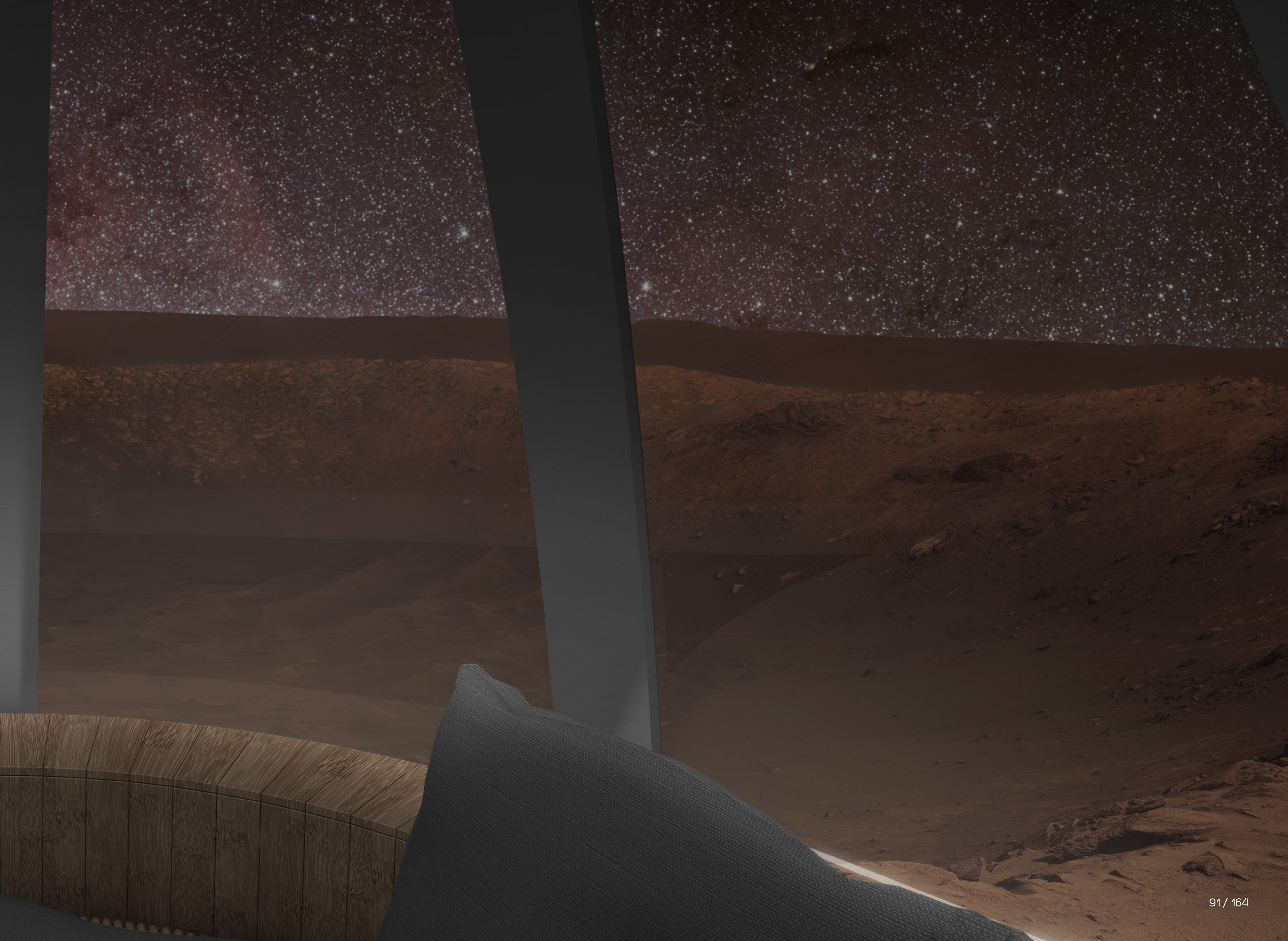
ETFE connection

To eliminate any air leaks from the habitat, the ETFE is connected directly to the pressure vessel layer of the core through additional external rectangular connectors. By welding these connectors on two edges to the core, one surface can be penetrated with bolts, holding the ETFE, and retain its airtightness. The reinforcement dyneema is connected perpendicularly to the core to eliminate any shear to utilize the elements full potential.



Core structure

Illustration 46.: Core structure



A.
welded cladding
waffle stiffeners
bracing beams
columns
airogel coating
door cavity
T/U/I - supports
interior cladding

B.
welded cladding
waffle stiffeners
bracing beams
columns
airogel coating
door cavity
door (welded cladding
 + waffle stiffeners)
T/U/I - supports
interior cladding

C.
welded cladding
waffle stiffeners
bracing beams
columns
airogel coating
T/U/I - supports
interior cladding

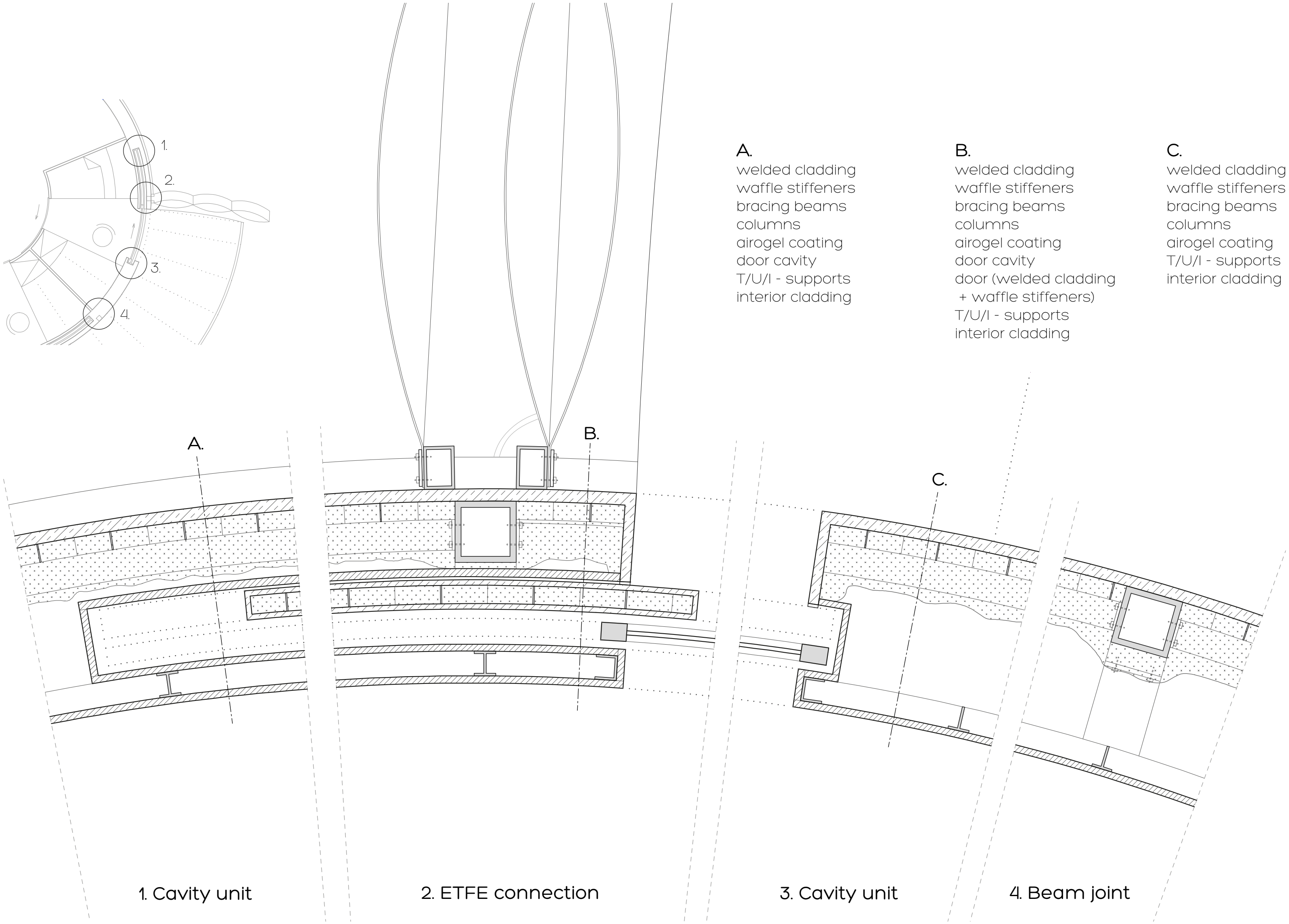
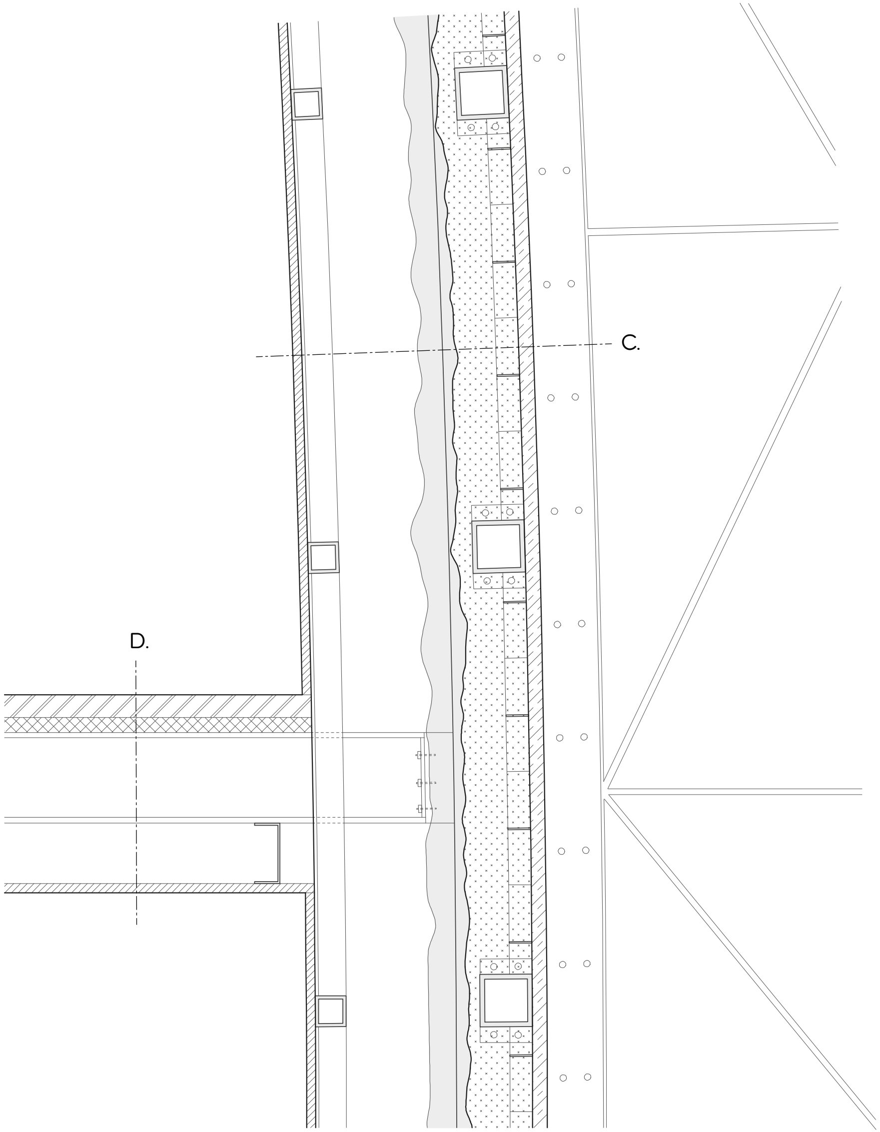


Illustration 48.: Detail / Core, scale 1:10

C.
welded cladding
waffle stiffeners
bracing beams
columns
airogel coating
T/U/I - supports
interior cladding

D.
final floor finish
acoustic insulation
floor plates
structural beams
hanging ceiling



Beam connection

Illustration 49.: Detail / Beam connection, scale 1:10


ARES III
2
NASA

TERRACE

Introduction

The terrace on the first floor together with all balconies in the habitat are deployable structures, which unfold in the habitat stage, after the ETFE membrane is inflated. Each of them is designed in order to fit inside the core openings, for transportation to Mars. The deployment out of the core requires pneumatic system which locks the structure to the rails placed around the core. Sliding on the rails, the terrace structure unfolds to its final position and fix to disable any movement (Illustration 51).

Dimensions

Each panel of the terrace is 50mm thick, made as prefabricated aluminium slab. The length is 4,1m, allowing to create rooms after it is unfolded.

Whole structure consists of 10 folding elements made of 4 plates and joined by hinges. One element angle has 15°.

Details

The unfolding system of joints is shown in the detail of terrace deployment (Illustration 52), from folded through partially unfolded to completely unfolded terrace. All hinge joints become rigid after the deployment, except the one in the middle of element. As the hinge is positioned on the top, this part stay unstable. To form rigidity, we proposed extra element – triangular plate or frame that needs to be added by occupants after their arrival (Illustration 51).

Another solution would be to allow a limited rotation to the top plates. Graphic statics of horizontally positioned plates (Illustration 53) leads to infinite forces, causing a deformation and rotation of plates after applying the load. To avoid or considerably reduce the deformation, the initial rotation would need to be applied. According to graphic statics, both plates could distribute the vertical load and thus, relatively remain its position. However, this solution introduces angle to the floor which creates a possible obstacle to comfortable movement of occupants.

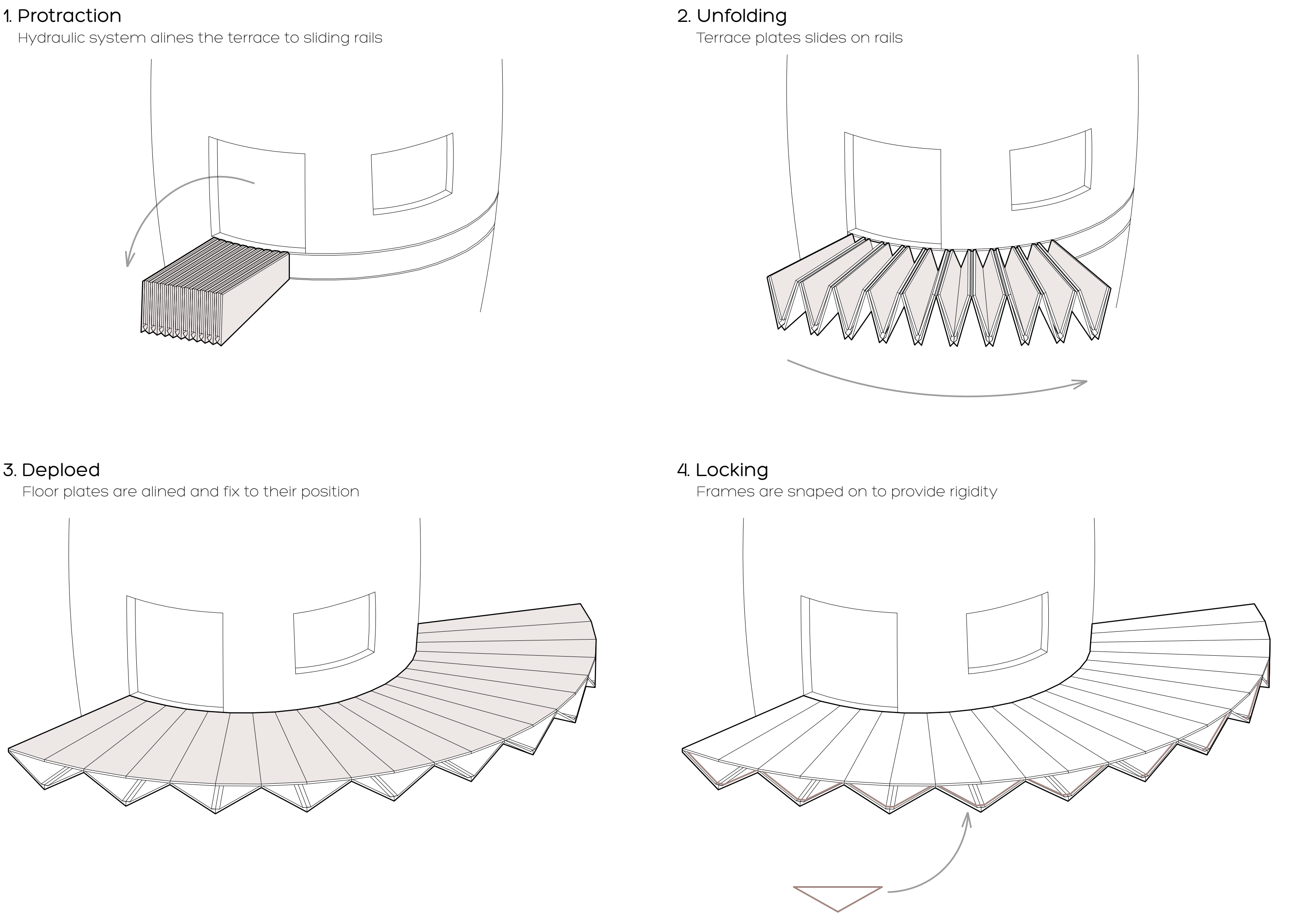


Illustration 51.: Terrace deployment

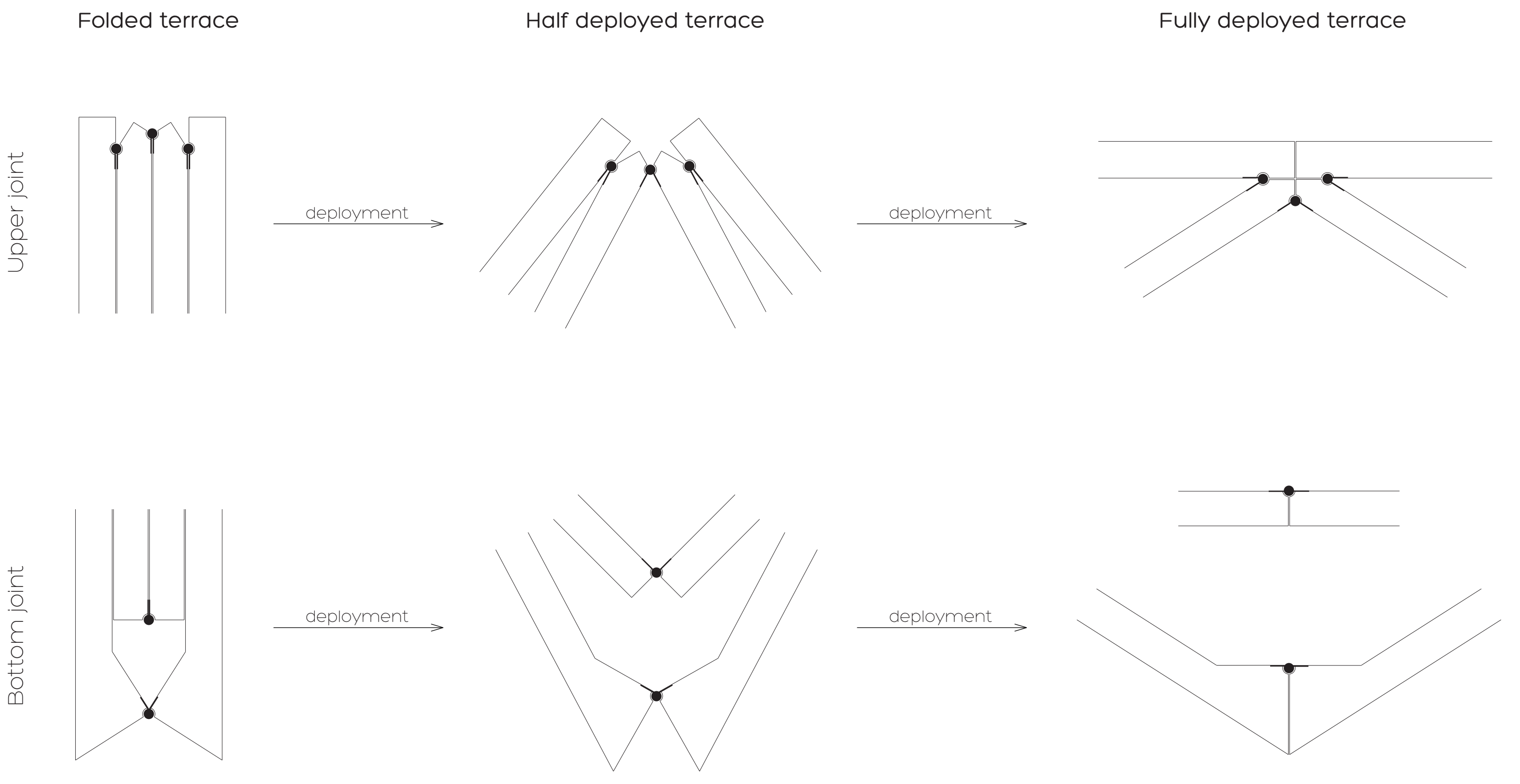
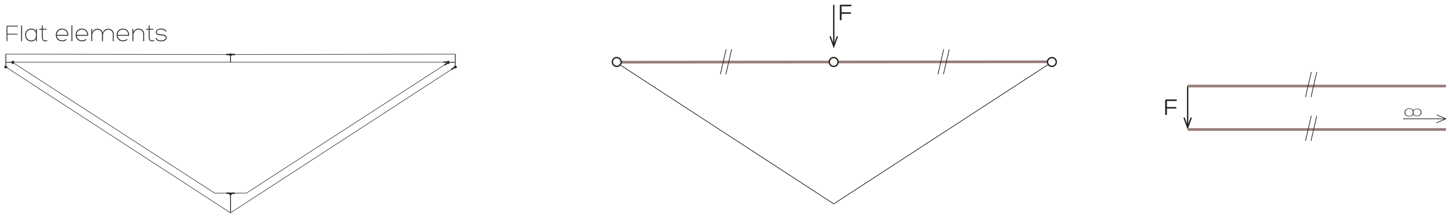


Illustration 52.: Detail / Terrace deployment, scale 1:10

Graphic statics

Flat elements



Angled elements

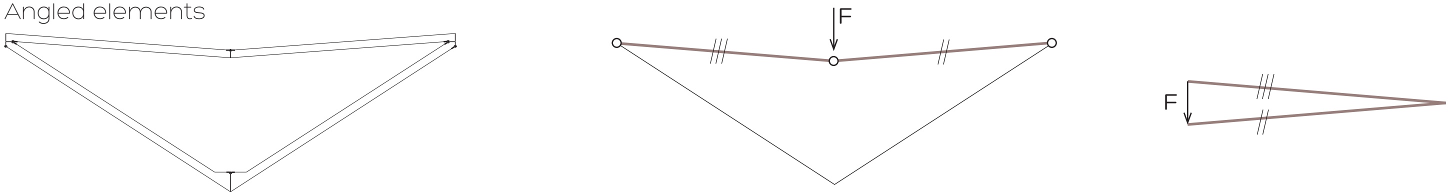


Illustration 53.: Graphic statics

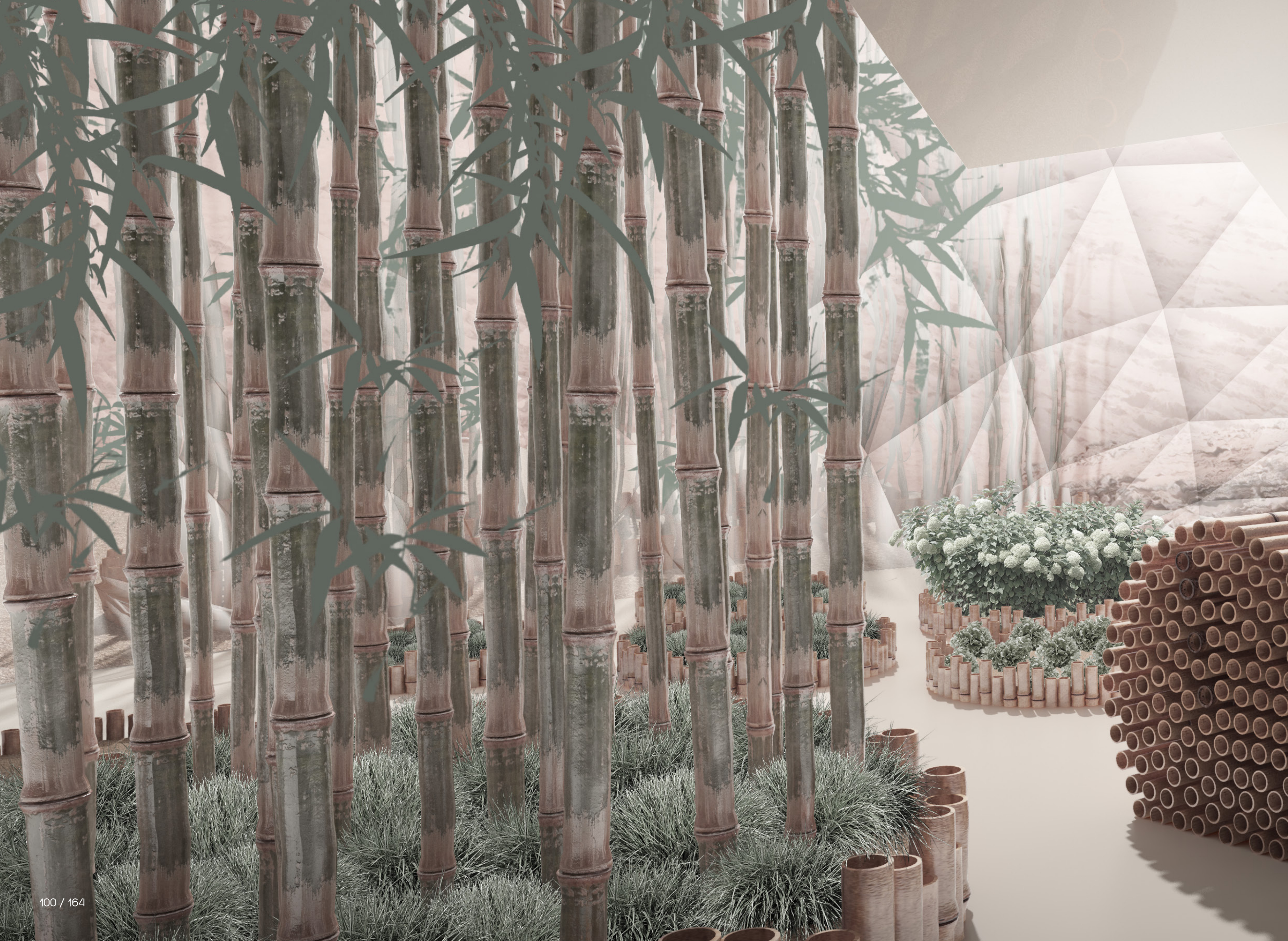


Illustration 54.: Daily planning center perspective

ETFE

Introduction

ETFE is a plastic like material and its transparency is higher than glass (94-97%). Moreover, it also transmits ultraviolet light, necessary for plant`s photosynthesis. ETFE properties assure high daylight factor in the habitat, transmitting all visible light wavelengths.

The habitat contains of two ETFE membranes, both connected to the middle of the core. Its dynamic, curved shape follows the nose cone volume of the core. The fundamental function of membranes is to create livable conditions in harsh Martian environment, providing thermal, atmospheric (see ECLSS) and visual comfort to the crew.

Both membranes will be folded for the transportation and deploy in the habitat stage. ETFE will be unfolded and attached to foundation. Afterwards, both layers will be inflated and create the extended inhabitable space.

Reinforcement

Due to large surface and extreme pressure load (see Pressure vessel analysis), both membranes require reinforcement. The support system is made of Dyneema ropes, which create pattern on the membranes. Due to its great tensile strength (3GPa), the cushions can be relatively big with small Dyneema diameter. The shape of the grid is triangular, with horizontal line and two crossing diagonals, which proved to be best working for the concave shape of outer membrane. The inner membrane cushions form dynamic system, able to inflate and deflate according to thermal conditions in the habitat. The pressure is continuously monitored by thermal control system (see ECLSS).

Calculation

The ETFE tensile strength upper limit used for calculation is 35MPa. The final calculation was made in Karamba, allowing large displacement as form-finding element. The initial shape for both membranes was created as a surface from network of curves.mFirstly, the Dyneema ropes were calculated. The pattern was applied, tested with different number of cushions for the most efficient structure. Both membranes have hinge supports around the core and ground. The load is applied on a mesh, ensuring equal division of pressure load on the ropes. The large displacement element in Karamba allows the structure to deform, so it finds the most efficient shape for load distribution. For both membranes, several iterations were made to find the most efficient maximum allowed displacement for form-finding. The inner structure performs the best with 1,4m and the outer with 2,3m. For the final calculation, pressure load was applied again and the deformed structure was recalculated.

The load applied to outer membrane is 50kPa, which required Dyneema ropes of diameter 1,9cm (maximum stress 2810MPa). The inner

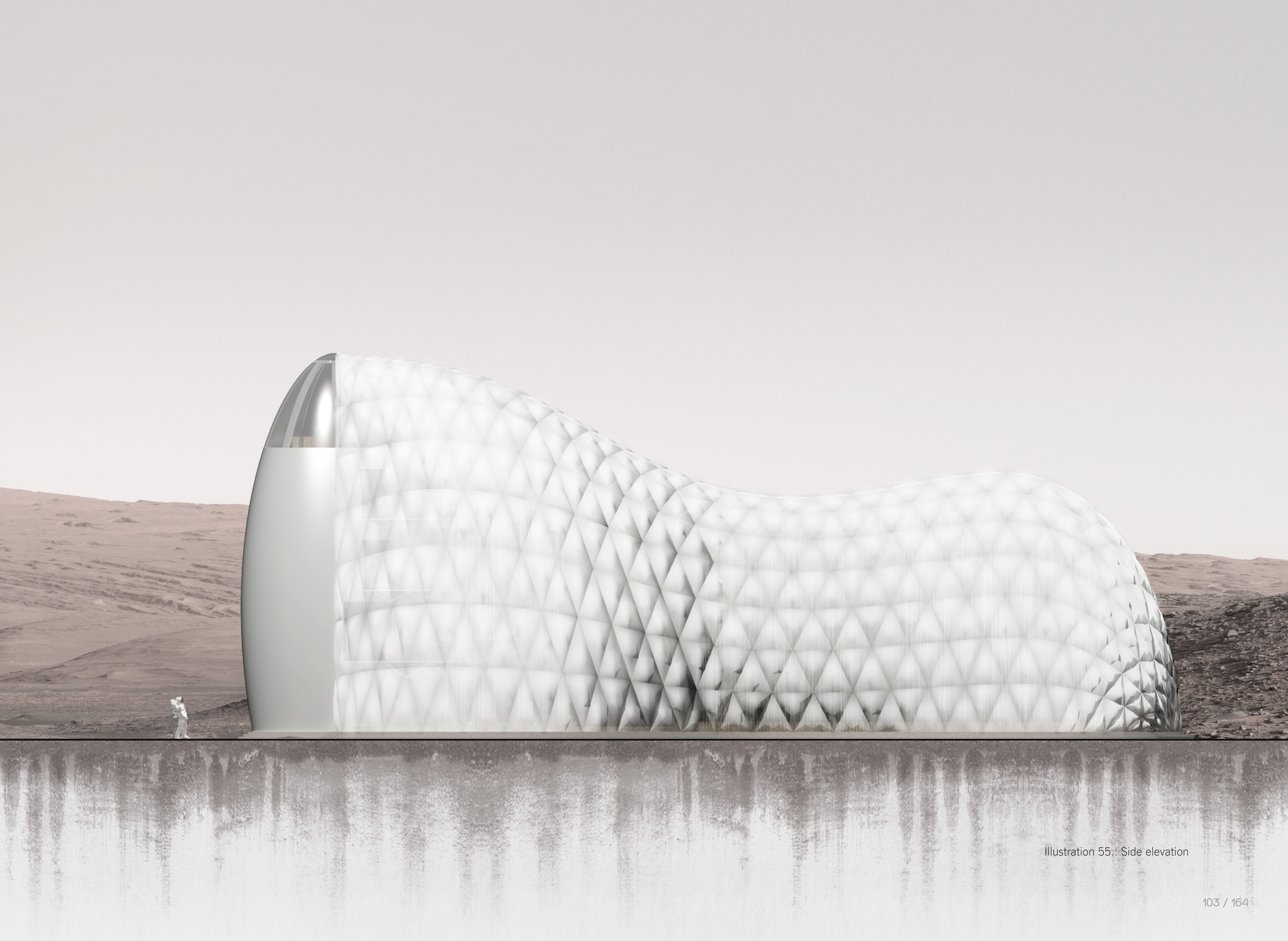


Illustration 55.: Side elevation

membrane with the pressure 51kPa (due to inflation of cushions) demands 2,1cm Dyneema (maximum stress 2865MPa). The inner membrane functions with only tension, while outer structure consists also elements in compression (60 elements). These segments are horizontal lines located in the concave part (Illustration 92). However, the diagonal segments should support the stability and thus, these elements do not influence the structure.

The deformation of both structures is relatively high, close to 0,5m (Illustration 95). As the membranes can deform without having any impact on the habitat, there is no requirement for the upper limit. Close to the core, membranes are connected by another ETFE in between the ropes, to decrease the deformation in between them.

Following the structure calculation, the biggest cushion was chosen for both structures. The inner membrane contains 405 cushions with the biggest 2,97m^2. The outer membrane`s biggest cushion (out of 779) has 3,03 m^2. For these cushions, same principle of form-finding calculation was applied with the maximum allowed displacement of 35cm. The supports for calculation were hinged, allowing the rotation around its edges. The required diameter for inner membrane is 1.5mm (pressure load 51kPa) and 1.4mm (pressure load 50kPa) for outer membrane (Stress in the cushions is displayed in Illustration 93, with the maximum limit for ETFE 3,5kN/cm^2. As the ETFE membrane are manufactured with maximum thickness of 0.3mm, all of the cushions will be created by 5 welded layers.

Detail

ETFE membranes are connected to the middle of the core in two places (Illustration 48). The connection to the ground is constructed as hinge join of Dyneema ropes to the drilled foundation elements in the habitat foundation. To protect the ETFE membrane from tearing, flooring made of rubber layer is added. The protection of ETFE from the bottom as well as minimalization of thermal conduction from the soil to the habitat is created by thermal insulation made of flexible silica aerogel insulation blanket of 10mm (Illustration 56). Its properties allow limited thickness and folding of the membranes, which is fundamental for transportation.

Single cushions are connected together by welding, with another strip of ETFE, integrating Dyneema in between (Illustration 57).

ETFE - connection to ground

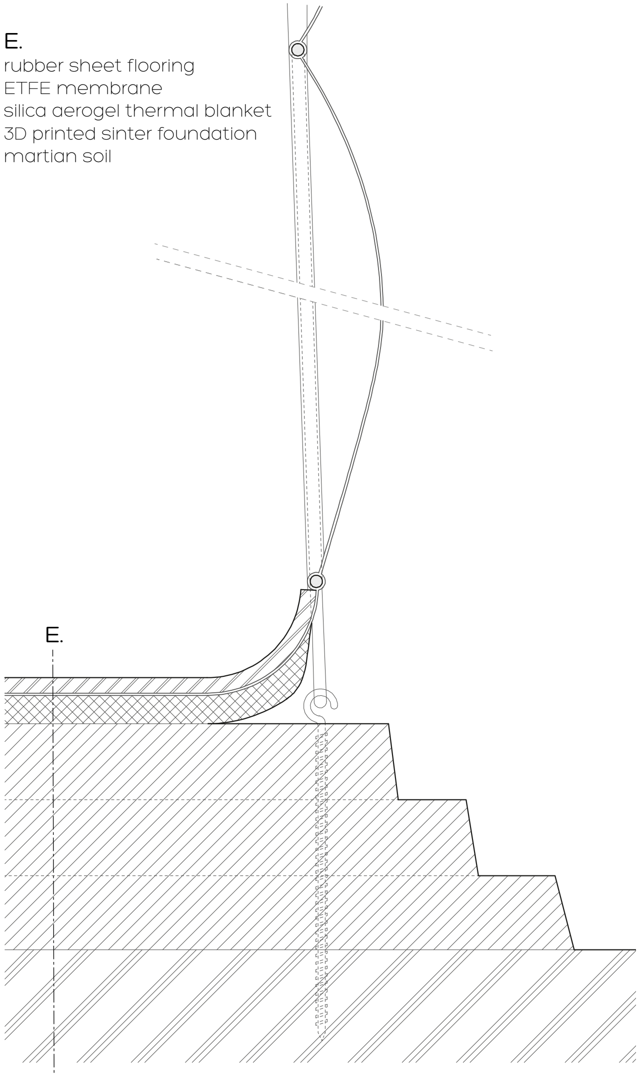


Illustration 56.: Detail / ETFE connection to ground, scale 1:10

ETFE - connection of cushions

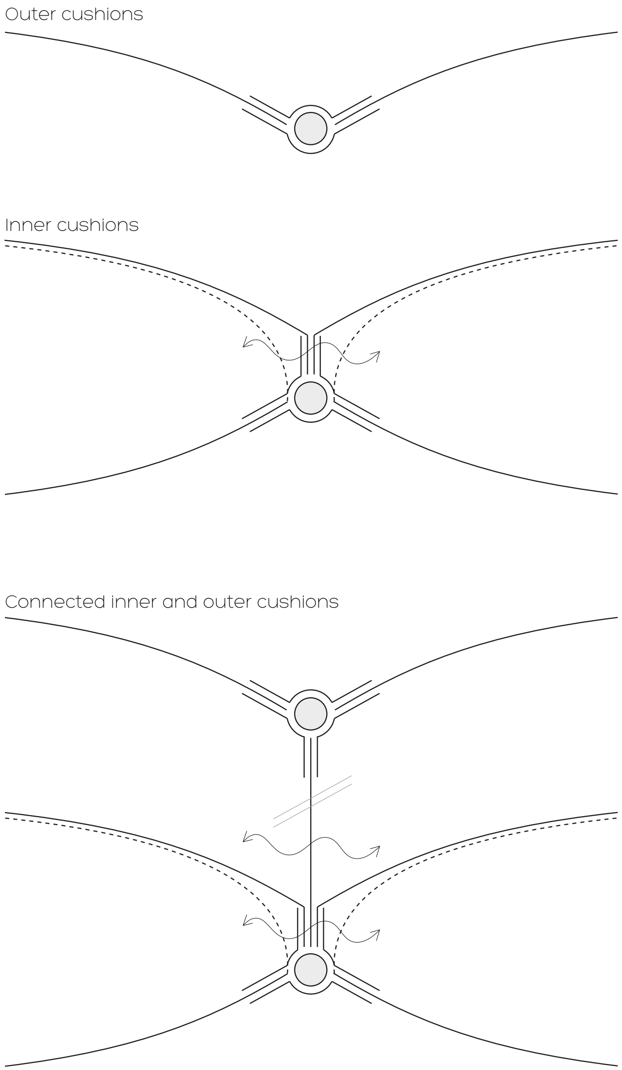


Illustration 57.: Detail / ETFE connection of cushions, scale 1:5

Illustration 58.: Exterior perspective

ECLSS

Introduction

Environmental Control and Life Support System provides air, water, energy etc. required for functioning and comfortable habitat. Due to harsh Martian environment, the demand on ECLSS is much bigger and more complicated than on Earth.

One of the main needs is energy production. The supply of electricity is ensured by nuclear energy made by radioisotope power system. Among other systems, radioscope is able to provide energy even in extreme temperatures or during dust storms (see Self-sufficiency analysis).

Water will be initially extracted from soil (see Self-sufficiency analysis), and the amount will be maintained by constant supply to cover for the losses from nonrecyclable water.

Ventilation

The entire habitat is mechanically ventilated by HVAC system. The atmospheric conditions will be continuously monitored, assuring the right composition of all gasses (similar to the Earth air with 21% of oxygen). Due to long stay on Mars, most of the gasses will be extracted from Martian atmosphere by ISRU plant (see Indoor comfort analysis). Moreover, the production of oxygen will be supported by photosynthesis of plants.

Pressure

The pressure in the core and the habitat garden will be 101kPa. In the bamboo forest is designed for only 51kPa and, therefore, the concentration of oxygen needs to be considerably higher. Otherwise, people could not stay there without oxygen mask. Both parts of the habitat will be constantly controlled by HVAC system placed in the technical room. To make possible movement in between the habitat garden, the forest and exterior, airlock is placed in between these areas. It deals with pressure differences, containing its own independent air-pressure system.

Thermal control

Thermal comfort in the habitat is solved conceptually as there is no existing specific data that could be used for simulations. The concept is based on thermal zoning, to lower the impact of high temperature fluctuations between day and night. As the atmosphere on Mars is comparable to vacuum, the dominant part of heat loss/gain is thermal radiation. Therefore, to regulate the temperature we designed dynamic cushion system, which controls the amount of transmitted thermal radiation from interior to exterior and the vice versa. In order to do so, inner membrane`s cushions have printed low emisivity coating with inverse patterns. Therefore, they do not transmitt thermal radiation when closed and the opposite. Our proposal is to open the cushions during the day, to allow heat gain from sun radiation, and close them for the night to avoid heat loss. Although this concept might work, it is difficult to estimate such a system and the habitat might be very cold or warm and would, therefore, require precise calculations. Even though a responsive system will be installed to monitor the habitat, the inflation and deflation of cushions could be insufficient. Thus, the core is designed so it can be completely closed if needed (especially for night drop of temperature), creating its own thermal zone.

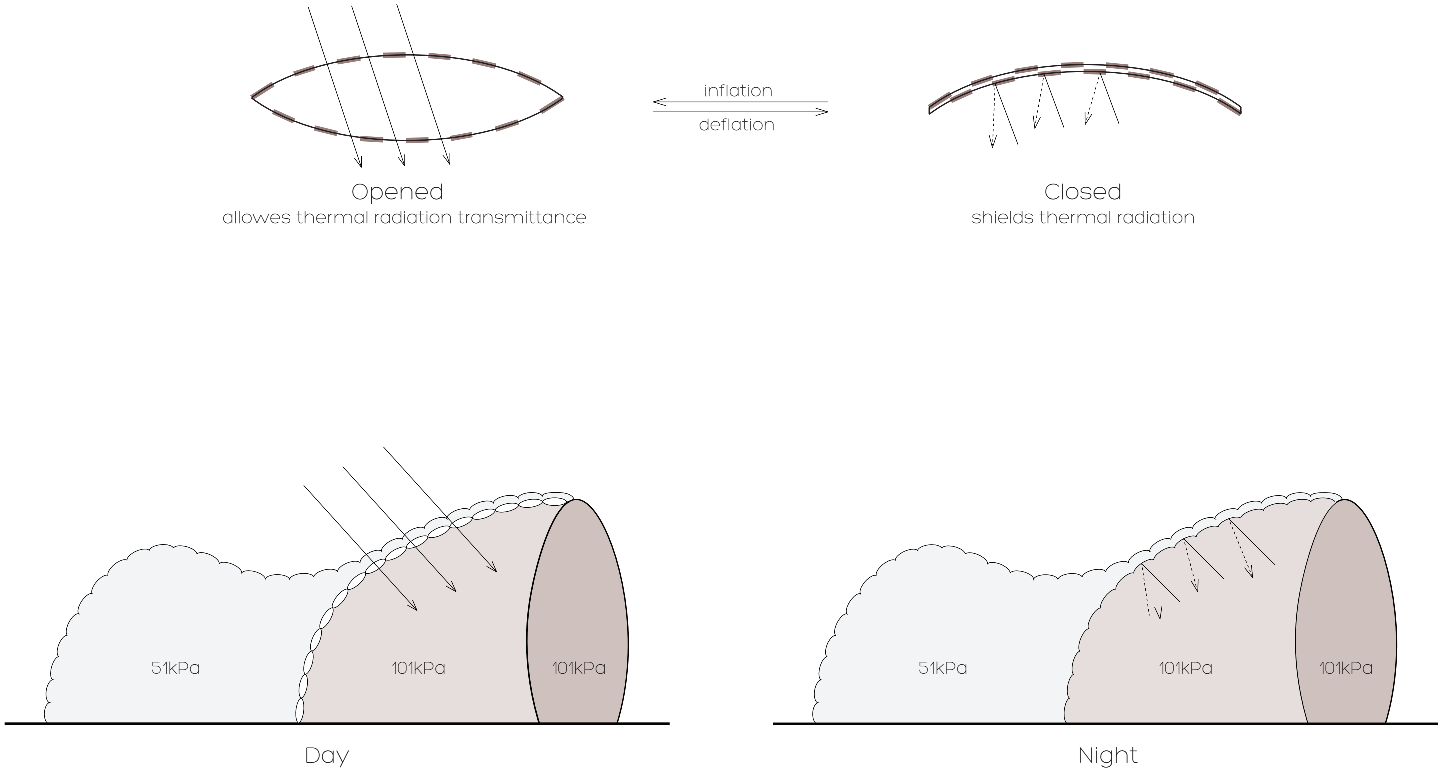


Illustration 59.: Thermal control

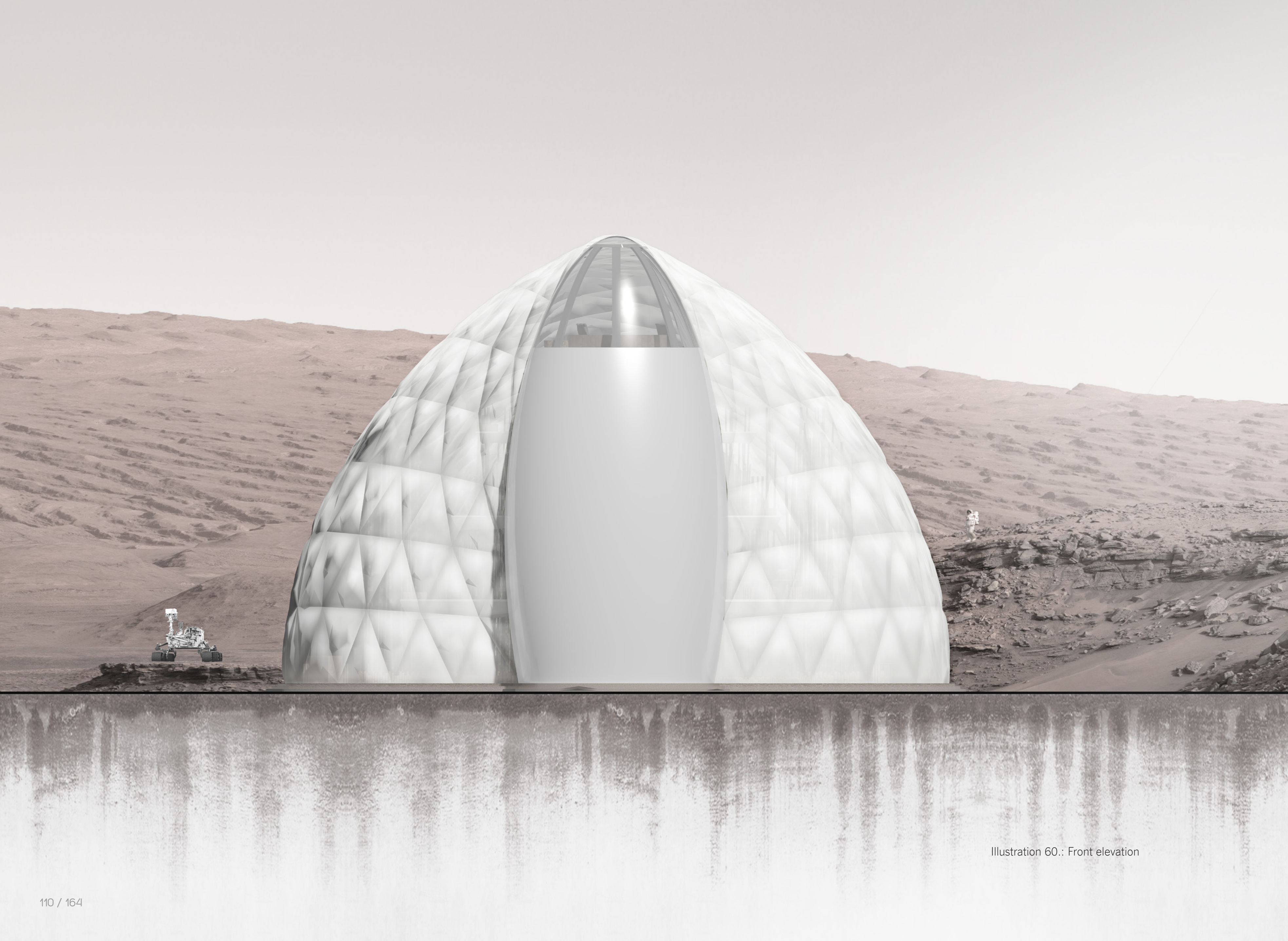


Illustration 60.: Front elevation

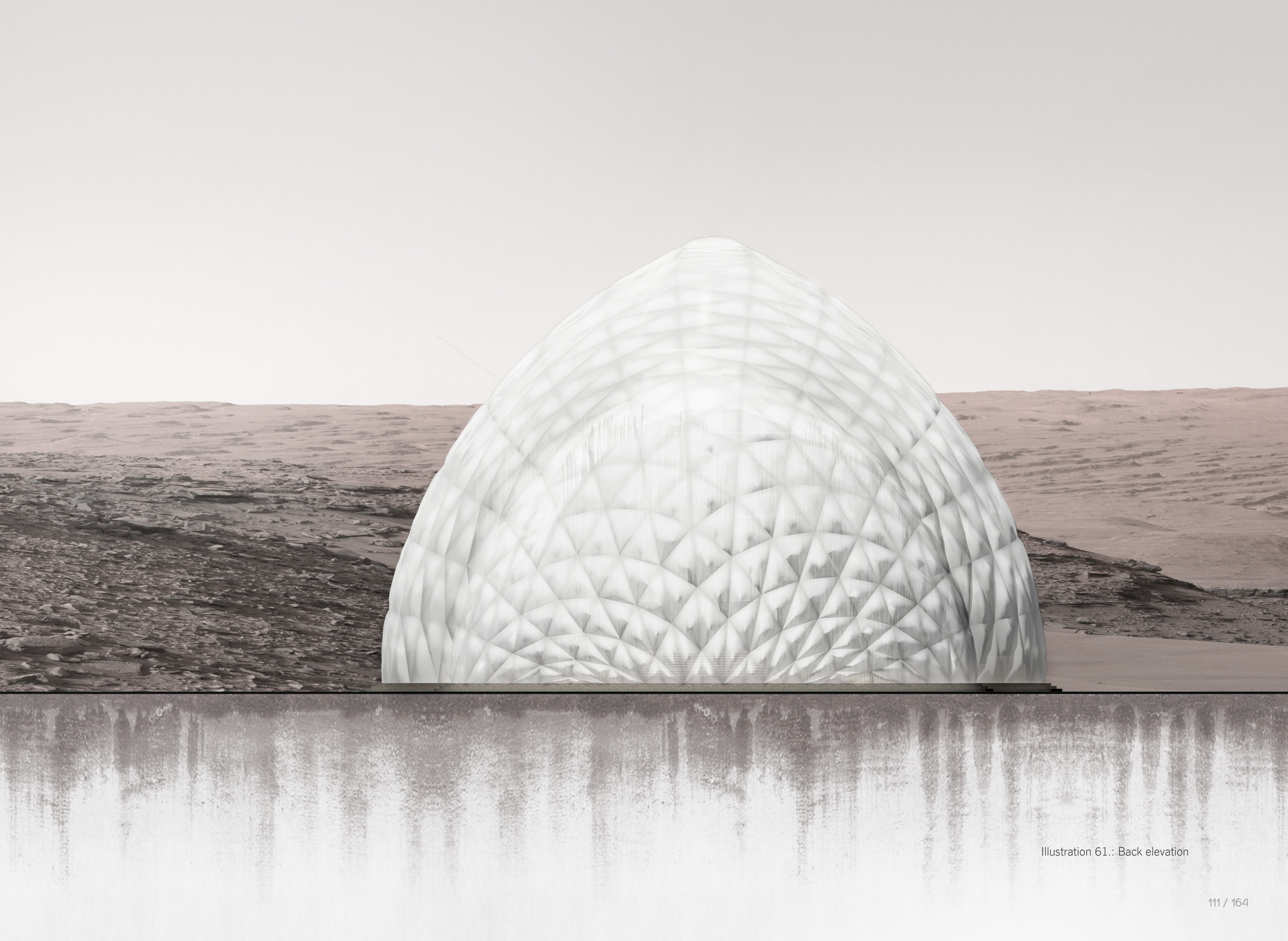


Illustration 61.: Back elevation

DESIGN PROCESS

habitat / dispositions / interior / core
terrace / structure / ETFE / ETFE calculations

• • •

Within this chapter, we describe the evolution of the project and our decision-making processes and the motivation behind them. We also present other solutions to some of the faced challenges and reasons for why they were discarded. We start by identifying the most significant developments in the composition of the habitat and its spatial divisions and qualities. In the second half, we describe the evolution of the engineering solutions of the various elements forming the habitat as a whole.

• • •

HABITAT

Introduction

In the beginning, we started by exploring the possibilities to build on Mars. Many existing proposals are ideological, conceptual future cities with no connection to the current technologies. Other proposals are underground, or "capsule" like dwellings, mostly designed by engineers. Our aim was to design a New Home, and thus, creating a "capsule" design without visual connection to surroundings, poor daylight conditions and minimal living space would not be an option. Based on the analysis, the design should provide comfort from both, psychological and physiological aspects. The design that the crew could consider their home.

Therefore, our starting point was to build on the ground, with the visual connection to the surroundings. The habitat should provide more than just a minimal required space. The place, where the inhabitants can freely choose where they would like to spend their time. We aimed for a design that allows for various activities the crew would do on Mars. Another consideration was to enhance the interaction between the crew members as well as to provide them with their own, private space. Besides the well-being of the crew, we also considered the transport to Mars and its construction after the arrival. Following the concept of 3 stage deployment, we started with the core and the surrounding habitat.

Design

Already from the beginning, we divided the habitat to the core and two extended spaces – habitat garden and the bamboo forest. The habitat was designed to allow of different activities based on the analysis. The core and the deplyable terrace contained leisure, dwelling, technical rooms and work area. Later we added also observatory (Illustration 66) on the top of the core, which would enable a clear visual contact with both, interior and exterior.

The overall volume of the design was changing throughout the process. The core moved from the middle of the habitat, from an isolated structure inside a membrane capsule, to the edge. Later in the design process, its position was changed, so the ETFE membranes connect in its middle part of the core, creating a connection between exterior and the interior and resulting in a more uniform architectural synthesis of forms. Its location to the north direction exposed the membranes to the sun, and thus, allowed of better thermal conditions in the habitat (Illustration 64). Other parts of the habitat were also redesigned - the shape and the connection of membranes and their patterns, the construction and deployment of the terrace, the shape and size of the core, etc. which are described in the following chapters.

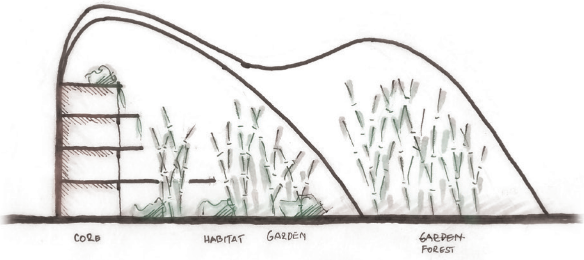


Illustration 62.: Longitudinal section

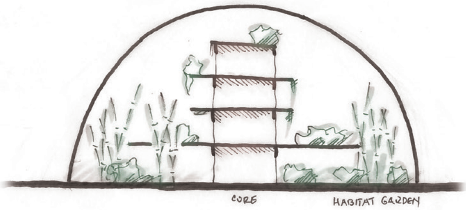


Illustration 63.: Cross section

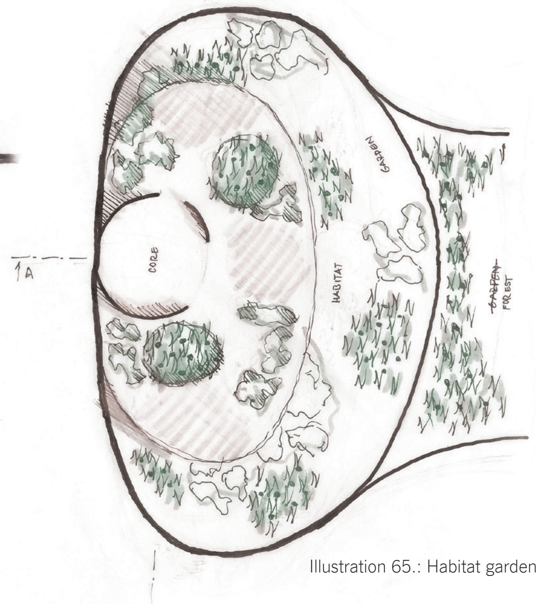


Illustration 65.: Habitat garden shape

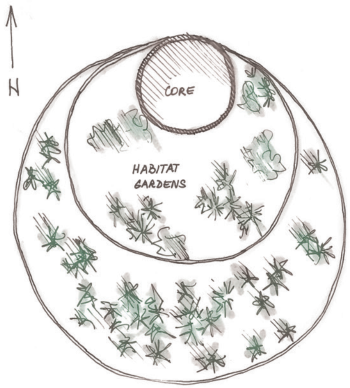


Illustration 64.: Habitat shape

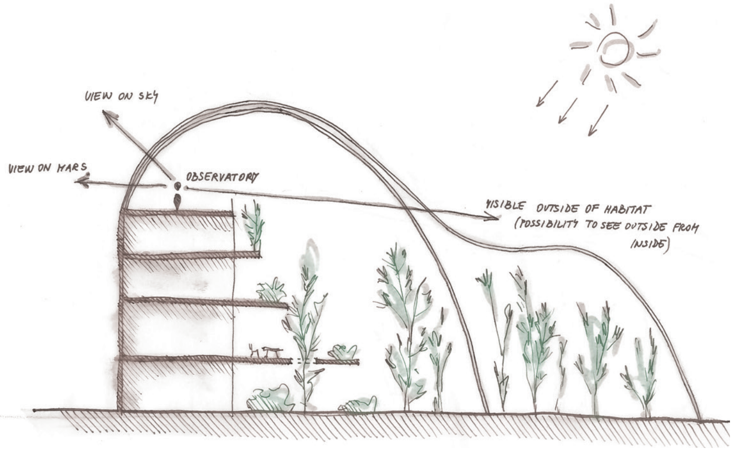


Illustration 66.: Views

DISPOSITIONS

Introduction

Due to our early and strong design parameters set after the initial analyses, the plans have gone through relatively minor changes, mostly related to dimensions and technical solutions. First and foremost, the parameter of a three-stage deployment formed very strong and clear geometrical boundaries for the Core, that, as a result, must be of circular cross section. The functionality and privacy zoning parameters and the verticality of the core resulted in the vertical division of the room program in the Core. And lastly, the parameter of a treehouse resulted in the inclusion of low and tall greenery in all plans from the very beginning of the design process. Thus, all three of these elements are present in all the plan iterations.

Core

As contemplated above, the vertical division was present from the beginning of the design process, however, the number of floors has changed. Initially, the core consisted of three floors – work, leisure and dwelling under a round top. However, after the first investigation on the spatial demands of the dwelling units, the respective dimensions for one floor containing all six units would exceed the width of a payload fairing and, therefore, the dwelling units needed to be divided into two floors. The height of the fairing allowed for an additional floor that allowed us to use it for the planned observatory.

The dispositions of the core altered through the process slightly based on the location of the staircase and the bathrooms on the dwelling floors. Two main options were considered for the location of them both, the middle of the core or at the edge of the circular plan. However, the central positions would create a spatial obstacle on all floors and the plans would not exhibit such freedom and openness as they do with the location at the edges.

Terrace and gardens

The location of the dining, library and the gym on the terrace adjacent to the kitchen and the use of greenery for space division have also been present since the beginning of the design process. However, the sizes and shapes of the terrace have gone through the largest alterations in the plans due to the development in the technical solution as described in chapter Terrace.

An airlock is required for transition between spaces with different atmospheric pressures. Firstly, to allow for a direct connection to the outside, an airlock was located next to the core. However, this setup would require two individual airlocks to allow transition between the inner layer of the ETFE and another one between the two layers that contain different pressures. Afterwards, one airlock was placed in a corner of the connection of the ETFE layers that allows for single-point transition between the outside, habitat gardens and the bamboo forest.

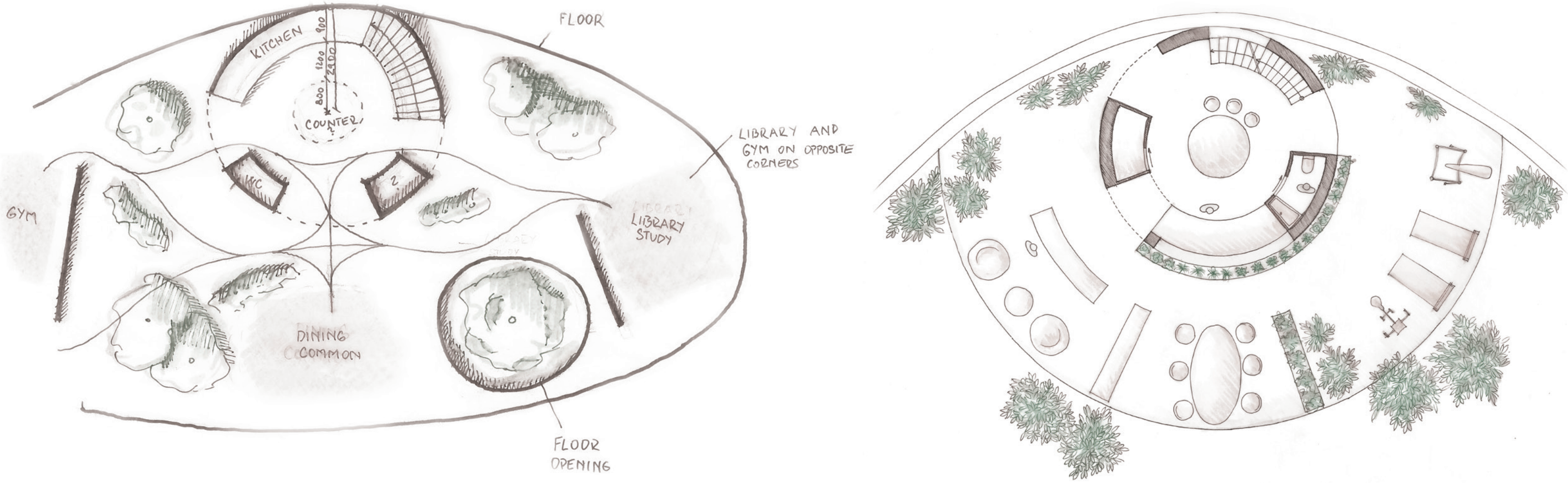


Illustration 67.: Floorplan iterations / work

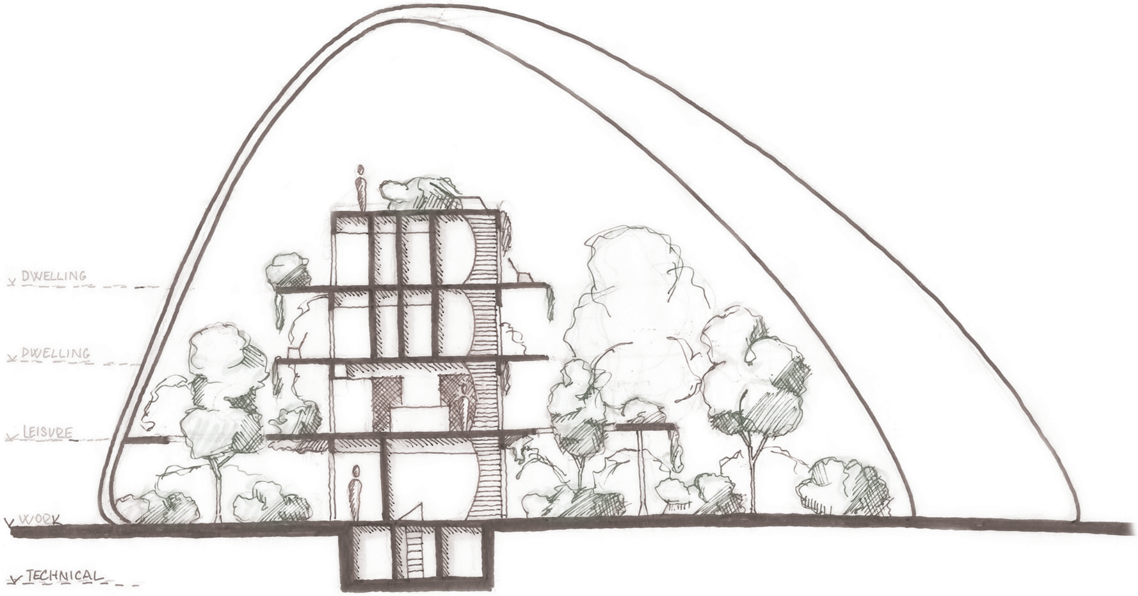


Illustration 68.: Longitudinal section / core in the middle

Illustration 69.: Floorplan iterations / leisure

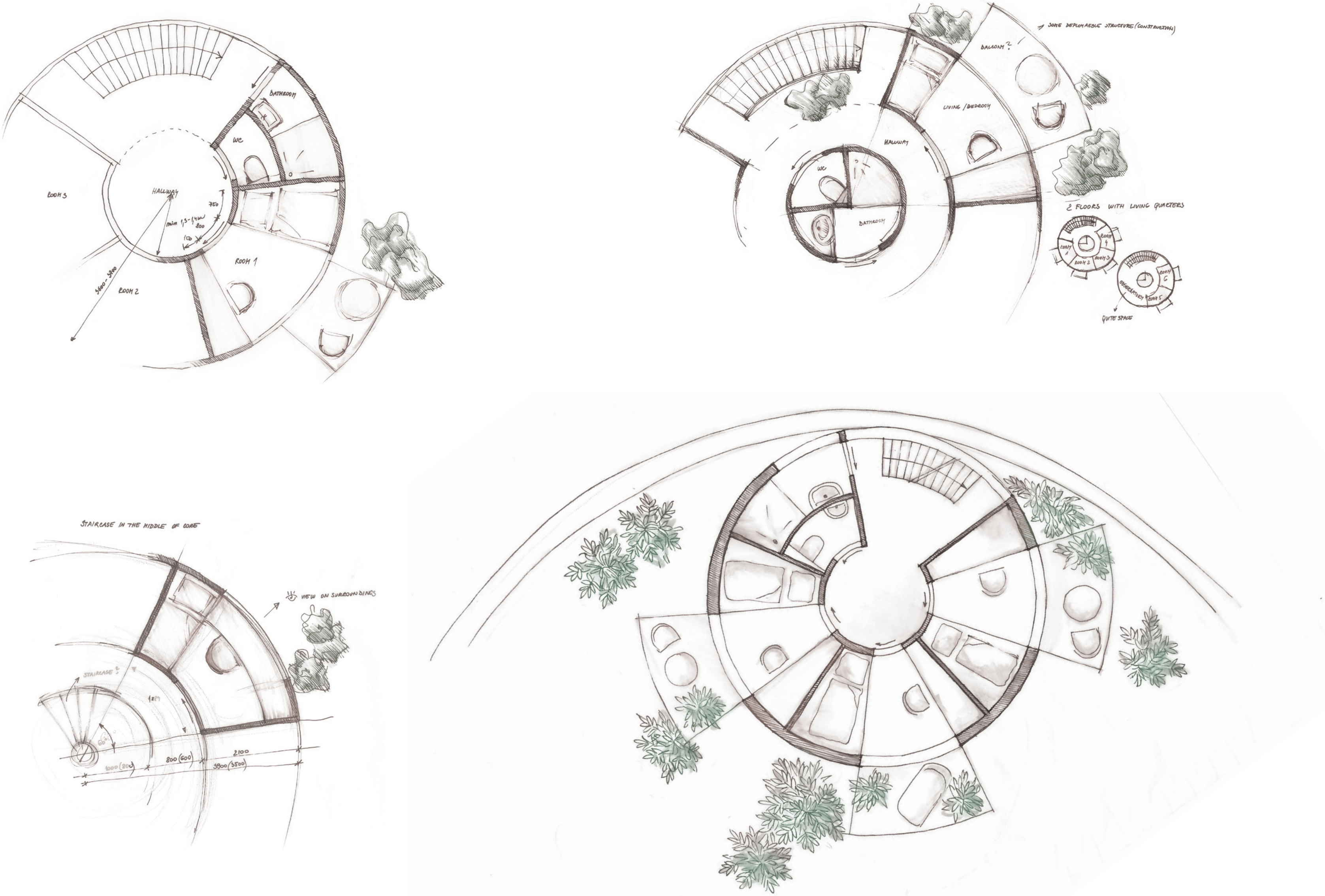


Illustration 70.: Floorplan iterations / dwelling

INTERIOR

Introduction

During the entire design process, the interior was designed in parallel with the structures of the habitat and the dispositions to reflect the knowledge gathered through the chapter Home and to compliment the spatial experiences set in the Design Parameters. In addition, elements of the pattern language were employed to reach qualities of privacy, intimacy, social cohesion and strong visual connections.

Views

The visual connections were one of the most important parameters in the design of the interior of the habitat and resulted in some of the largest developments. These connections were considered on a few levels: interior-exterior, interior-habitat and core-habitat, that would merge all the elements of the design into one.

Firstly, the visual connection of the habitat to the outside was very important to battle the confinement that could result as a large stressor on the mission crew and was one of the main parameters in choosing the envelope material and the construction above ground. Similarly, the shape of the envelope was largely informed by the possibility to see parts of the envelope exterior from the interior.

Greenery

As much as the visual connections, greenery is another one of the most important aspects of our design and has been considered since the beginning of the design process as means of achieving a natural sensation of a home in the habitat. However, one of the largest developments in the process was the decision to use bamboo as the primary greenery due to its many benefits described in chapter bamboo. This decision largely affected the atmosphere of the habitat as it changed the context for the concept of a treehouse from a temperate forest into a rainforest and the possibilities to largely utilize the resource it provides.

Furniture

Ever since the decision for the use of bamboo, we have considered use of this resource for expansion and improvement of the space. This could be achieved by expansions of the terrace and balconies and by crafting additional furniture. To offer a vision of the final space, we have also designed the possible bamboo furniture. This design has been mainly driven by simplicity of the required methods and shapes and minimizing the need for complex machinery.

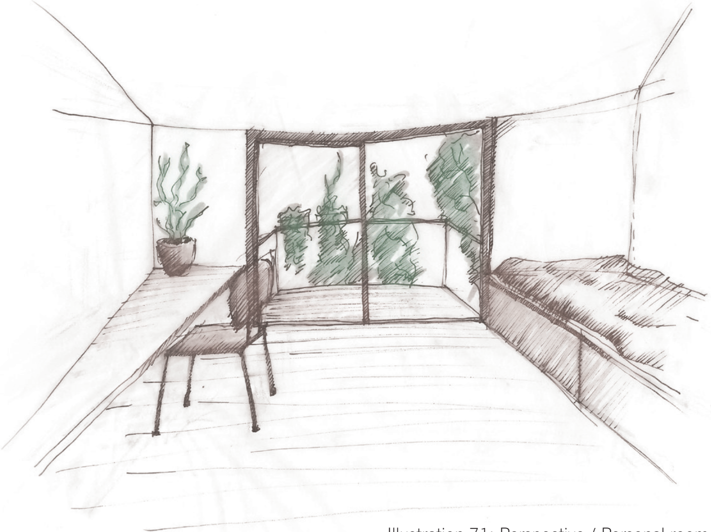


Illustration 71: Perspective / Personal room

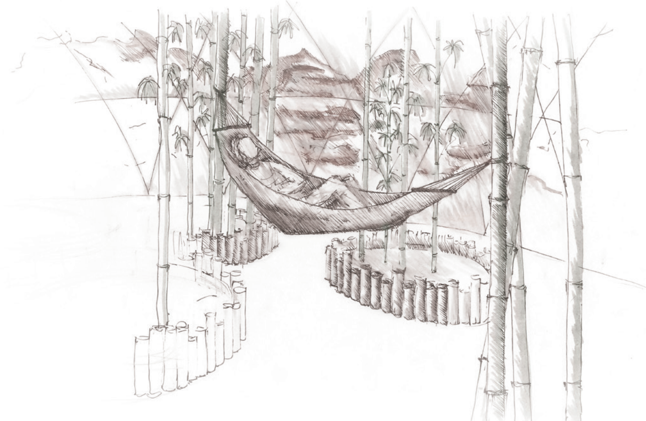


Illustration 72.: Perspective / Quite place

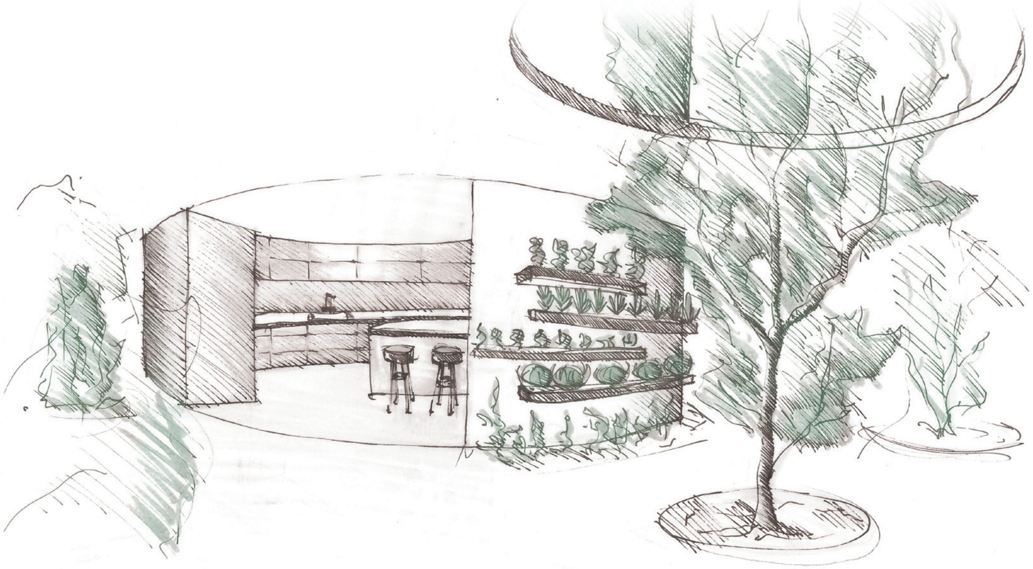


Illustration 73.: Perspective sketch / Kitchen

CORE

Introduction

Our initial design parameter of using a fully prefabricated central structure with deployable expansion had a significant impact upon all the structures involved. Most importantly, the prefabricated structure needed to conform to the currently used space rockets used to carry payload into space; most significantly atop the ISS. Such a consideration creates very specific boundaries for the shape, dimensions and payload of the structure. Due to the numerous unknowns of the payload calculation, this particular consideration informed the design of the core more conceptually by the choice of structure system, described below, and the materiality of the interior.

Shape

As mentioned before, the main volumetric boundary for the core is the way it will be transported onto the surface of Mars. The payload delivery shuttles are cylindrical with a hemispherical top. It is, therefore, clear that the shape of the core should be design to utilize the provided space. At the first steps, our design was strictly cylindrical to utilize the provided space fully and with a diameter of 7m that fits well within the standards of state-of-the-art rockets.

However, such a strictly sharp geometry was not ideal in combination with the highly organic and pressure designed ETFE membrane and their mutual connection was required to eliminate any sharp corners to avoid excessive pressures in these points. Thus, a more organic core shape was designed, of similar dimensions, to allow for a very clean and continuous connection where the ETFE acts as a direct continuation of the core.

Structure

Firstly, due to the very simple cylindrical shape and relatively small spans, skeletal system possessed many advantages as it would largely lower the weight of the entire structure and give the possibility to eliminate any internal structure. This system would provide the core with broad flexibility by using only non-loadbearing partitions. The ideal setup for this system seemed to be a series of eight columns assembled in the circular cross section of the core within 45° of each other. This particular geometry offers axial symmetry which is crucial for the later described connection of the ETFE to the core. Furthermore, it provides the ideal length for a staircase that will be supported by the horizontal beams.

The system for these horizontal beams required a different system from the usually used conventional skeletal systems arranged in an orthogonal system, where the beams connect at the column and, therefore, don't have to cross. For our radial composition of eight columns, eight beam sections would need to converge in a single point in the middle which would put large stress on their common connection. To deal with this challenge we are using a single circular element that allows for individual connections for each beam and redistributes the bending moment from each beam into two parts.

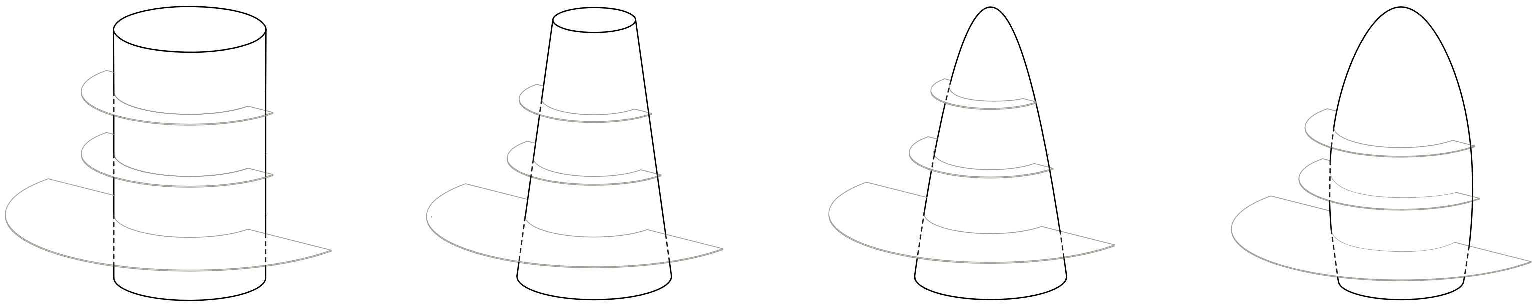


Illustration 74.: Core shape studies

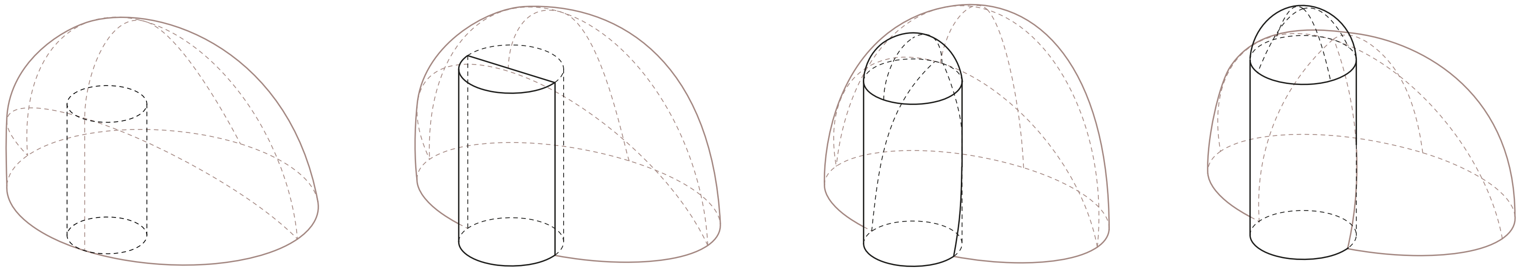


Illustration 75.: ETFE connection to the core

Construction

The above described change of disposition of the core in relation to the ETFE resulted in the need of the core to partially act as a pressure vessel too, as one half of it would be exposed to the Martian environment. In addition, as there are many unknowns and potential risks, we have decided to use the entire core as an independent closable pressure vessel as a safety solution to any possible failures of the ETFE and to provide the possibility for its maintenance. Such an endeavor put a lot of focus on the construction of the core and all its details.

Firstly, one of the construction implications is the need to incorporate a single continuous layer within the walls that will act as an independent pressure vessel. The first option we have investigated is the Cloud Gate (Illustration 76) that is constructed of welded sheets of steel that is later sanded and polished in a few phases that result in a single continuous piece of a large-scale, airtight construction. However, this type of structure results in enormous weight due to the use of heavy steel.

However, as mentioned before, payloads are a large parameter for any space engineering and we, therefore, required a vastly different solution. Thus why, we have turned to the knowledge, experience and skills of shipbuilders. Similarly to our requirements, they, too, need a very light structure with air/water-tight cladding for which they use a system of aluminum columns with additional bracing and stiffeners, covered with welded aluminum sheets, largely reducing the weight of the entire structure. The ISS uses a similar system, only with inverted construction as it requires layers of space-debris protection due to its location in Low Earth Orbit. Such a system of a thin layer and internal bracing and structure results in a considerably thinner and lighter construction where the ISS shell is only 2.5 mm aluminum compared to 11mm of steel of the Cloud Gate.

In addition, the choice of aluminum as the main structural and vessel material brings many additional advantages over the alternatives. Firstly, as mentioned before, it has extremely high strength to weight ratio. It is also easily fabricated and assembled. Unlike many other materials, it performs better in cryotemperatures, unlike steel that becomes brittle. It has very low requirements for maintenance, is not prone to corrosion and is airtight when closed. Above all, it is a material with one of the highest reflectivity, not absorbing sun radiation heat, unlike steel that absorbs large percentage of radiation and creates extremes indoor temperatures when exposed to sunlight.

Insulation

Due to the theory of heat transfer in vacuum described in chapter Indoor Comfort, we aimed for usage of MLI insulation as it seemed like the ideal solution for our project, closed described in Indoor comfort. However, after the decision to use the core as an independent pressure vessel and due to the possible need to thermally divide the habitat from the core during nights, as described in ECLSS, this system no longer works, as the MLI facing the habitat would not be in vacuum which would result in high convection losses. It is therefore clear, that a different system must be used to protect the inside of the pressure vessel. Widely used materials on Earth are not feasible as they all quickly deteriorate with cryotemperatures.

The ideal solution we have found is a lately growing material in its utilization, silica aerogel. It is the lightest material with extremely small airgaps which results in extreme insulation performance and large weight reduction compared to the metal MLI. In addition, it can be applied with various spraying techniques that are ideal for any complexity of the geometry. Lastly, unlike many other material, it is not affected by cryotemperatures.

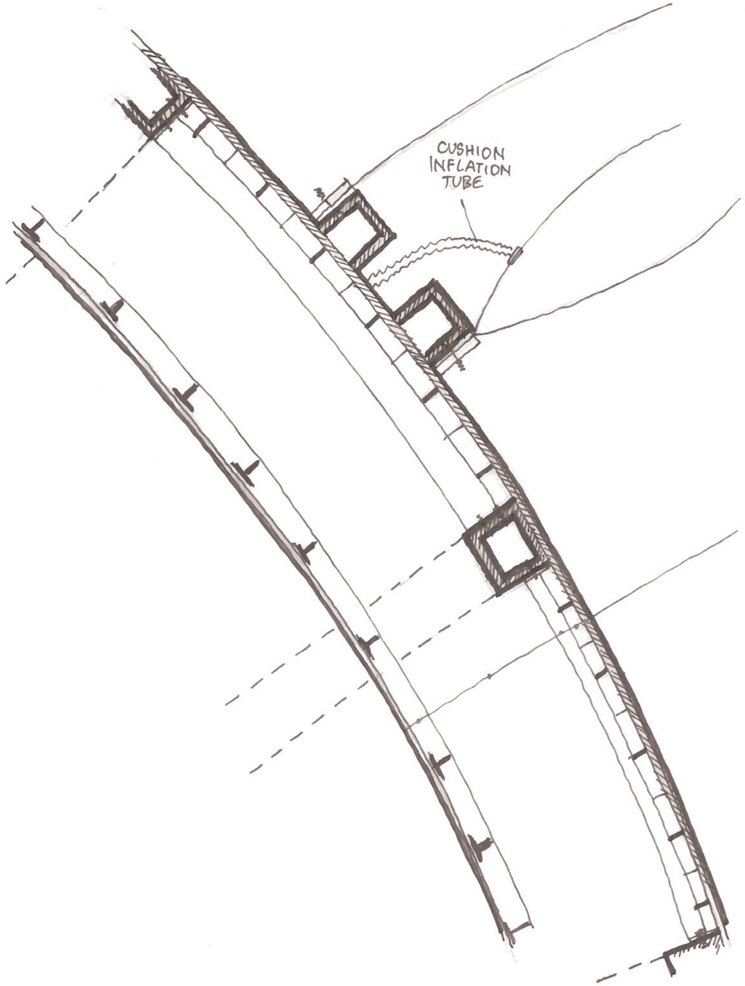


Illustration 76.: Detail / ETFE connection to the core

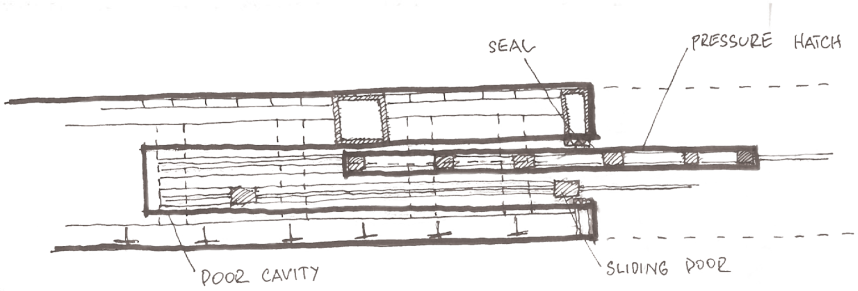


Illustration 77.: Detail / Sliding door system

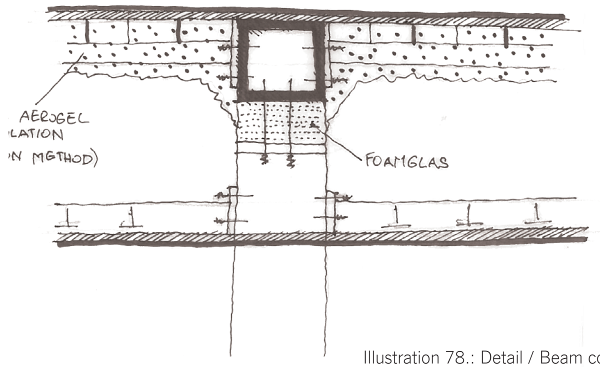


Illustration 78.: Detail / Beam connection

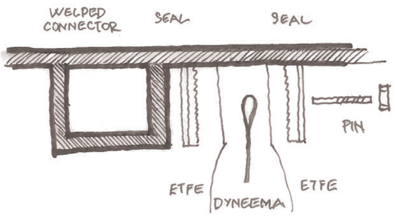


Illustration 79.: Detail / ETFE fixation

TERRACE

Initial investigations

In order to create the floor on the first level outside of the core, we investigated possible options. First, 3D printing of the structure out of in-situ materials. Although this alternative offers freedom in creating any shape, the terrace would need to be printed inside the habitat, under ETFE membranes. The size of 3D printing machine and its spatial requirements and possible impact on membranes are the main disadvantages. The second option is to let the occupants build the terrace by themselves. Relatively simple solution requires time to build it after the crew arrives and thus, taking part from their mission. The third solution would be to bring the structure from Earth. Such a structure would need to unfold during the habitat stage. Rather complex solution of structure would not require any additional time or robots to be built on Mars. Therefore, our further investigations focused on foldable structures.

Origami

The initial investigation was origami structures folded from paper. Different folding systems gave us an idea of what we could use in the habitat, which origami would also work with material thickness, how it would be deployed and where it would be stored. The pictures (Illustration 80) show explored origami structures.

Different structures

After primary investigation, we focused on the terrace in relation to the core. Its shape, structural system, way of deployment etc. The structural systems for terrace we tested were diverse, from pneumatic beams, arches, columns, flexible V columns, tension cable system and folded plates (Illustration 81). Furthermore, the shape and structure of balconies were adjusted to the same structural system of terrace.

Details

For easy folding system and relatively compact shape with possibility to fit in the core openings, we chose the structure made of folded plates. We focused on its folding – created several models (Illustration 82) to better understand the joints between individual plates. The model showed issues with the hinge joints between the plates, as another two were folded in between them. First, we tried to solve it using the click-in systems and additional ropes to create a rotation point when unfolding, assuring that plates will reach their position. These details were rather complicated and thus, we changed then to simple hinge joints with extended triangular parts. The unstable upper two plates with hinge in the middle will be fixed by adding triangle plate or frame. Moreover, the structure after unfolding should be fixed to the core.

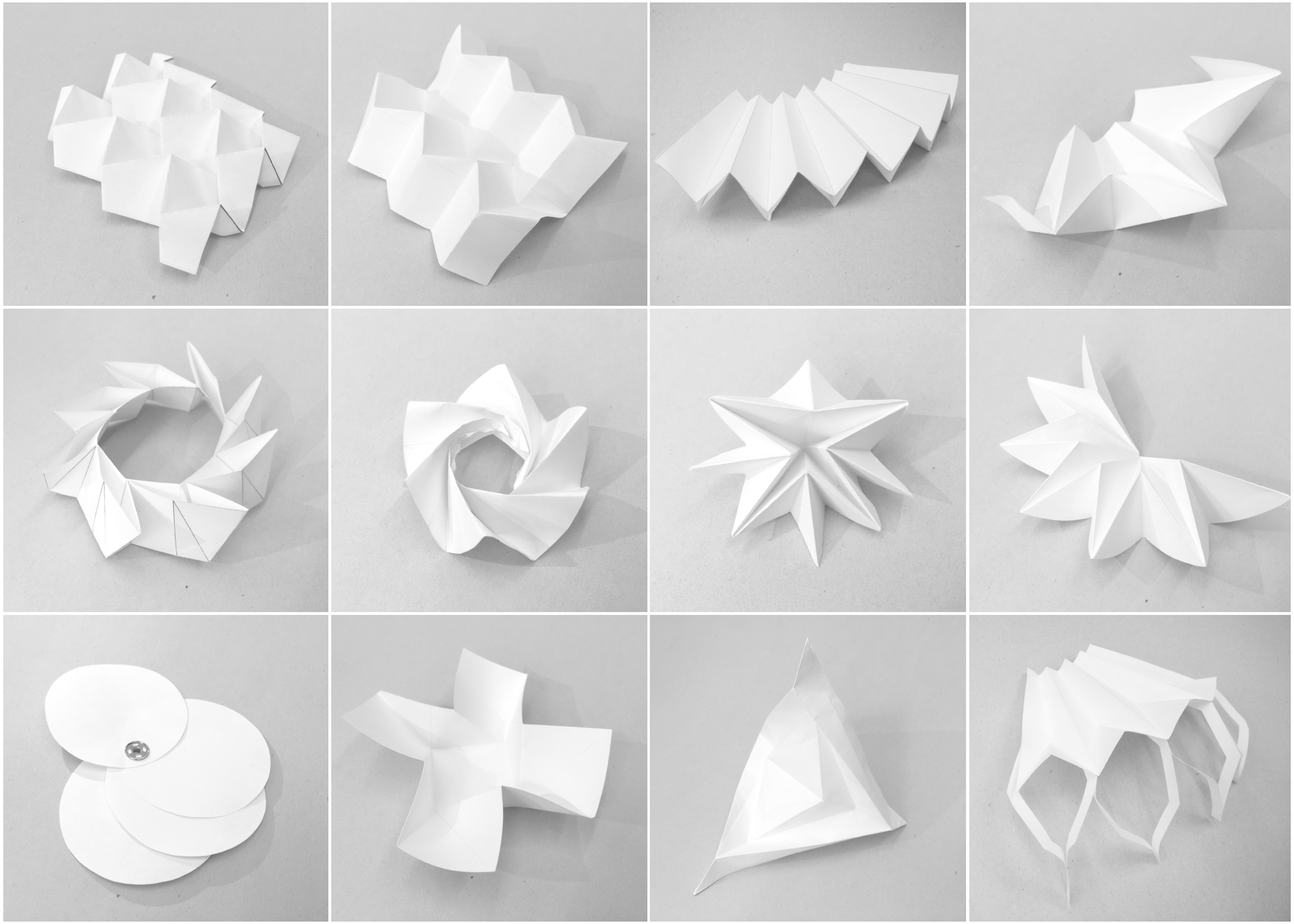


Illustration 80.: Origami

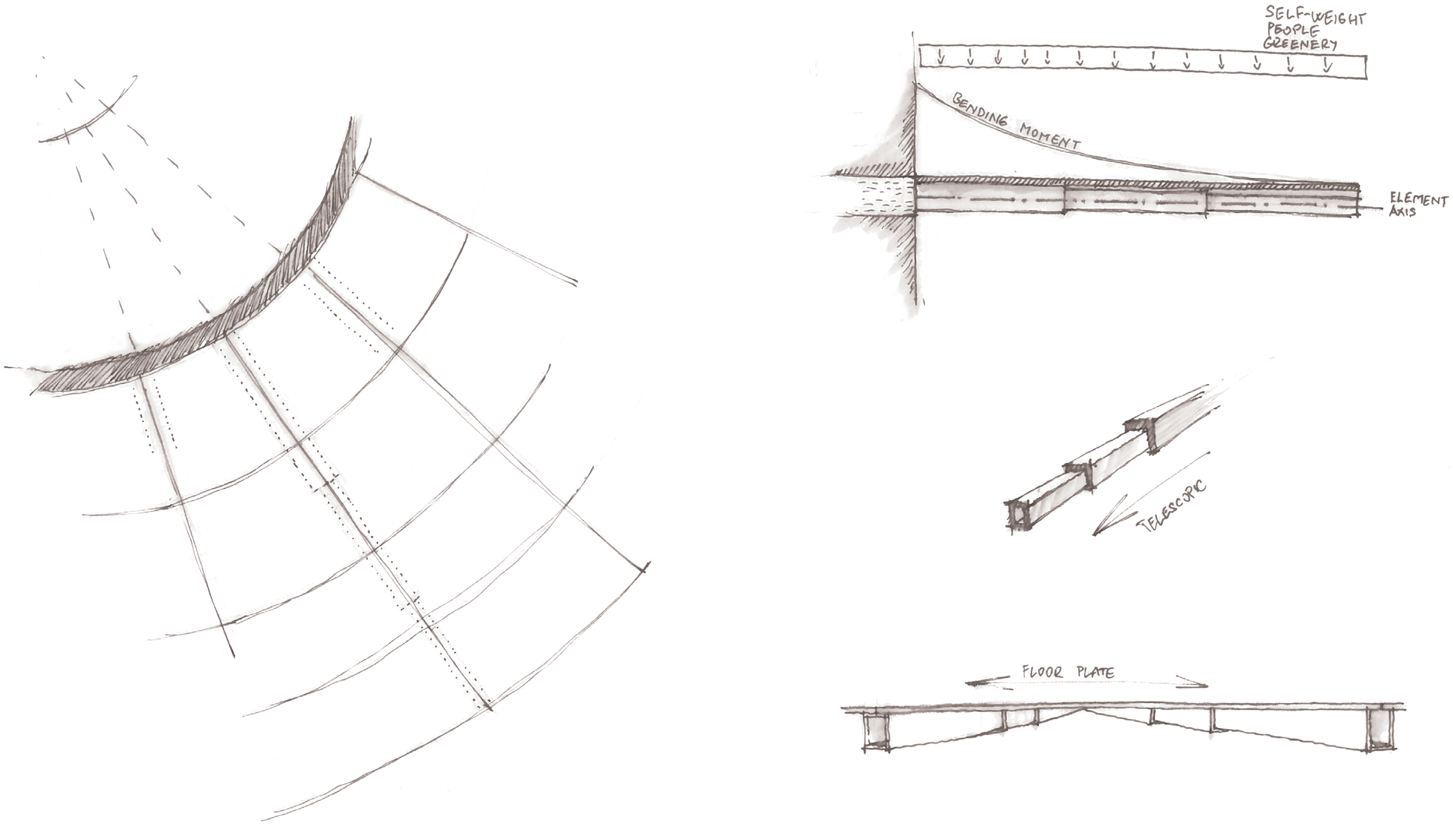


Illustration 81.: Deployable terrace studies

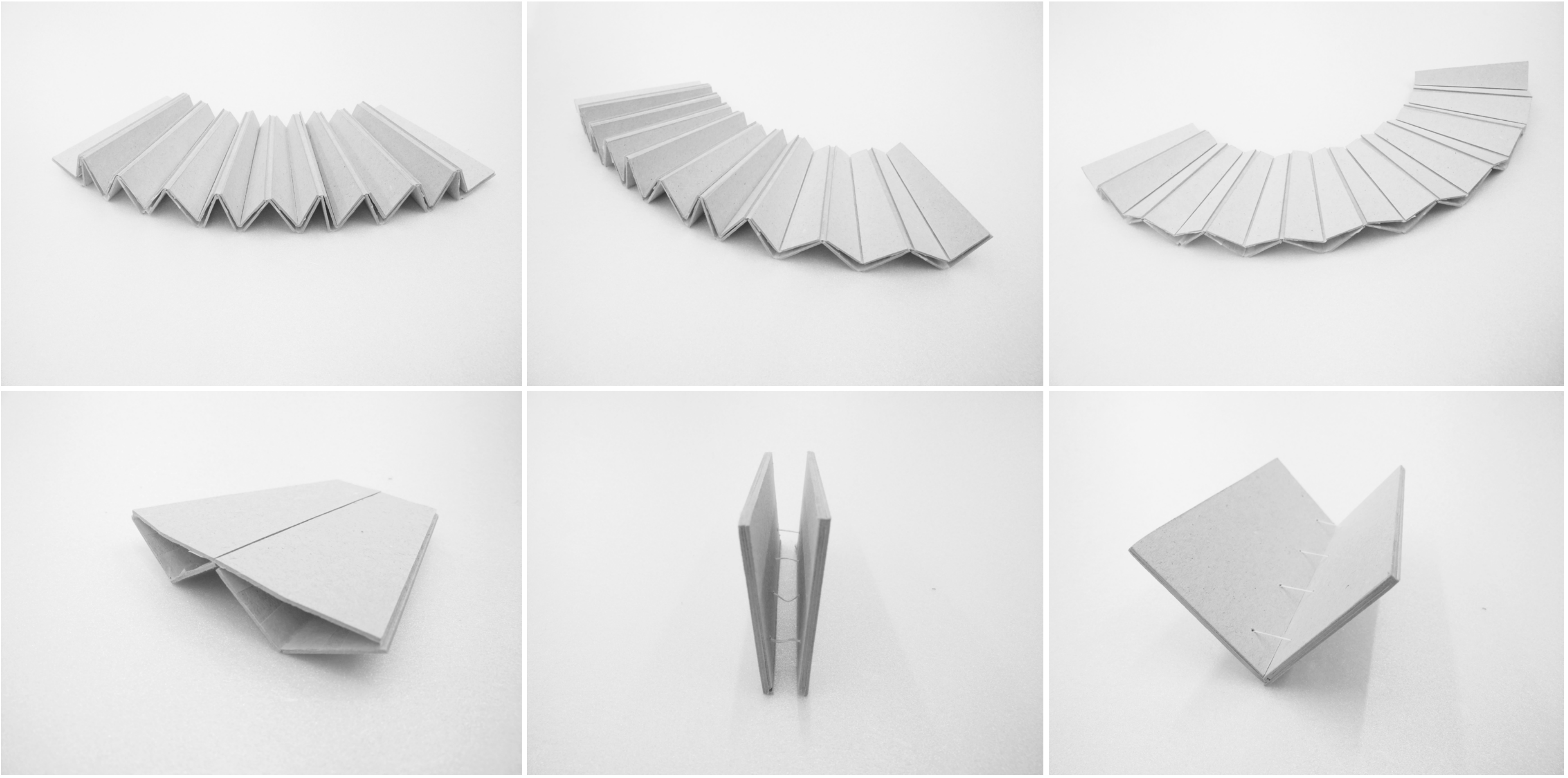


Illustration 82.: Deployable terrace studies

STRUCTURE

Gay-Lussac's Law

We started the investigation of possible influence of Gay-Lussac's law on the structure. To ensure that its impact would not endanger the structure, we made a simple calculation based on equation:

deal gas V = const. P/T = const.

Example: Fluctuation of interior pressure - temperature 20°C ± 2°C

T1 = 20°C = 293,15K
T2 = 22°C = 295,15K
T3 = 18°C = 291,15K
P1 = 101kPa

$V_1 = V_2$
$P_1/T_1 = P_2/T_2$
$(101.10\hat{}3) / 293,15 = P_2 / 295,15$
P2 = 101,69kPa

$(101.10\hat{}3) / 293,15 = P_3 / 291,15$
P3 = 100,39kPa
$\Delta P_{2,3} = P_2 - P_3 = 1,3kPa$

Fluctuation of exterior temperature, pressure (Curiosity rover, 2017)
$P_e = 0,8 \pm 0,15kPa$
$T_e = -45 \pm 45°C$

The calculations showed that fluctuations of pressure in interior are comparable to outside atmospheric pressure on Mars. Moreover, both exterior pressure and interior pressure fluctuations are fractions from the required interior pressure. Therefore, for further calculations and investigations, we assumed constant pressure difference from ambient of 100kPa.

Additional Weight

In order to chose the most apropriate structural system, we examined also the possibility of using heavy material on the top of habitat (see Structure analysis). The calculation shows required thickness of material for $1m^2$.
Inside pressure f_i = 101kPa = $101N/m^2$
Regolith density ρ = $1,52g/cm^3$
Martian gravity g = $3,73m/s^2$

$f_e = f_i$
$m. g = f_i$
$\rho. V. g = f_i$
$\rho. 1. 1. d. g = f_i$
$d=f_i / (\rho. g) = 101\ 000/(1520.\ 3,73) = 17,8m$

Due to need of massively thick cover, this structural method was proven to be inappropriate.

Other Structural Systems

Other structural system like deployable dome or tensegrity structure would require complex model, or advanced robotic mechanisms to assemble on Mars. On the other hand, pneumatic structures offers the most advantages in comparison to other structural systems, for instance their leightweight, possibility of simle deployment and relatively transparent material. Therefore, we decided to use and further investigate pneumatic structures.

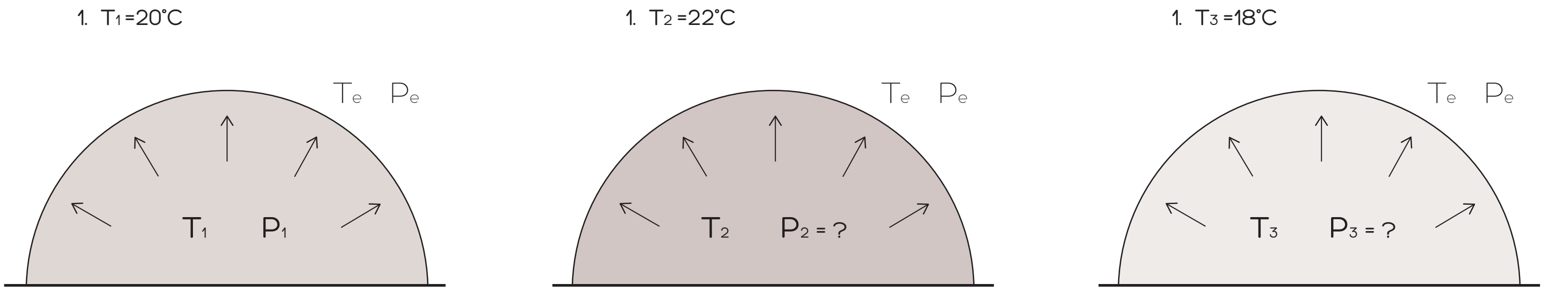


Illustration 83.: Gay Lussac`s law

ETFE

Material

Air inflated structures are mostly made of plastic materials, from which the most used is ETFE membrane, especially for its properties. Long lasting material with strong resistance to chemicals and extreme temperatures meet the requirements for harsh Martian environment. Moreover, dust or other particles do not stick to its surface. Its light transparency is higher than glass, 94-97% and it also transmit ultraviolet part of electromagnetic spectrum, which would be necessary and beneficial for plants in the garden. The high transparency would assure adequate daylight factor inside the habitat. In addition, thin ETFE membrane allows easy folding system, for transportation to Mars. The membrane would be bent around the core.

Geometry

As mentioned in the Pressure vessel analysis, the most efficient geometry is a sphere. To ensure the possibility of building pressure vessel on Mars from ETFE, we made an empirical calculation for spherical shape.

$M = 3/2 \,.\, \Delta P.\, V.\, \rho/\sigma$
P – difference between pressure in. and out.
V – volume of pressure vessel
ρ – density of the pressure vessel material
σ– maximum tensile strength of pressure vessel material

Example: Sphere with radius 5m made of ETFE membrane
$P = 100kPa$
$V = 524m^3$
$\rho = 1700kg/m^3$
$\sigma = 45MPa$

$M = 3/2.\ 100.\ 524.\ 1700/45000 = 2969kg$

$S_{ETFE} = 314m^2$
$V_{ETFE} = S/\rho = 1{,}7m^3$
$d_{ETFE} = V/S = 0{,}005m = 5mm$

As the thickness is within several millimeters, the calculation demonstrates the possibility to use similar construction method.

Zoning

By creating two or more zones placed in each other, the pressure difference would be distributed between couple pressure vessels. The summary of the partial differences between them is equal to pressure difference from ambient, the gauge pressure (see PICTURE). The decreased pressure differences reduce stress in the material. Smaller tension allows the usage of thinner structures or structures made of materials with lower stress tolerance. Furthermore, zoning benefits the weight of structure as shown in the example.

$P = P_1 + P_2 + P_3$ $\quad P_1 > P_2 > P_3 > P_e$

Example: two pressure vessels, inner sphere r = 4m and outer sphere r = 5m (see Illustration 16)

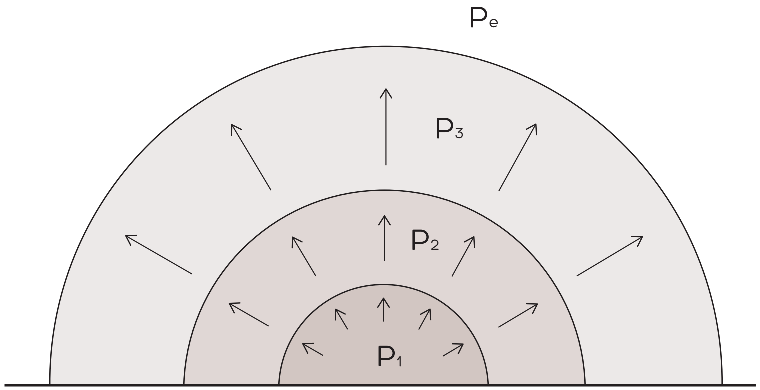
$P = P_1 + P_2$
$P_1 = 50kPa$
$V_1 = 268m^3$

$P_2 = 50kPa$
$V_2 = 524m^3$
$\rho = 1700kg/m^3$
$\sigma = 45MPa$

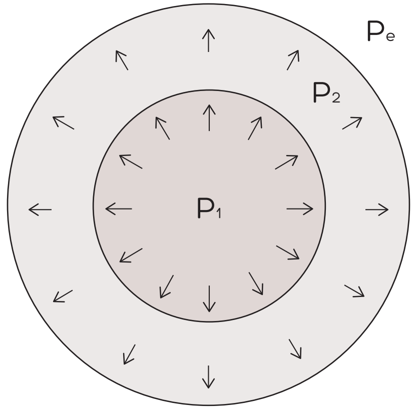
$M_1 = 3/2.\ 50.\ 268.\ 1700/45000 = 759kg$
$S_{1-ETFE} = 201m^2$
$V_{1-ETFE} = 0{,}45m^3$
$d_{1-ETFE} = V/S = 0{,}002m = 2mm$

$M_2 = 3/2.\ 50.\ 524.\ 1700/45000 = 1485kg$
$S_{2-ETFE} = 314m^2$
$V_{2-ETFE} = 0{,}87m^3$
$d_{2-ETFE} = V/S = 0{,}003m = 3mm$

$M = M_1 + M_2 = 2244kg$



Zoning



Spherical pressure vessel

Illustration 84.: Pressure zoning

Cushions, reinforcement

Previous calculations showed the possibility to use ETFE, but its required thickness is not commonly fabricated. Thus, the pneumatic structure needs a cable support. We examined several possibilities of placement the reinforcement – in between the membranes, welded in the membrane or placed on the top. For easy deployment of the structure, we decided to place the cables in welded joints.

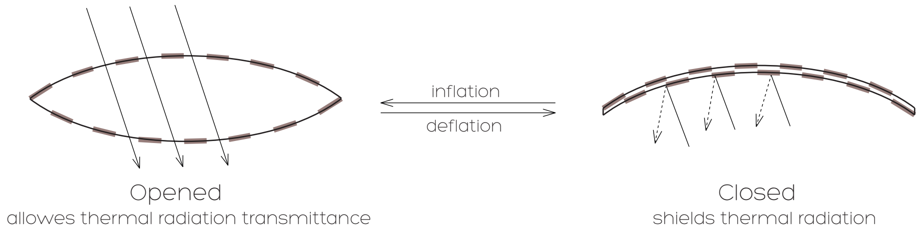
In the beginning, we intended to apply steel cables. Our investigations proved this material to be inapropriate due to its relatively high weight and difficulties with folding system. Suitable exchange for steel was dyneema, often used for cranes and ships for its great strength, which is 15 times higher than of steel. Dyneema is lightweight material, resistant to UV light, chemicals and high temperature changes.

Cable grid on the top of ETFE can create diverse patterns using different geometries (Illustration 89). Furthermore, it allowed us to create cushions out of ETFE membrane. One layer of ETFE membrane would not offer exceptional thermal insulating properties, therefore it was necessary to create multiple layers. Especially, radiation (causing the biggest heat loss on Mars) could be shielded by applying thin low-emissivity coating. It reduces the transmission of thermal radiation and allows to control temperature inside the habitat. More advanced system is dynamic cushions (Illustration 85) with low-emissivity coating printed with inverse patterns, so when the cushion is inflated, it would transmit thermal radiation and when closed, it would shield them. In this way, it would be possible to control indoor environment temperature – to heat and also cool down by inflating and deflating the cushions. Besides all of the advantages of cushions usage, there is a disadvantage. Its double curved surface refracts light and create a slightly distored image.

Overal shape

After our investigations and preliminary empirical calculations, we decided to use two membranes for the habitat. Initial shape was circular, with detached core in the middle and later next to the inner membrane. Due to visual disconnection and „bubble“ affect, we shifted the core and connected ETFE membranes to the middle part of the core. The shape of membranes changed as well, inner one was prolonged to the sides, with outer membrane following. Introducing observatory in the design, we wanted the membrane to be visible from inside-out and thus, we introduced the back curve to the outer membrane. The shape from the top view changed from eliptical to „eight“ shape. Firstly, more spherical-like volume was changed to more dynamic, supporting the organic conic core shape.

Dynamic system reactive to the environment



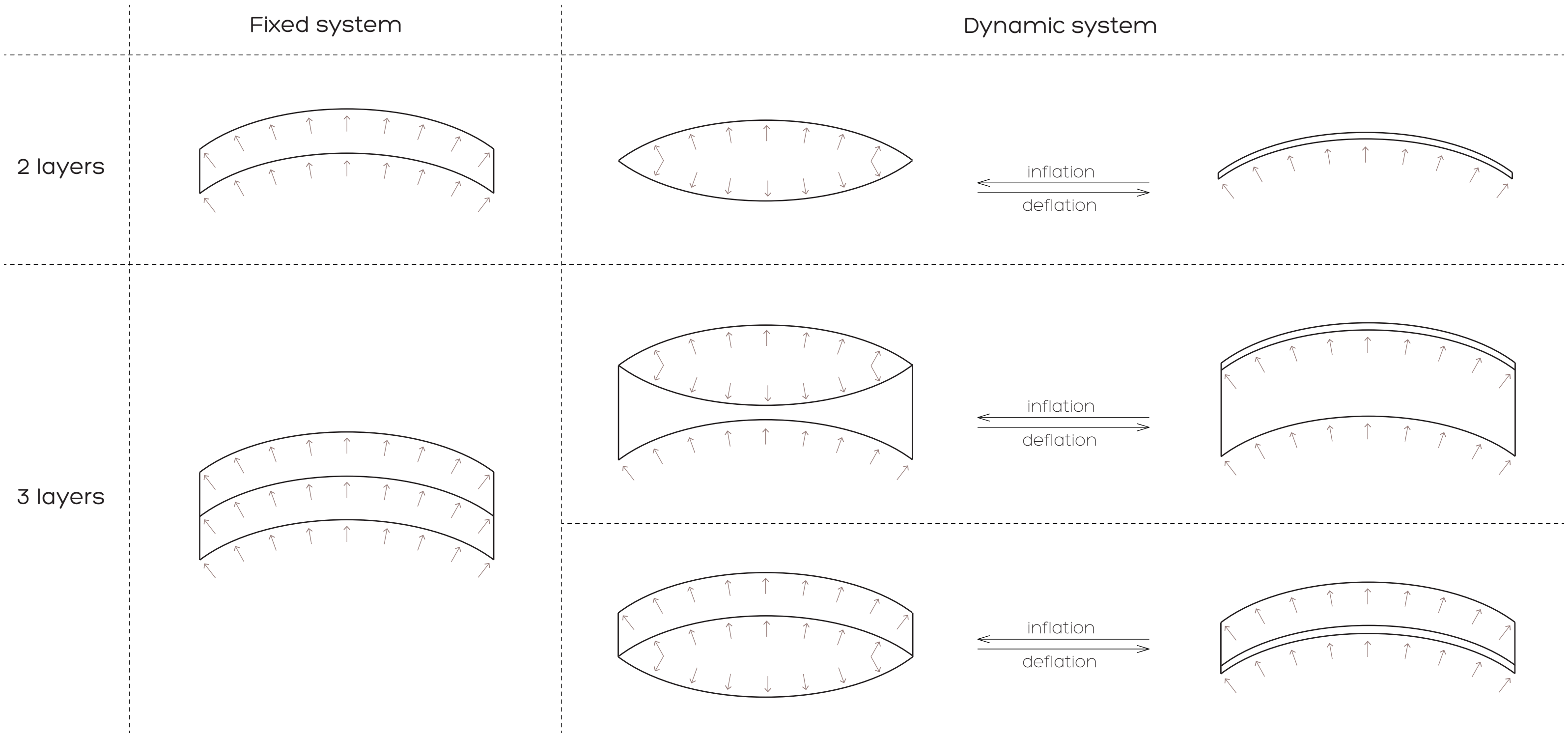


Illustration 85.: Dynamic cushion systems

ETFE calculation

Material

For all calculations, we used two materials – ETFE and Dyneema. ETFE breaking point is 52MPa (tension), but for structural calculation a limit of 35MPa is taken, due to high elasticity of the material. Dyneema`s tensile strength is 3GPa.

Robot

We intended to make first calculations in Robot. Simple half sphere with applied pattern created as panels in Grasshopper did not export, even with few panels. Therefore, we changed concept of calculation to single bars with node loads (only for a calculation of Dyneema ropes). Due to difficulties with recalculating the loads according to area, the calculations were inaccurate and, moreover, the structure was instable. For equal distribution of loads, instead of node loads, we applied cladding. We examined several patterns for cushions on half sphere of 22m diameter, 50kN/m^2 load and approximately 200-215 bars for each model. All of the models had hinged supports and fixed connection between bars. Diamond patterns were stable only if calculated in compression. Due to its big displacement, bending moment as well as compression, these models were not suitable (Table 1). When calculated in tension, they were instable. To avoid instability, we investigated triangular patterns (creating rigid parts made out of three bars), which were stable with "tension only" elements. However, one of the model had a great displacement and another had an error (Table 2).

Kangaroo

Not functioning models in Robot led us to explore the shape of displacement in other software. We used the same models and applied inner pressure to them, inflated them. All structures proved working, showing diverse shapes of displacement for different patterns (Table 1, Table 2). The deformations seemed reasonable to its grid, but we could not calculate any of the structures.

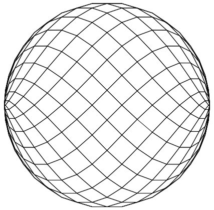
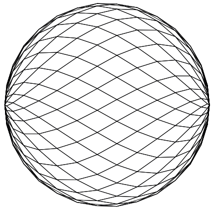
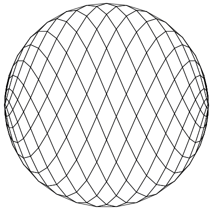
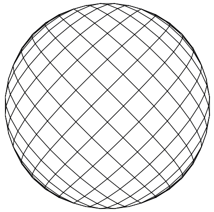
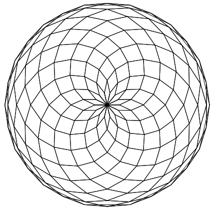
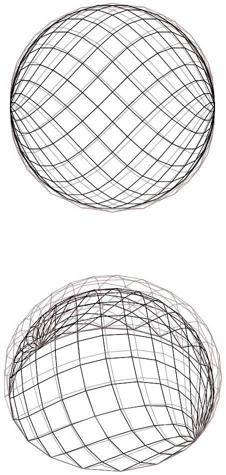
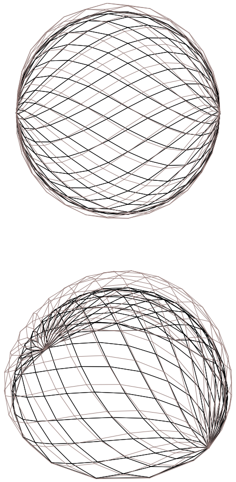
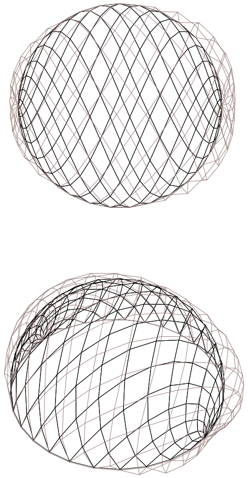
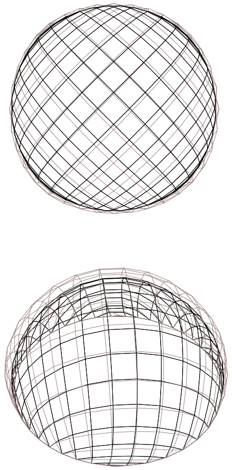
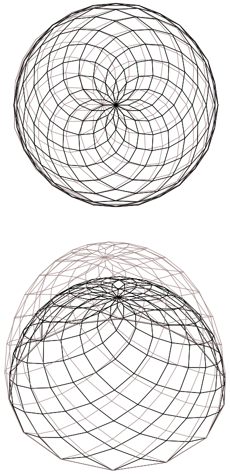
DIAMOND	equal	horizontal	vertical	equal - symetrical	equal - top
shape					
Robot	instability error	instability error	instability error	instability error	instability error
Kangaroo					
Karamba all. def. 2m	M = 6,5kNm N = 1032 - 0kN deformation 15m - not working	enormous deformation - not working	enormous deformation - not working	M = 12,8kNm N = 1007 - 73kN deformation 53m - not working	enormous deformation - not working

Table 1.: Diamond pattern calculations

Karamba

For further understanding of pneumatic structure, we worked with Karamba. Starting with simple calculation of half sphere applying different patterns, which proved most of the structures working. Afterwards we used large displacement as form-finding element. First, we allowed specific maximum displacement and then we calculated deformed shape with reapplied loads. Dyneema structure with diamond grid resulted to enormous displacements and thus, this grid is not suitable for our model. On the other hand, triangle patterns appeared working (Table 1). We tried different patterns with combination of different maximum allowed displacement (Table 3). The results with allowed displacement were better than spherical shape, due to the patterns. To allow the structure to obtain spherical like shape, we changed the height of sphere and gradually changed allowed displacement. The Table 4 different height shows, that the closer to sphere shape it can deform, the better the results are. To create the shape of outer membrane, we investigated two joined spheres and also lowered them to create possibility to obtain close-to-sphere shape (the results are showed in Table 5). The structure was working, with few compression elements in concave part between the spheres. However, there are always ropes in two other directions, assuring the stability of structure (Illustration 90).

To calculate our final structure, many triangular patterns were examined. The most appealing by its visual properties as well as results was triangular-hexagon like pattern, consisting of three directions of ropes. The distribution of pattern is equal, in order to guarantee more even distribution of stress in the ropes. The shape was created based on several curves, which shapes we changed several times to obtain more effective structure.
To eliminate the compression elements, we tried to pre-tension ropes crossing them. The result showed that the compression elements just moved away from the pre-tensioned ropes, keeping the same number of elements in compression (Illustration 91).

To calculate ETFE cushions, form-finding in Karamba was used, with the same principal as for Dyneema structure. We took the biggest cushion from rope-grid and created the model out of mesh with hinged joins – rotation only in perpendicular direction to cushion edges.

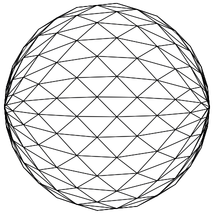
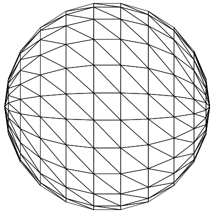
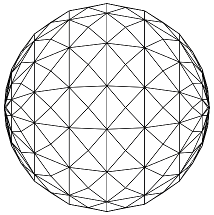
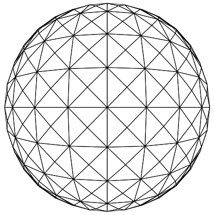
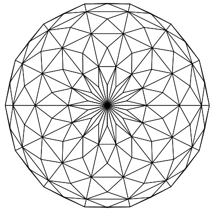
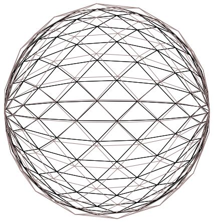
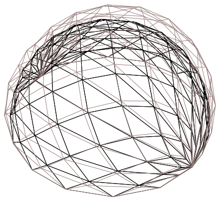
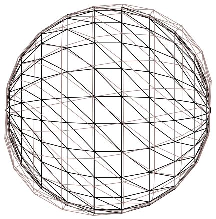
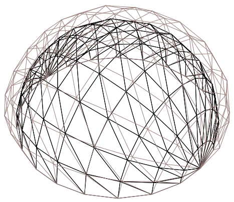
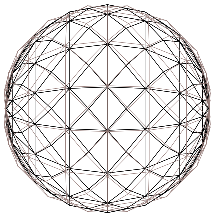
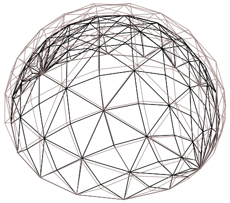
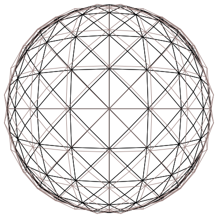
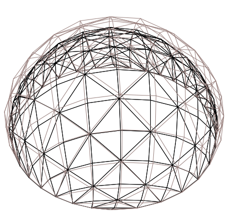
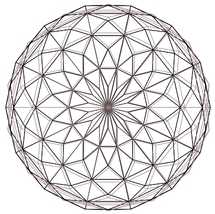
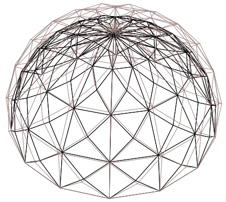
TRIANGLE	hexagonal	diagonal	equal	equal - symetrical	equal - top
shape					
Robot	errors	M = 0kNm (tension only) N = 1575 - 0kN deformation 1,3m	M = 0kNm (tension only) N = 916 - 21kN deformation 0,65m	M = 0kNm (tension only) N = 1227 - 0kN deformation 0,76m	M = 0kNm (tension only) N = 10446 - 10440kN deformation > 100m
Kangaroo	 	 	 	 	 
Karamba all. def. 1m	6 = 3409MPa M = 0,12kNm N = 1070 - 0kN deformation 0,367m	6 = 4697MPa M = 0,61kNm N = 1474 - 0kN deformation 0,347m	6 = 3023MPa M = 0,07kNm N = 949 - 0kN deformation 0,299m	6 = 3782MPa M = 0,05kNm N = 1187 - 296kN deformation 0,287m	6 = 2540MPa M = 0,16kNm N = 797 - 36kN deformation 0,291m

Table 2.: Triangle pattern calculations

EPILOGUE

conclusion / reflection

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This chapter is a summary and a closing remark upon the habitat design and the design processes behind it. The first chapter, Conclusion, synthesizes the project as a whole, lists all the addressed challenges set in the chapter Synopsis and demonstrates the implications of our design. The second chapter, Reflection, lists elements of the design that will be addressed in further stages and contemplates on the architectural challenges and processes for extraterrestrial typologies.

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CONCLUSION

Approach

We have started the project by identifying and gathering challenges in developing a Martian habitat that will host a six-member crew for the period of a year and a half. From this broad range of challenges, across many different fields, we have chosen two most important areas that require the inclusion of architects in their design – physiological and psychological well-being of the crew that we call the Anthropological Approach and the design of a pressurized structure, that attempts to lower the transportation payload while providing a sufficient spatiality, considerations we call the Technical Approach.

In response to these selected challenges, we have employed detailed analyses of the Martian environment, its dangers to the human body and psychological challenges of the secluded and isolated mission. Furthermore, we have investigated the ideal of a home, whether it can be an architectural response to the psychological challenges and what are the physical translations of the ideal of home.

For the technical approach, we have analyzed the structural implications of pressurized structures and its potential structural solutions, possible methods of construction in an extraterrestrial environment that can assure inhabitable conditions and lowering the need for a resource supply from Earth. Lastly, in response to the acquired knowledge, we have assembled a list of design parameters that were used as a starting point for our further design.

Design

Using the previously acquired knowledge and assembled parameters, the final proposal consists of a fully prefabricated central structure that will be transported onto Mars in the form of a lander spacecraft, containing additional folding-plate balconies and an elastic ETFE envelope, that will both deploy upon landing and thus expand the inhabitable spaces of the habitat and form a spatial and visually open Martian base. In addition, our proposal seeks to provide the crew with the sensations of safety and belonging, and grant the crew the possibility to extend and enhance their living environment as the spatial demands of the crew evolve over time, through the incorporation of bamboo crop within the design of the habitat.

Implication

At the beginning of the project, we embarked on a journey, full of enthusiasm, of creating a NEW HOME for the first manned mission onto Mars that might, one day, become the home of all of us. However, during our improving understanding of all the challenges, we have realized there are very strong evolutionary ties to Earth that must be reflected in the design of the habitat to allow for the experiences mankind has learnt to rely upon. The truth is, Earth is our real home and we should, first and foremost, try to preserve it.

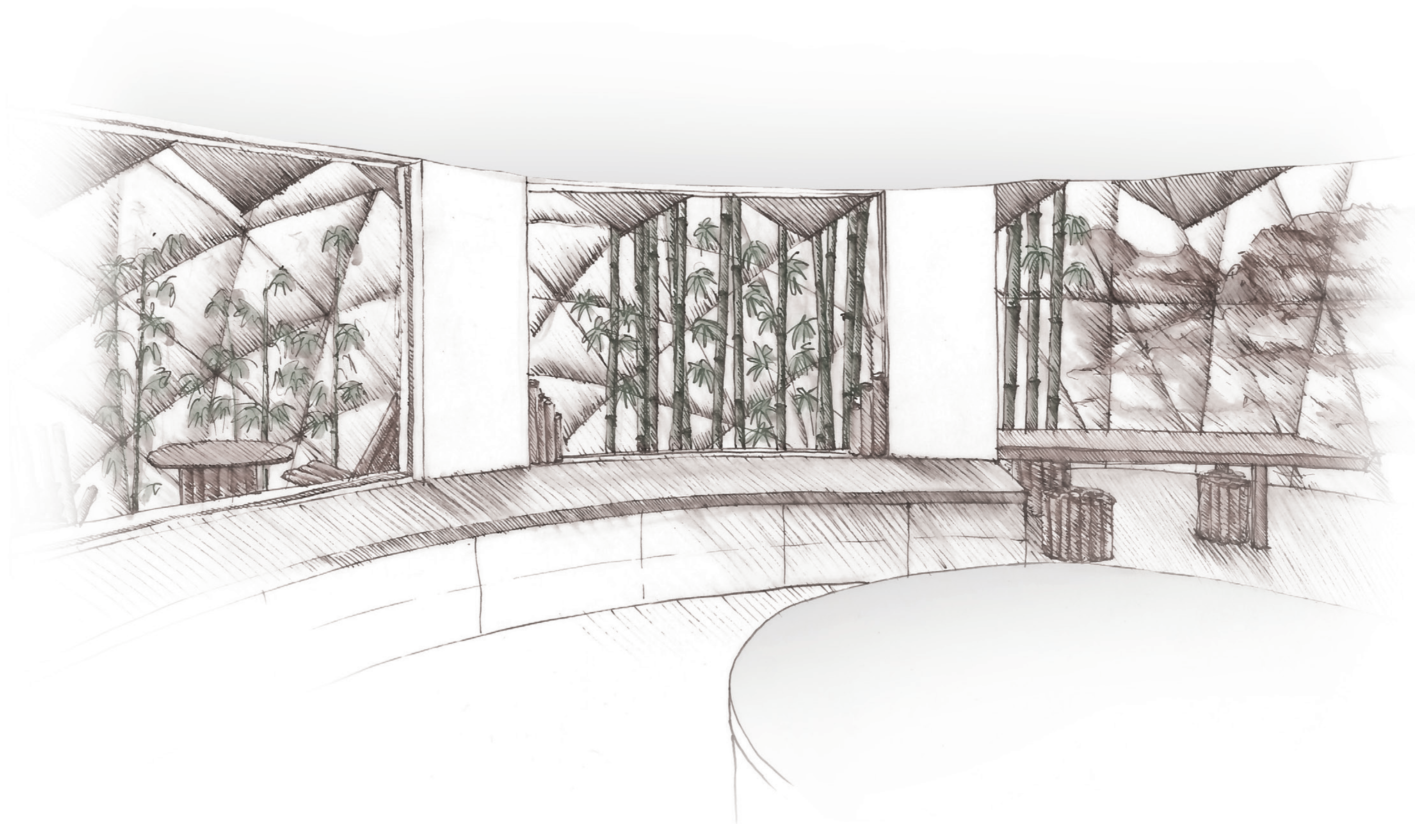


Illustration 86.: Perspective / Kitchen view

REFLECTION

Process

We believe that each design project requires different approach based on its typology, context and other circumstances. As much as the typology, context and construction methods of a Martian habitat are different from any other traditional aspects of Earth's architecture, our approach to the project was different from our previous design endeavors as well. Due to our lack of sufficient knowledge of space engineering at the beginning of the project, our design process was very research-driven where every design challenge first required us to study the theory, critically asses it for the Martian environment and conclude the design implications rather than producing numerous iterations.

By following the TMIDP methodology, we have successfully managed to estimate all of the anthropological and most of the technical challenges that would be later faced within the design process. This allowed us to efficiently address these challenges and find appropriate design solutions in a sound and well-balanced design spanning a large range of different fields, from phenomenology, anthropology, psychology and sociology to botany, fluid mechanics, space engineering all the way to planetary science, all managed by the synthesis and considerations of architecture.

Further development

Even with the initial goals for the project that were appropriate for the time frame and a fair time management, some further challenges appeared during the design process due to the choice of architectural concepts, choice of construction methods or software challenges. These challenges and aspects of the design fell outside of the given timeframe and will be addressed and developed in further stages of the project.

Firstly, the limited timeframe resulted in some more traditional approaches in an otherwise very futuristic project that requires all new and innovative solutions. One of the examples is the offered view of the future bamboo furnishings that are still individual pieces of furniture, unlike the rest of the project that seeks to integrate the aforementioned fields in a single piece of architecture. In addition, the structural challenges of the ETFE membrane resulted in an underdeveloped concept for its transportation and deployment. Lastly, even with the effects of time and flexibility on the idea of a home being an important parameter in the design of the habitat, no comprehensive theory and design visions of possible changes and extensions were offered.

Challenges

As described above, the design of a Martian habitat brings completely new typology, new perspectives on context and construction methods that offer very few, and in many cases no existing examples that could provide us with inspiration or set of solutions that could be used. Unlike the architecture on Earth, that offers thousands of different examples of all typologies in many different context, carried out in various methods, we were forced to employ our imagination, study the corresponding theory and estimate many unknowns to create all three aspects from the little that exists in this field. All these challenges confronted all of our architectural knowledge, both theoretically and practically.

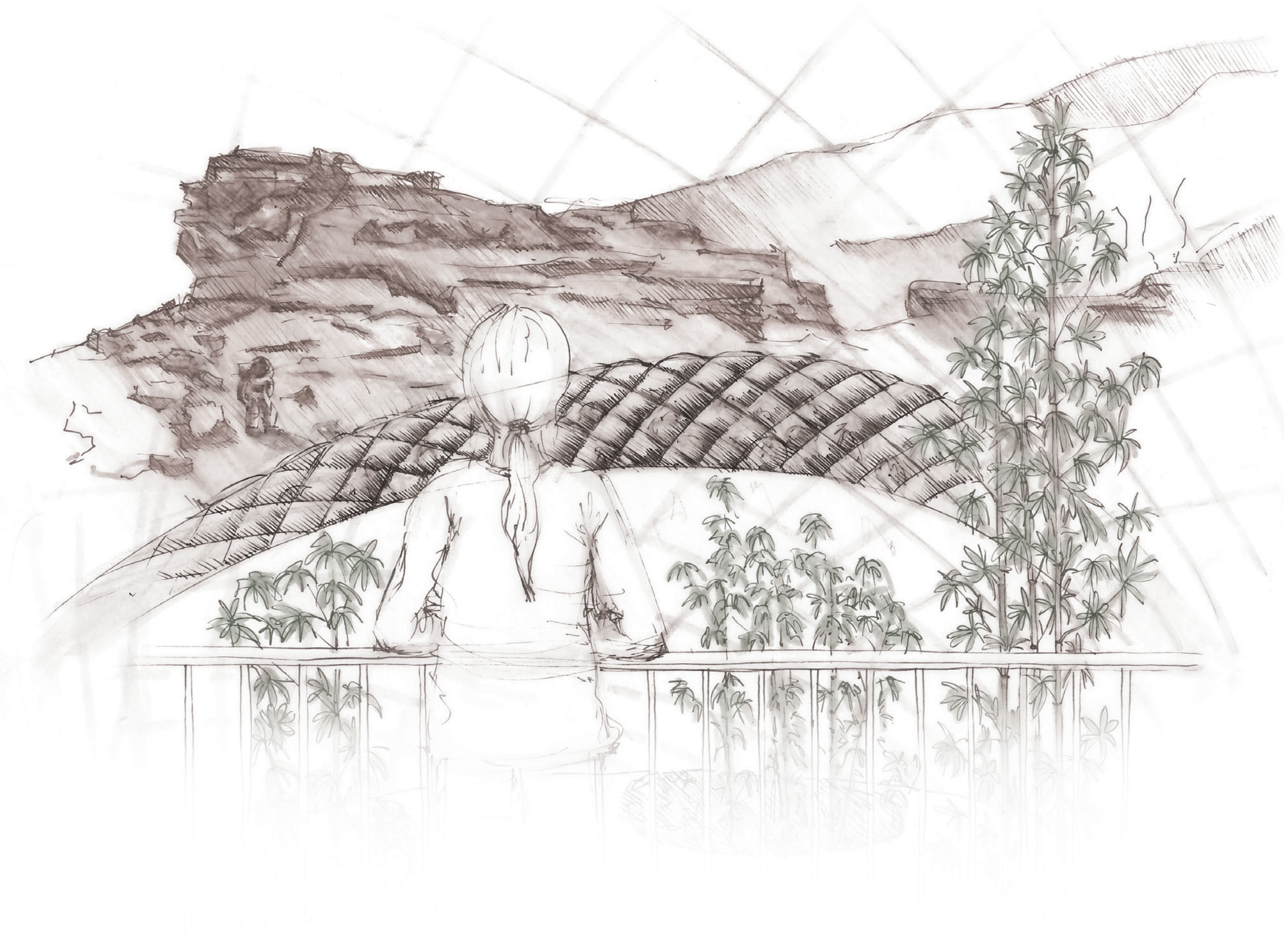


Illustration 87.: Perspective / Observatory view

APPENDIX

dictionary / illustrations / calculations
reference list / illustration list

• • •

The final section of the report gathers additional explanatory information regarding different elements of the project. The Dictionary is a comprehensive list of used terms for any reader unfamiliar with space engineering. The next chapter consists of additional tables and illustrations further explaining the structural properties and calculations of the envelope and, in the end, complete tables of references and illustrations are provided.

• • •

DICTIONARY

Areo/ – a combining form meaning “the planet Mars,” used in the formation of compound words (such as areocentric, areothermal)

Airlock – an intermediate chamber with two airtight doors or openings to permit passage between two dissimilar spaces (such as two places of unequal atmospheric pressure)

ESA – European Space Agency – an intergovernmental organization dedicated to the exploration of space. It has 22 member states and is closely associated with the European Union.

EVA – Extra-vehicular Activity – any activity done by an astronaut or cosmonaut outside a spacecraft beyond the Earth’s appreciable atmosphere

ISS – International Space Station – space station, or a habitable artificial satellite, in low Earth orbit that serves as a microgravity and space environment research laboratory in which crew members conduct experiments

Life Support Systems – an artificial or natural system that provides all or some of the items (such as oxygen, food, water, control of temperature and pressure, disposition of carbon dioxide and body wastes) necessary for maintaining life or health

Lander – a spacecraft which descends toward and comes to rest on the surface of an astronomical body

LEO – Low Earth Orbit – an orbit around Earth with an altitude between 160km and 2000km

Mars One – an organization that has proposed to land the first humans on Mars and establish a permanent human colony there by 2032

NASA – National Aeronautics and Space Administration - an independent agency of the executive branch of the United States federal government responsible for the civilian space program as well as aeronautics and aerospace research

Payload Fairing - a nose cone used to protect a spacecraft against the impact of dynamic pressure and aerodynamic heating during launch through an atmosphere

Regolith – A layer of loose, heterogeneous superficial material covering solid rock. It includes dust, soil, broken rock, and other related materials and is present on Earth, the Moon, Mars, some asteroids, and other terrestrial planets and moons

SEV – Space Exploration Vehicle –

SpaceX – Space Exploration Technologies Corporation – an American aerospace manufacturer and space transport services company

Sources: http://www.dictionary.com; https://www.merriam-webster.com; https://en.wikipedia.org

Illustration 88.: Plan -1 / Technical rooms 1:150

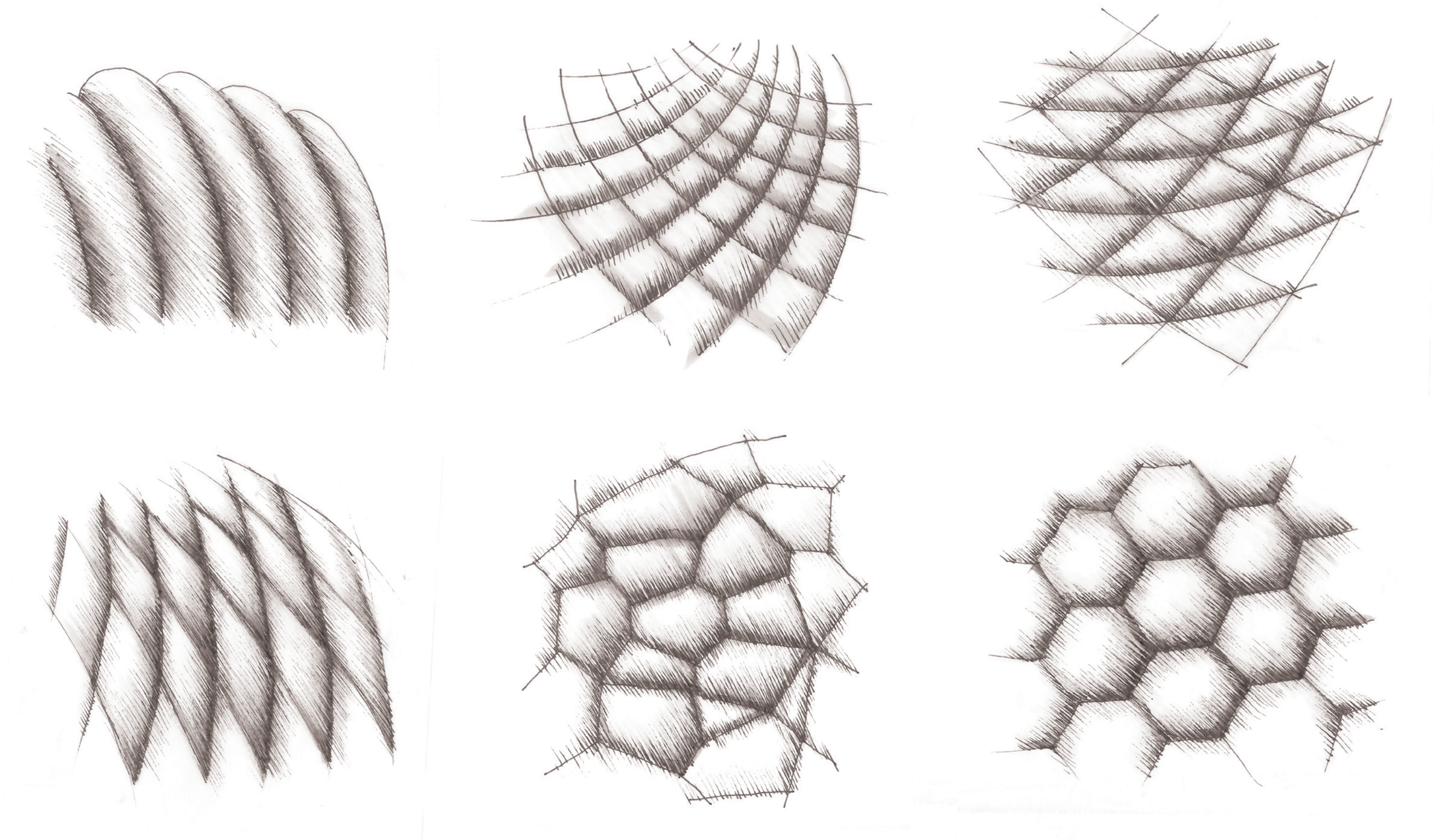
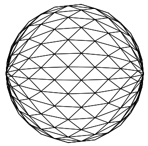
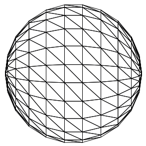
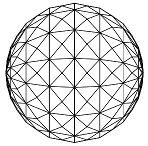
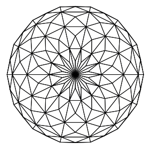
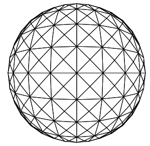


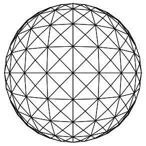
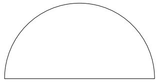
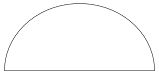
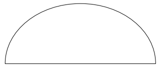
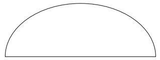
Illustration 89.: Different ETFE patterns

CALCULATIONS

Different patterns						
						
Maximum allowed displacement (m)	Dyneema diameter 2cm	Hexagonal	Diagonal	Equal	Equal - top	Equal - symetrical
0	Max axial stress (Mpa)	4206	5074	2823	3337	2485
	Normal force (kN)	1320 - 332	1593 - -435	886 - 0	1048 - 24	780 - -22
	Max bending moment (kNm)	1,13	1,14	0,2	0,39	0,22
	Displacement (m)	1,18	0,5	0,36	0,451	0,307
0,3	Max axial stress (Mpa)	3236	4900	3066	3511	2240
	Normal force (kN)	1016 - 0	1538 - -68	962 - 0	1102 - 224	703 - -27
	Max bending moment (kNm)	0,12	1,2	0,13	0,04	0,15
	Displacement (m)	0,449	0,39	0,266	0,291	0,221
0,5	Max axial stress (Mpa)	3249	4782	3060	3626	2332
	Normal force (kN)	1020 - 0	1501 - -53	961 - 0	1138 - 258	732 - -28
	Max bending moment (kNm)	0,11	0,97	0,11	0,05	0,14
	Displacement (m)	0,399	0,36	0,261	0,283	0,232
1	Max axial stress (Mpa)	3409	4697	3023	3782	2540
	Normal force (kN)	1070 - 0	1474	949 - 0	1187 - 296	797 - -36
	Max bending moment (kNm)	0,12	0,61	0,07	0,05	0,16
	Displacement (m)	0,367	0,347	0,299	0,287	0,291
2	Max axial stress (Mpa)	3566	4629	3242	3939	2935
	Normal force (kN)	1120 - 0	1453 - -53	1018 - 0	1236 - 324	921 - -61
	Max bending moment (kNm)	0,16	0,24	0,05	0,05	0,44
	Displacement (m)	0,448	0,408	0,419	0,316	0,404
3	Max axial stress (Mpa)	3708	4718	3508	4067	3331
	Normal force (kN)	1164 - 0	1481 - -84	1101 - -47	1277 - 346	1046 - -87
	Max bending moment (kNm)	0,19	0,37	0,1	0,05	0,8
	Displacement (m)	0,554	0,545	0,558	0,344	0,535

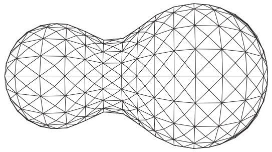
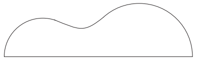
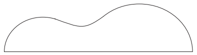
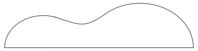
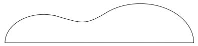
Legend — Extreme values — Optimal values

Table 3.: Calculation / Different patterns

Change of sphere height					
Maximum allowed displacement (m)	Dyneema 2cm	Height 11m	Height 10m	Height 9m	Height 8m
	Max axial stress (Mpa)	2485	2582	2861	3210
	Normal force (kN)	780 - -22	810 - -113	898 - -206	1008 - -522
	Max bending moment (kNm)	0,22	0,75	1,79	3,16
0	Displacement (m)	0,307	0,389	0,562	0,792
	Max axial stress (Mpa)	2240	2336	2513	2757
	Normal force (kN)	703 - -27	733 - -54	789 - -100	865 - -234
	Max bending moment (kNm)	0,15	0,2	0,45	1,04
0,3	Displacement (m)	0,221	0,283	0,397	0,557
	Max axial stress (Mpa)	2332	2382	2485	2662
	Normal force (kN)	732 - -28	748 - -41	780 - -69	835 - -108
	Max bending moment (kNm)	0,14	0,18	0,25	0,42
0,5	Displacement (m)	0,232	0,29	0,381	0,507
	Max axial stress (Mpa)	2540	2487	2499	2579
	Normal force (kN)	797 - -36	780 - -43	784 - -56	810 - -75
	Max bending moment (kNm)	0,16	0,17	0,21	0,29
1	Displacement (m)	0,291	0,314	0,358	0,429
	Max axial stress (Mpa)	2935	2778	2657	2585
	Normal force (kN)	921 - -61	872 - -57	834 - -54	811 - -56
	Max bending moment (kNm)	0,44	0,35	0,27	0,23
2	Displacement (m)	0,404	0,381	0,374	0,386
	Max axial stress (Mpa)	3331	3123	2934	2786
	Normal force (kN)	1046 - -87	980 - -81	921 - -70	874 - -58
	Max bending moment (kNm)	0,8	0,69	0,53	0,37
3	Displacement (m)	0,535	0,48	0,438	0,413

Legend: Close to sphere shape — Extreme values — Optimal values

Table 4.: Calculation / Change of sphere height

Joined half spheres					
Maximum allowed displacement (m)	Dyneema 2cm	Full half sphere	1m lower	2m lower	3m lower
	Max axial stress (Mpa)				
	Normal force (kN)				
	Max bending moment (kNm)				
0	Displacement (m)	not working	not working	not working	not working
	Max axial stress (Mpa)	3593	13513	3782	3866
	Normal force (kN)	1763 - -1766	6629 - -5060	1855 - -724	1896 - -626
	Max bending moment (kNm)	21,5	37	2,24	1,47
0,3	Displacement (m)	5,85	26049	0,684	0,568
	Max axial stress (Mpa)	2698	2969	3326	3845
	Normal force (kN)	1323 - -454	1456 - -984	1631 - -487	1886 - -461
	Max bending moment (kNm)	0,86	1,85	1,1	2,24
0,5	Displacement (m)	0,317	0,8	0,491	0,624
	Max axial stress (Mpa)	2937	3048	3233	3516
	Normal force (kN)	1441 - -268	1495 - -368	1586 - -552	1725 - -265
	Max bending moment (kNm)	0,58	0,46	0,36	0,73
1	Displacement (m)	0,258	0,269	0,356	0,384
	Max axial stress (Mpa)	2904	3000	3138	3251
	Normal force (kN)	1424 - -285	1472 - -288	1539 - -280	1595 - -403
	Max bending moment (kNm)	0,28	0,3	0,3	0,24
2	Displacement (m)	0,242	0,234	0,238	0,28
	Max axial stress (Mpa)	2807	2878	2981	3036
	Normal force (kN)	1377 - -255	1412 - -286	1462 - -303	1489 - -298
	Max bending moment (kNm)	0,72	0,5	0,33	0,19
3	Displacement (m)	0,271	0,247	0,238	0,233
	Max axial stress (Mpa)	2799	2826	2862	2867
	Normal force (kN)	1209 - -188	1386 - -240	1404 - -277	1406 - -289
	Max bending moment (kNm)	1,14	1,12	0,85	0,62
4	Displacement (m)	0,337	0,302	0,28	0,262

Legend: Close to sphere shape — Extreme values — Optimal values

Table 5.: Calculation / Joined half spheres

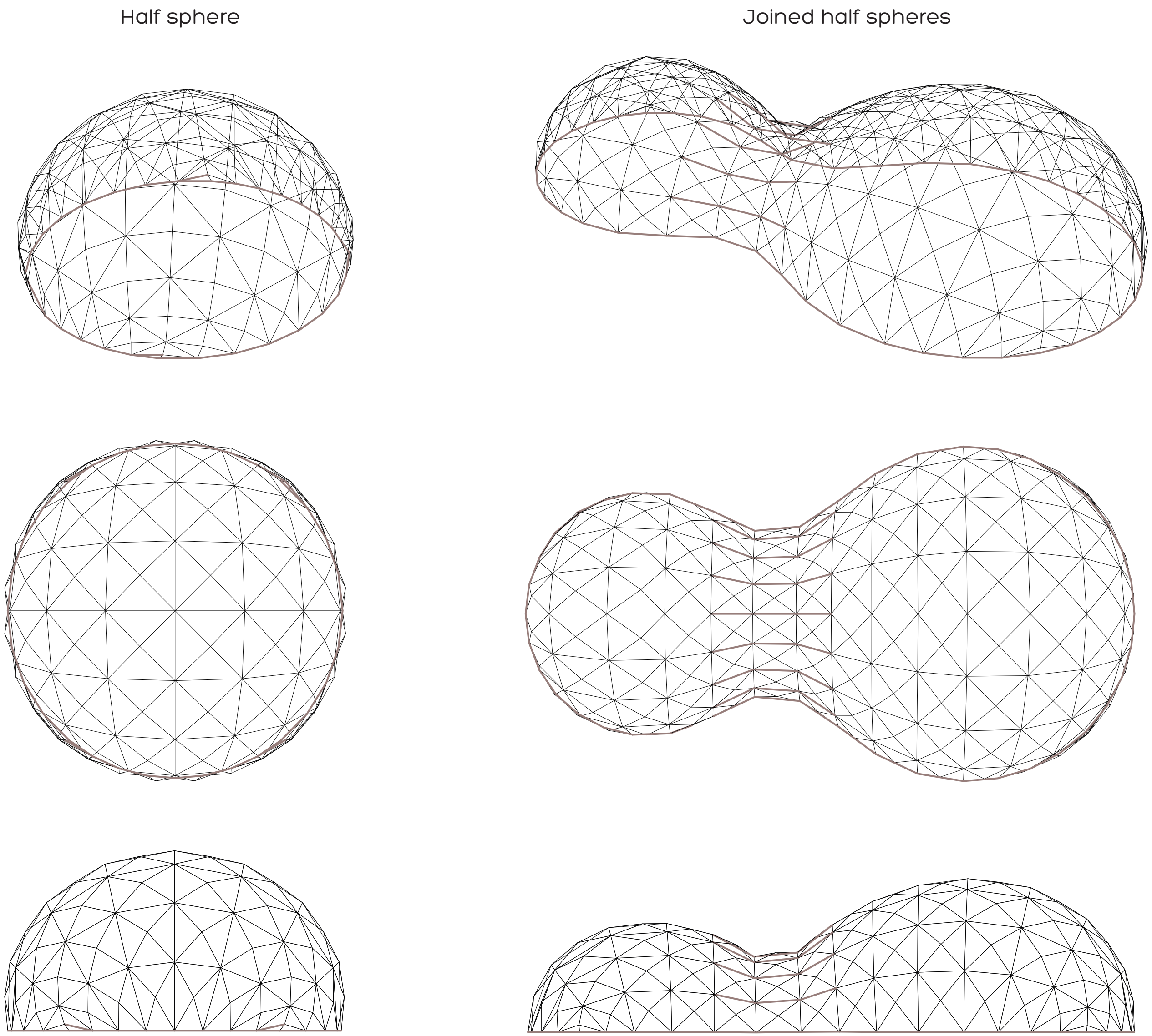


Illustration 90.: Compression elements

Elements in compression

Pretensioned elements

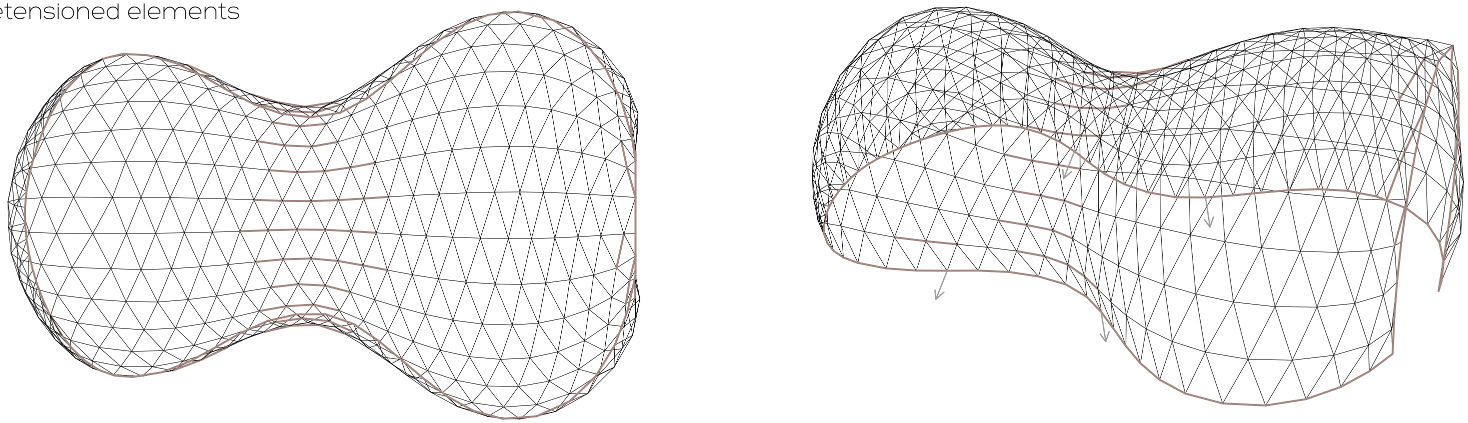


Illustration 91.: Compression elements - pretensioned structure

Final structure

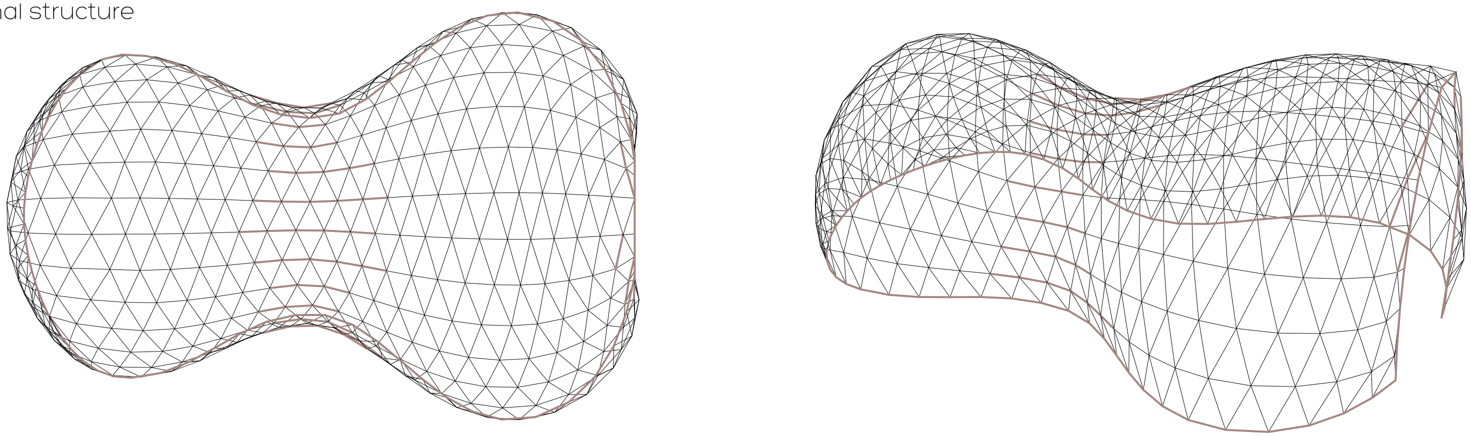


Illustration 92.: Compression elements - final structure

Stresses in cushions

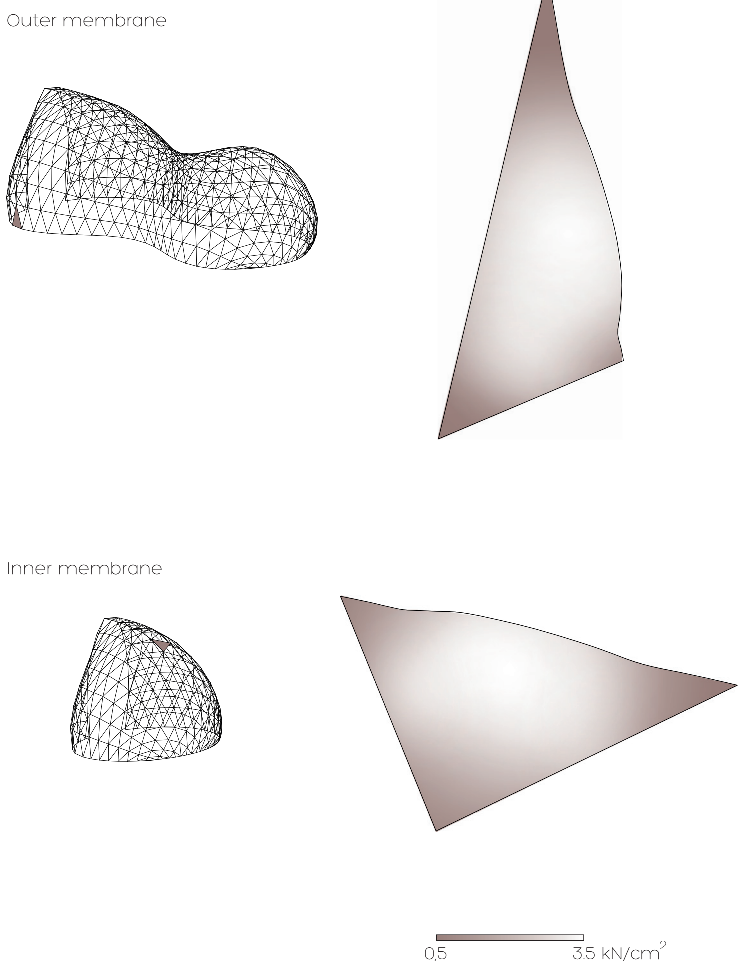


Illustration 93.: Stresses in ETFE cushions

Final structure

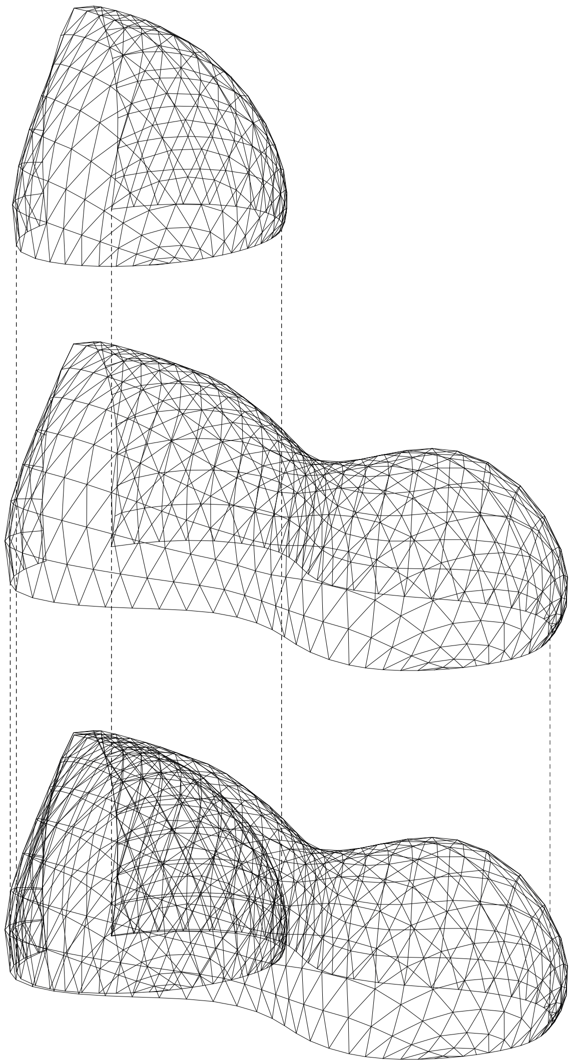
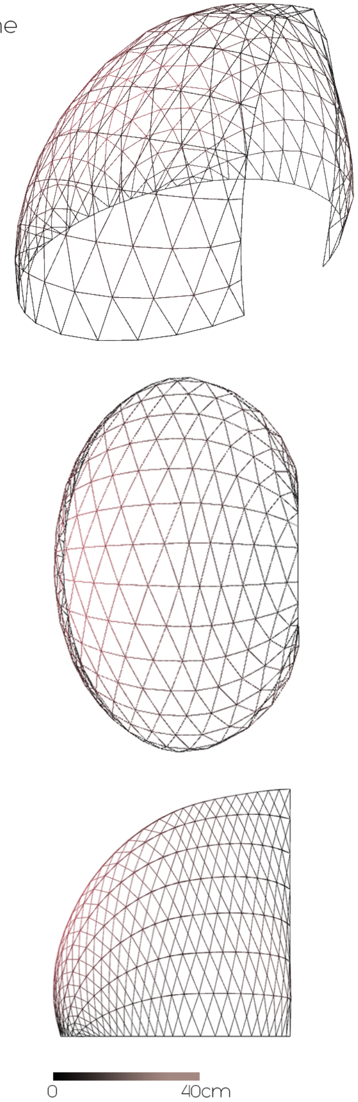


Illustration 94.: Final structure

Deformation

Inner membrane



Outer membrane

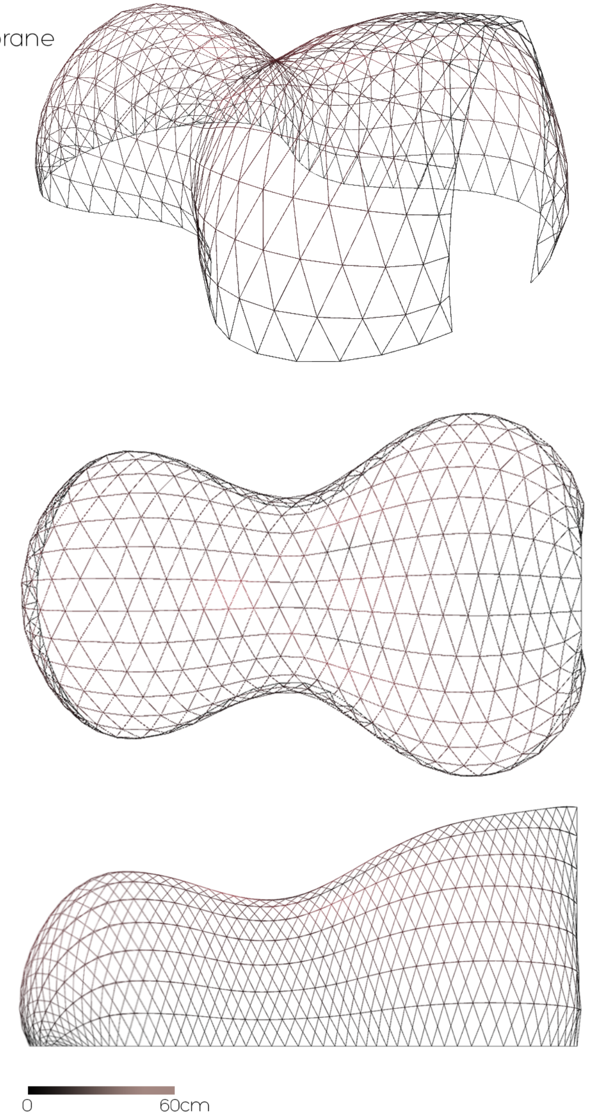


Illustration 95.: Deformation - final structure

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Illustration references

All illustrations and tables are own, except:

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https://uploads6.wikiart.org/images/norman-rockwell/willie-gillis-in-college-1946.jpg

Illustration 12.
http://www.housebeautiful.co.uk/garden/makeovers/news/a252/a-garden-for-all-seasons/

Illustration 13.
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