Biomimetic Structures for Martian Habitats :
In the Light of Form-Finding

July’24

Politecnico di Torino

Biomimetic Structures for Martian Habitats :
In the Light of Form-Finding

Politecnico di Torino
MSc, Architecture for Sustainability Design

Supervisor
Assoc. Prof. Amadeo Manuello Bertetto

Co-Adviser
Prof. Bernardino Chiaia
Phd. Candidate Jonathan Melchiorre

Authors
Şevval Türkan Alp
Berke Gündoğdu

July 2024

Politecnico
di Torino

Acknowledgements

This is one of the most difficult sections of the report, as there are so many people to thank and we are unable to convey their support here. As two architects with a design background, we realised how difficult it was at first, but then opened up to a very enjoyable world when we delved into the fundamentals of space and perhaps more generally the natural sciences, which we have long followed with curiosity, in order to put the scientific basis of our research on a solid footing. Although, as two architects, we had a basic engineering education, the problems we had to solve went beyond our basic training. All the names below helped us along the way with their ideas, material support and pleasant conversations that broadened and changed our perspective.

We owe our deepest and most sincere thanks to our project advisor, Assoc. Prof. Amedeo Manuello Bertetto. Even though the research process was getting longer and longer, and there were times when we were sometimes concentrating and other times drifting, he never spared us his support and opinions (even when we got lost in deep corridors on subjects other than our main topic). Then we would like to thank Jonathan Melchiorre, an engineer and PhD candidate at PoliTO, who helped us with his ideas in difficult times. He was one of the main contributors to the development of the main structure of the thesis. We would like to express our sincere gratitude to Prof. Bernardino Chiaia, who supported us at the beginning of the process and helped us to access the main resources on biomimicry.

As we have been in different places during the research and writing of this thesis, we have been very fortunate to receive support from people in different places. We would like to express our sincere gratitude to Professor of Geology A. M. Celal Şengör, who, in line with our desire to understand the planet Mars on a scientific basis, opened his library to us at the beginning of our research and enlightened our way with his views on Mars. Of course, we would also like to thank Gamze İyem, the owner of Masa Book. She helped a lot to make this happen and never refused her support.

We cannot thank Dr Kürşad Özdemir enough, who, in line with his previous studies on spatial architecture, gave us his full support and answered our questions without tiring whenever we asked. We would also like to thank Süheyla Müge Halıcı, who we met through Dr Kürşad Özdemir, for her valuable contributions. We would like to express our sincere gratitude to Prof. Cengiz Toklu, a civil engineer who is carrying out studies on the structures of the Moon and Mars in Turkey, for his time and valuable ideas. We also cannot express our gratitude enough to Arzu Söğüt for her ideas on the biology section.

We would also like to thank Göknur Aslan, Ebru Akçeken, Sibel Çakıl, Güruzar Evran and Fatma Özgül Sürmeli from the ITU Mustafa İnan Library, who we met through A M Celal Şengör and who helped us with the materials.

Finally, we would like to express our gratitude and appreciation to all the giants who have inspired us to work on this subject and who, step by step throughout human history, have provided us with all the information that forms the basis of our research.

Uncovering the Red Planet
Part 1

Content

Introduction

Ensuring the survival of our species and perhaps another habitat on another planet like Mars is a multidisciplinary and highly complex task. It requires the coordination of research from astronomy to geology, from physics to biology, from psychology to architecture, and a familiarity with each other's concrete evidence. Interdisciplinary methods and the cross-fertilisation of ideas allow these fields to develop and revitalise themselves in all directions. Space Architecture feeds on this interdisciplinary dialogue and draws its infrastructure entirely from the natural and human sciences. To design the 'shelters' needed to sustain human life on the surface of Mars, space architecture must draw on the accumulated knowledge of the natural and human sciences and engineering disciplines (Häuplik-Meusburger & Bannova, 2016; Ozdemir, 2013).

Space architecture does not deal with different issues from terrestrial architecture, but the issues it deals with are newly discovered and the solutions are much more complex. While extreme environmental conditions are only an issue for terrestrial architecture in certain regions of the Earth and in a limited area, this is the reality of space architecture. For this reason, especially when designing a habitat on a planet with extreme environmental conditions such as Mars, most of the research to date has focused on designing structures that can withstand these and similar environmental conditions.

However, most of the research has been on designing structures that are resistant to stresses arising from construction cost, radiation protection, micrometeoroid or thermal differences. These are of course important and guide the design to a degree that cannot be ignored, but the main structural load to be considered for a sustainable and permanent Mars settlement, which we will explain in more detail in the future, is the load distribution consisting of the pressure difference (Järvstråt & Toklu, 2004; Yashar et al., 2019; Soureshjani et al., 2023; Pavese et al., 2023). Any Mars structure, together with the materials obtained from local sources, must be able to withstand the internal pressure of 101.3 kPa and the external atmospheric pressure difference of 0.6 kPa. Recent research in this area shows that the low tensile strength of local materials has forced designers and researchers to look to Earth for materials to increase tensile strength. It should be noted, however, that for a fully sustainable Mars settlement it is essential that only indigenous materials are used (Kennedy, 2002).

To design and implement this in extreme conditions such as the surface of Mars, it is necessary to understand how nature works and to consider the efficient and optimal structures that nature offers. Taking inspiration from natural forms and processes, and offering promising solutions, gives hope for future research. It is necessary to focus on durable and efficient designs by showing how natural forms provide optimal stress distribution and minimum energy consumption. Using nature's self-regulating systems, perfected over billions of years, biomimicry offers an invaluable strategy for developing innovative, high-performance solutions for Martian habitats.

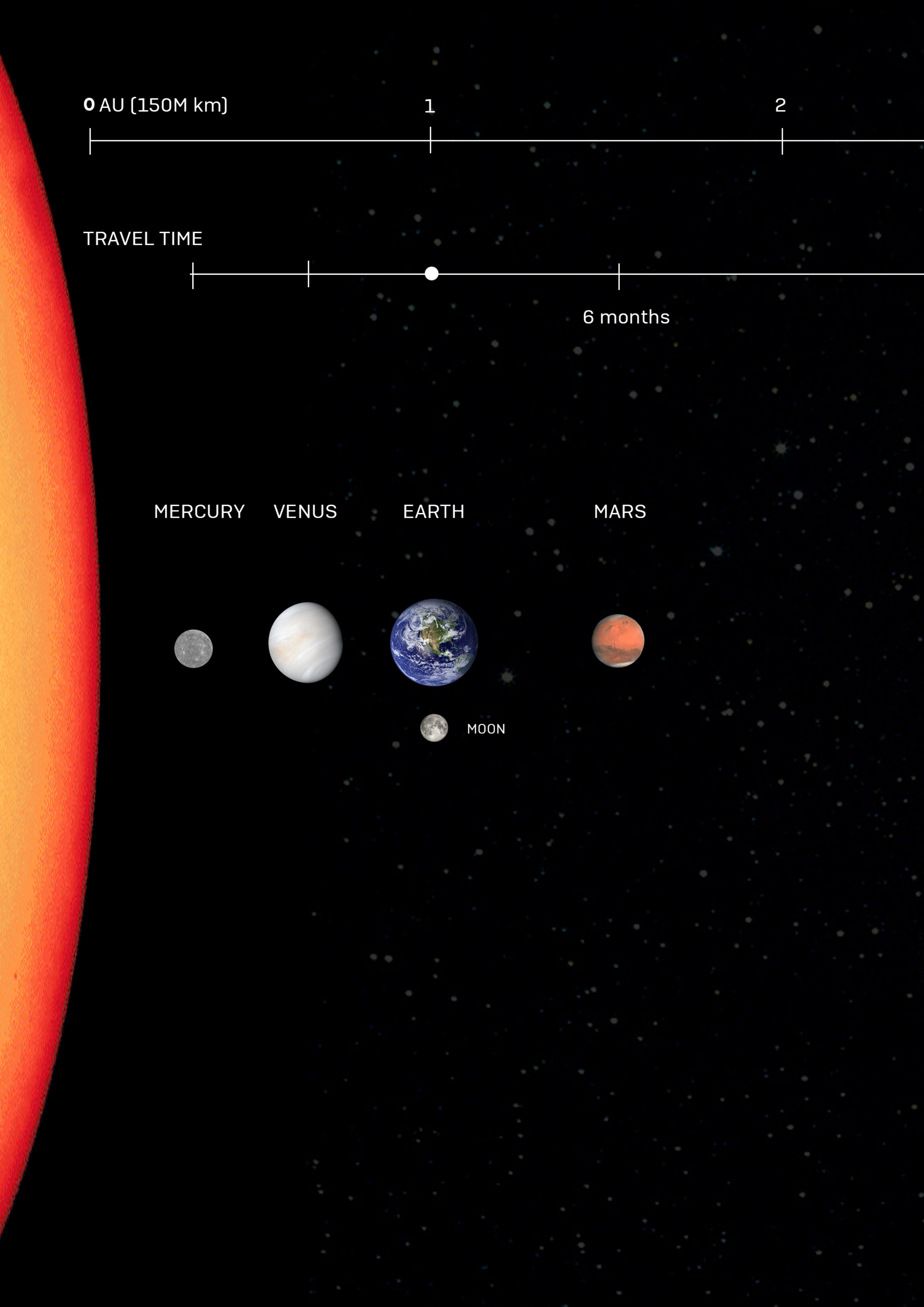
This research explores the intersection of biomimicry and architectural innovation in the context of limited materials, addressing the unique and primary challenge to sustainable habitat creation on Mars: pressure differential. It aims to develop habitats that are not only productive and durable, but also capable of supporting human life independently of Earth, by studying natural principles and applying them to man-made structures.

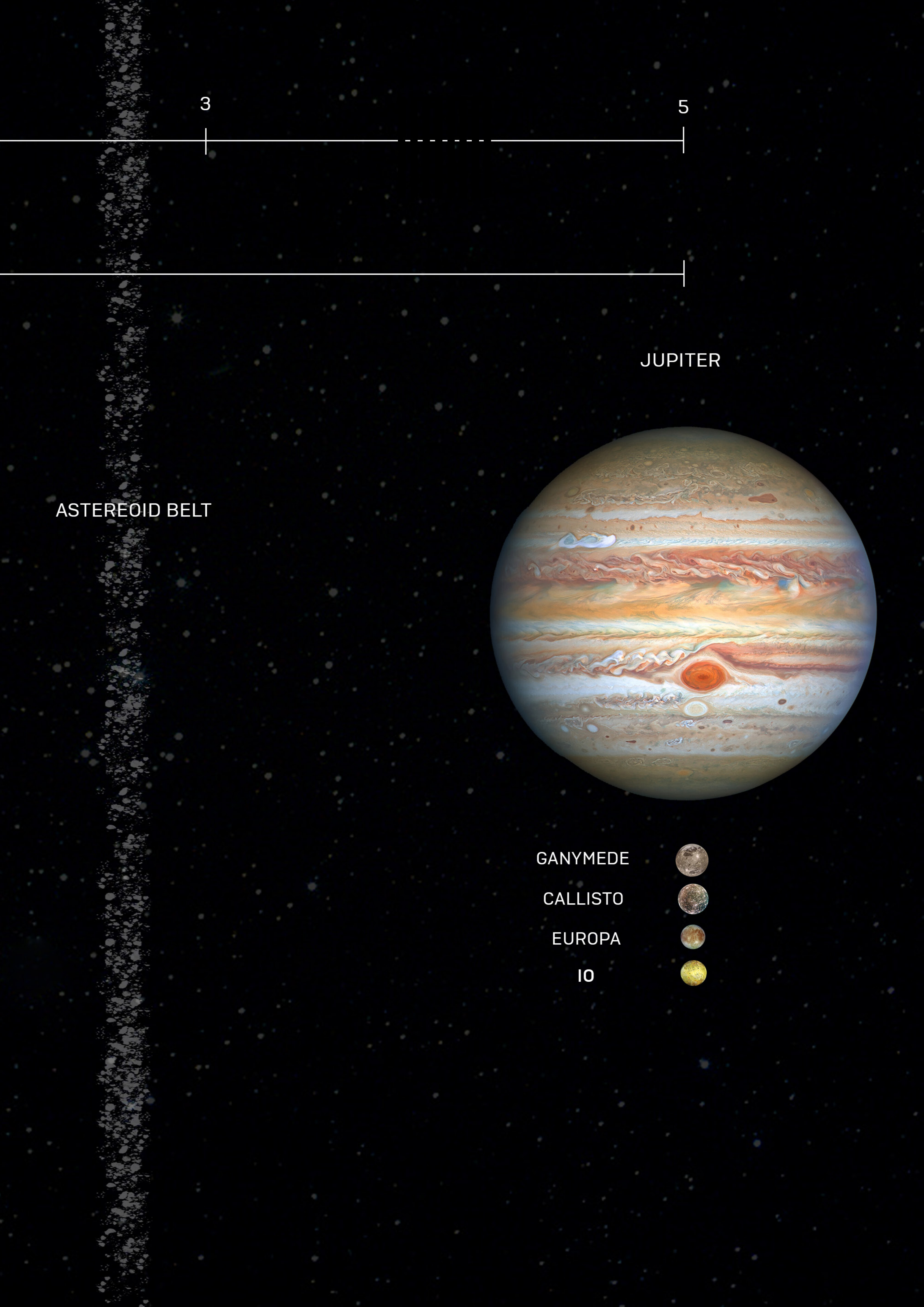
For example, on a planet where the tensile strength of local materials is low, what form should we follow to minimise the load caused by pressure differentials? How can we take inspiration from the natural world when designing the form? Are there any organisms in nature that have been subjected to internal pressure and somehow maintained their homeostasis? If so, how did they achieve this resistance? It also seeks answers to questions such as: can we apply this behaviour of organisms to Martian structures, either formally or behaviourally?

The answers to these questions and the results of this research, despite all their drawbacks, will make a small contribution to the design of building forms based on pressure differentials, which has not been given much importance in this field. These results will be useful for other studies in this field and will also help to fill the gaps in this research in the future.

It is also true that we encountered certain limitations in carrying out this research. As we are both architects, we did not have sufficient knowledge in the necessary scientific and engineering fields, so we spent most of our time trying to fill this gap. As mentioned above, the multidisciplinary and complex nature of the issues means that researchers from many different disciplines need to be involved, and the time limit for such research creates certain problems. However, despite all these drawbacks, the results of the research are promising for more detailed research in the future.

As mentioned above, we will try to approach this problem in the same way as terrestrial architecture. Chapter 1 provides a background to the design and significance of Mars by providing a context, i.e. an overview of the history of Mars exploration and its current environmental conditions, while looking at the geological history of Mars. Chapter 2 will give a brief summary of the Martian habitats and classifications, as well as the main form-giving environmental factors on planets like Mars, and will address the problem of pressure, which, as mentioned earlier, is the main form-giving factor on Mars. Chapter 3 attempts to solve this problem, which is materially difficult and economically unsustainable, by looking to nature and taking inspiration from the cellular level of plant cell walls, specifically Arabidopsis Thaliana. Chapter 4 explains the structure designed using the form-finding method, based on the form taken by plant cell walls under internal pressure under loads arising from Martian environmental conditions, and examines the results of the structural analysis of the structure. Finally, Chapter 5 concludes the research by discussing the results of the proposed structure.


0 AU (150M km)
1
2
TRAVEL TIME
6 months
MERCURY
VENUS
EARTH
MARS
MOON


3
5
JUPITER
ASTEREOID BELT
GANYMEDE
CALLISTO
EUROPA
IO

Part 1
Uncovering the Red Planet

The history of the Red Planet cannot be formally separated from the way we perceive the Earth and, by extension, the Solar System and the Universe. The history of our discovery of the Red Planet runs parallel to -and always supports- our discovery and accurate positioning of the Solar System. This chapter will therefore summarise the major advances we have made in our understanding of the Universe, the Earth and Mars, from ancient times to the observational instruments of the 21st century.

1.1 A Brief Introduction to History of the Exploration of Mars

The evolution of our perception of the universe

It is generally accepted that the birth of science, and perhaps the birth of philosophy as it was then called, took place in Miletus, a city in modern Turkey. One of the main reasons for this is that in ancient civilisations such as Babylon, Egypt and Sumer, our understanding of the universe, matter and the creation of the world was explained by myths shaped by certain prejudices, whereas the pre-Socratic natural philosophers sought to explain these views by putting reason and human experience in the foreground rather than certain presuppositions. This view is also supported by the ideas of the natural philosophers about what they consider to be the sole principle of the formation of all material things. Regardless of the fact that Thales pointed to water, Anaximander to apeiron and Anaximenes to air, what is important for us is that here is one of the first descriptions of the universe that was developed with reason. In all the legends, in Egypt, Mesopotamia or other societies, while the earth was on the ground and the sky was above the ground, Anaximandros was one of the people who realised this change (Rovelli, 2014). Based on references in ancient texts such as Pliny's 'Histoire Naturelle' by this man, whose written works have not survived, the understanding that the earth is suspended in the air and the sky surrounds it is a revolution (Thales & Anaximandros, 2019). Apart from Anaximander, other Greek philosophers' descriptions of the shape of the Earth varied; Parmenides described the Earth as a sphere, Anaximenes, Anaxagoras and Democritus as flat, while Thales placed water under the flat Earth (Aristotle & Babür, 1997).

These sharp ideas, which have advanced our perception of the universe, have also sought to provide a basis for more accurate and detailed predictions. There was another view that was more comprehensive than these descriptions, and perhaps in keeping with the spirit of the times, that anchored the Earth-centred understanding of the universe that had long prevailed: Aristotle's geocentric model of the universe. Aristotle was one of those who realised that the Earth was not flat but round, and put this into a logical framework based on lunar eclipses. Aristotle's thesis that the Earth was stationary and that the Moon and Sun revolved around it in an orbit, which he believed to be circular for mystical reasons, was put on paper by Ptolemy (Mlodinow & Hawking, 2010). Ptolemy created a mathematical model of the universe by performing a complex calculation of spheres in his work 'Almagest' (Dk, 2017).

However, some shortcomings in this model would be recognised in later periods. The definition of the orbits as circular and the calculations of the orbital motions of the planets, which did not coincide with observations, used a different mathematical formulation for each planet and therefore did not fully reflect a single and complete system (Coles, 2001). However, despite all these shortcomings and deficiencies, it was the dominant view of the period up to the time of Copernicus.

Although Nicolas Copernicus argued in his work 'De Revoluitonibus Orbium Coelesitum' that the Sun was fixed and that the Earth and other planets moved, he was still unable to explain orbital motion completely and clearly. It would be Johannes Kepler who, using the spectacular observations of Tycho Brahe, would complete the heliocentric model of the universe. In his work 'Mysterium Cosmographicum', Kepler explained the laws we know as Kepler's laws and proposed that the planets revolved around the Sun in an elliptical orbit (Topal, 2020).

After the invention of telescopes, it was possible to make more detailed and efficient observations, and in his work 'Siderius Nuncius', Galileo Galilei obtained data that supported Kepler's model of the universe, especially with his observations of Venus in 1909 (Dk, 2017). The events that followed were even more rapid if we look at human history. The advances made by observers such as Huygens, Ole Romer and Cassini would lead to a great revolution in the future. Although Newton was able to explain the laws of planetary motion when he published 'The Principia' in 1687, there were some gaps in classical physics.

Einstein, who used a marvellous 'mind experiments' to sort out the scattered theories and came up with the theories of relativity, argued against Newton's idea of gravitation, that masses bend the fabric of space-time and therefore smaller masses move in the bent fabric of space-time around objects with large masses. As Einstein, because of some prejudices against his own theory, he had to add cosmological constants and assumptions to his theory, arguing that the universe was not expanding. However, Edwin Hubble's observations suggested the opposite. Apart from this problem, Einstein's model did not work correctly at very small scales, and it was necessary to establish a link between quantum mechanics and relativity, or one of them had to be correct.

Many physicists, including Stephen Hawking, have spent much of their lives trying to formulate the so-called 'theory of everything', but no tangible theory has emerged. Theories such as string theory or knot theory have been proposed, but theoretical physicists argue that there can never be a single theory and that the two theories cannot be unified. Since we are not the addressees of these discussions, we will leave these deep discussions to the theoretical physicists and conclude our very brief summary.

As we can see, our understanding of the universe has not followed a straight and smooth path. In civilisations such as Babylon, Sumer, China, Egypt and even ancient Greece, mythologies dominated our understanding of the universe for a long time. The Miletus in Ionian region, which lies in the territory of modern Turkey now, approached this understanding from a different angle, lighting the fuse with explanations based on reason and logic. We made some progress, but like Aristarchus' heliocentric model of the universe (Heilbron, 2001), we forgot about them for many years, and although they were in front of our eyes, we did not look back at them because of some prejudices or presuppositions, and we refused to look at them. The history of the discovery of Mars is also full of myths, speculation and prejudice, although it parallels our perception of our home, the Earth, the Solar System and the Universe. Perhaps this is how evolving and progressing.

Observations of Mars before large telescopes

Mars, one of the five planets visible to the eye, has always been a subject of curiosity for communities living in different geographical areas since ancient times. Because of its red-orange colour, most of them associated it with war and war gods, as the Romans called the gods of war (Barlow, 2008). For the Egyptians it was 'Her Desher', for the Babylonians 'Nirgal' and for the Greeks 'Ares' (De Blasio, 2018). What they all had in common was a symbol of war and violence. The Chinese called it 'Huo Hsing' or the Japanese 'Kasei' star, the Incas 'Auqukuah', the Sumerians 'Simud', the Hebrews 'Ma'adim' (Weintraub, 2020).

Observations of Mars have always been important for the models of the universe mentioned in the previous chapter. Observers who sometimes had difficulty in explaining the elliptical orbital motion of Mars suggested that it was making the so-called retrograde motion, Ptolemy's model of a universe full of spheres also had difficulty in explaining this motion, and Mars did not rotate in a circular orbit anyway. Of course, as mentioned in the previous section, the insistence on this model was due to the mystical belief in the geocentric model, and the first steps towards abandoning this model came from Nicolas Copernicus. When Copernicus placed the sun at the centre and rotated the planets around it, some of the problems were solved. Copernicus also calculated the sidereal period of Mars, the time it takes a planet to return to its original position relative to the Sun, and found it to be 687 days (Barlow, 2008).

Using the magnificent observations made by Tycho Brahe in his book 'Astronomia Nova' before the advent of large telescopes, Kepler, who was actually Tycho's assistant, led to the elliptical determination of planetary orbits. Kepler used mathematical calculations to further explain the heliocentric model of the universe based on these observations.

After

When Galileo Galilei started using larger telescopes instead of small ones, the mystery of Mars began to be unravelled. Huygens mapped the black spot in 1659, Cassini mapped the polar caps in 1666, and Maraldi went further. Herschel tried to estimate values such as the tilt of the axis and the length of a Martian day from his observations. The first complete map of Mars was made by Madler and Beer in 1840. The values they gave were very close to Herschel's (Barlow, 2008).

Developments up to this point had in fact led to the development of speculation and legend. With each step forward in understanding Mars, the boundaries of speculation and legend became narrower. It had evolved from a god of war to a planet.

But the observations of Mars by Giovanni Schiaparelli, an architect, engineer and scientist born in Piedmont and educated in Turin, seemed to usher in another era of speculation without his knowledge. After Schiaparelli called the thin black lines he observed 'canali', another observer, Percival Lowell of Boston, who also had an observatory in his name, saw them as artificial 'channels' and began observations to prove this theory. For a very long time, Mars observations became a field of speculation to prove 'intelligent Martians' (Weintraub, 2020).

Lowell took his theory further and suggested that the creatures living on Mars, which has a dry atmosphere, had designed these channels to transport water from the poles (Dk, 2017). In his book in 1906 'Mars and It's Canals' and his book in 1908 'Mars as the Abode of Life', Lowell took his theories even further. Even the French observer Camille Flammarion, who became famous before Lowell with his book 'La Planete Mars', had adopted this idea and expressed it in his book. The priest Angelo Secchi, director of the Collegio Romano Observatory in Rome, had also put forward similar ideas.

E.M. Antoniadi, born in Istanbul, studied astronomy and began working at the Meudon Observatory within the Paris Observatory under the direction of Camille Flammiarion. Initially he was a supporter of the idea of the channels, but with the passage of time and as a result of the observations he made, he made his views clear in his book 'La Planete Mars', published in 1931, and explicitly rejected the idea of artificial channels on Mars in the chapter entitled 'Reflections on the channels' (Weintraub, 2020).

Alfred Russel Wallace, one of the most important scientists of the time, whose name we often hear from the theory of evolution, although he was not an observer, also rejected Lowell's idea of Martian civilisation in his 1907 book "Is Mars Habitable?", saying that the planet was a frozen and dry desert and too far from the Sun to support life.

For a long time, however, this area of speculation remained alive, including in academia. From Kuiper's lichens to Sinton's algae, the field of speculation gradually narrowed until the age of space missions, which we enter in the next chapter, began.

A chronological look at spacecraft missions

Until the US Mariner spacecraft, Mars was shrouded in mystery. The Mariner 3 and 4 spacecrafts were successfully launched in 1964, but Mariner 4 was the first to make a successful flyby. Mariner 4 sent back photographs of the Martian surface and made measurements of atmospheric composition, magnetism and pressure. This mission was followed by Mariner 6 and Mariner 7. The Mariner 6 and Mariner 7 spacecraft had similar resolutions to Mariner 4, but were only able to photograph 10 percent of Mars (Watters & Schultz, 2010; Coles et al., 2019).

Launched in 1971, Mariner 9 was the first spacecraft to orbit another planet, returning on 13 November 1971. When it reached Mars, its observations were delayed due to a sandstorm on the planet, and it was restarted after the storm had passed. As a result, Mariner 9 photographed almost the entire surface, taking pictures of valleys, volcanoes and canyons. It also sent back more detailed data on surface features, temperature gradients and atmospheric content (Barlow, 2008).

Mars 3, one of the Soviet spacecraft sent in the same years, was the first spacecraft to successfully land on the surface of Mars. The Mars 3 spacecraft lost its signal less than 1 minute after landing on the surface of Mars and could not be recovered. Until the Viking spacecraft, the Mars 5, 6 and 7 spacecrafts were able to send back some data, but they could not remain in operation for long.

The Viking 1 and Viking 2 missions were launched 20 days apart in 1975. Viking 1 landed in the Chryse Planitia region of Mars and operated until 1982. Viking 2 landed in Utopia Planitia, but was temporarily inactive due to a problem. The Viking spacecraft completely scanned the Martian surface, sending back higher resolution images and providing valuable data in areas such as temperature, density, composition of the atmosphere, magnetism, wind and physical properties of the soil (Carr & Evans, 1980; Barlow, 2008; Coles et al., 2019).

Launched in 1996, the Mars Global Surveyor (MGS) orbiter remained in operation until 2006. Its Mars Orbiter Laser Altimeter (MOLA) and Thermal Emission Spectrometer (TES) provided detailed surface and atmospheric data.

Following these missions, another cornerstone mission was Pathfinder, which landed on Chrysia Planitia in 1997. Pathfinder, carrying a Rover named SoJourner weighing 10.6 kg, worked on andesite and basalt rocks for only 3 months, but expectations were that Pathfinder would work for a month and SoJourner for a week (Coles et al., 2019; Barlow, 2008).

Mars 1	CNSA	1962
Mariner 3	US	1964
Mariner 4	US	1964
Zond 2	CNSA	1964
Mariner 6,7	US	1969
Mariner 8	US	1971
Mars 2,3	CNSA	1971
Mariner 9	US	1971
Mars 4,5,6,7	CNSA	1973
Viking 1,2	US	1975
Phobos 1,2	CNSA	1988
Mars Observer	US	1992
Mars Global Surveyor	US	1996
Mars 96	RUS	1996
Pathfinder	US	1996
Nozomi	JAP	1998
Mars Odyssey	US	2001
Spirit, Opportunity	US	2003
Mars Reconnaissance Orbiter	US	2005
Phoenix	US	2007
Curiosity	US	2011
MAVEN	US	2013
InSight	US	1964
ExoMars 2022	ESA	1964
Mars 2020 I Perseverance, Ingenuity	US	1964
MMX	JAP	2020
HOPE	UAE	2020
Mangalyaan 2	IN	1964
Tianwen-1	CHI	2023

Table 1: Spacecraft missions to Mars

Sent in 2001, Mars Odyssey was another successful mission that is still in operation. With its THEMIS, GRS and MARIE instruments, it continues to send data on the Martian atmosphere, surface characteristics and physical properties.

After the United States and Soviet missions, the European Space Agency got involved and launched the Mars Express mission in mid-2003. The Beagle 2 lander it carried was designed to land on Isidis Planitia to investigate weather and climate conditions and search for signs of life, but its signal was lost immediately after landing. But Mars Express Orbiter continued its operation and helped us understand the geological evolution of the surface, including its mineralogical composition, with instruments such as HRSC, OMEGA and SPICAM. It even discovered atmospheric methane and discovered large sulphur-rich deposits in Valles Marineris (Coles et al., 2019; Barlow, 2008; Malin et al., 2024).

Spirit and Opportunity, the two Mars Exploration Rovers (MER), were launched in mid-2003. Spirit landed in Gusev Crater on 3 January 2004 and Opportunity landed in Meridiani Planum on 25 January 2004, 22 days after Spirit. Weighing 174kg, Spirit continued to operate until it got stuck in the dust (Rocard, 2020) in 2011, travelling about 5 miles and sending back complex geological data from the area where it landed. Opportunity, also weighing 174 kg, ended its operations in 2019. Both rovers were incredibly successful geological experiments and both found ancient water remains (Malin et al., 2024; Mars Exploration Rover NASA Facts, 2004; Coles et al., 2019; Weintraub, 2020).

Another spacecraft still in operation today is the Mars Reconnaissance Orbiter (MRO). MRO has taken a detailed look at the history of water on the planet with instruments such as SHARAD and HiRISE, and has also conducted studies of possible ancient shorelines (Coles et al., 2019).

The Phoenix lander, launched in 2009 and the first successful polar landing, spent five months studying water and ice resources. It discovered water ice below the surface and under alkaline soil (Malin et al., 2024).

The 900kg, six-wheeled Curiosity, a key part of the Mars Science Laboratory mission, was launched on 26 November 2011 and landed in Gale Crater on 6 August 2012. At the start of its journey, Curiosity's scientific instruments found chemical and mineral evidence of past habitable conditions on Mars. It is still finding rock records from a time when Mars may have supported microbial life (Coles et al., 2019; Mars Science Laboratory/Curiosity, n.d.).

Following Curiosity, the Mars Atmosphere and Volatile Evolution (MAVEN) mission was launched on 18 November 2013. The orbiter, which reached Mars in 2014, is still in operation, observing and sending back data about the Martian atmosphere.

Following on from Mars Express, ESA launched the ExoMars (Exobiology on Mars) mission in 2016 with the Trace Gas Orbiter, the first part of the two-part mission. The orbiter, which was sent to study gases containing biological traces such as methane, is still on mission.

The InSight lander, which was sent to study the internal structure of Mars, namely its core, mantle and crust, was launched on 5 May 2018. InSight, which landed on Elysium Planitia, worked like a geological laboratory, with instruments such as seismometers and

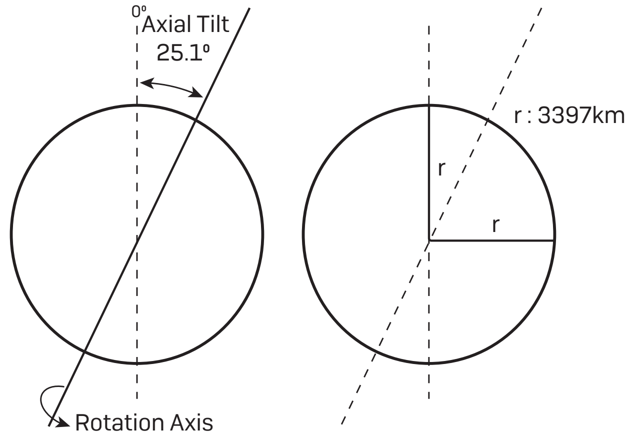


Figure 1 : Axial tilt and radius of Mars

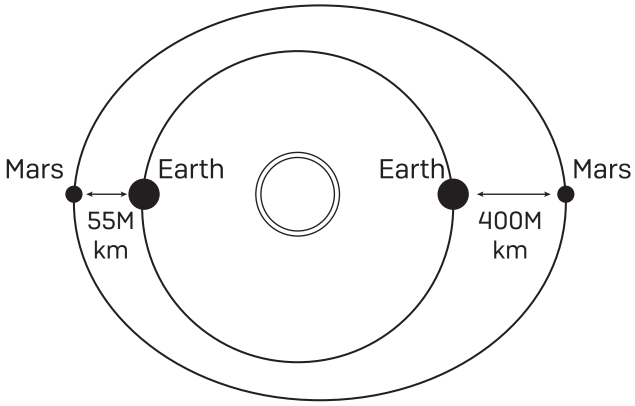


Figure 2 : Closest and furthest positions on avarage

environmental sensors (InSight, 2015), and after obtaining detailed data on the internal structure of Mars, its mission was completed in 2022.

Finally, the Perseverance spacecraft, perhaps one of the most comprehensive rovers ever sent and part of the Mars Sample Return mission, landed in Jezero crater on 18 February 2021 (Mars 2020, 2019). Perseverance, which landed in the region to study past microbial life on Mars, also carried a small helicopter: Ingeniuty. Weighing 1.8 kg and measuring 49 cm in height, this Mars helicopter was powered by solar energy (Aung & Balaram, 2020). Ingeniuty, which was completed just before the time of writing, stayed in service much longer than expected, completing 72 flights. Perseverance, on the other hand, continues to collect rock and soil samples and to make observations and investigations in the Jezero crater, which is thought to be an ancient lake.

1.2 Physical Properties of Mars

Size, shape and related

Mars has an average radius of 3397 km (Smith et al., 1999), which puts it between the Earth (6378 km) and the Moon (1738 km). It also has a mass of 6.4185x10^23kg, which is 11% of Earth’s mass (Carr, 2007). Its gravity is 3.72076 m/s2.

Its sidereal period, the time it takes to complete one tour on itself, has been measured to be 24 hours, 37 minutes and 22.65 seconds. And this period is called a Martian day or ‘Martian sol’.

Mars also has an axis tilt and, like Earth, has four seasons. Although the axis tilt of Mars is 25.1 degrees, this value can vary between 14.9 degrees and 35.5 degrees for various reasons (Ward, 1973).

Mars also has two satellites called Phobos and Deimos, which were discovered and named by Asaph Hall in 1877, 6 days apart. The surface of Phobos, which is larger and orbits further inland than Deimos, has an irregular shape due to its low mass and density. Deimos, which is smaller and farther away than Phobos, has a similar appearance for similar reasons. Phobos orbits the planet 3 times in almost one Martian sol, while Deimos completes this tour in 1.2 Martian sols.

Orbital motion of Mars

The distance of Mars from the Sun is about 1.5 times the distance of the Earth from the Sun, so Mars is 1.5237 AU (2.279x10^8km) from the Sun. With an eccentricity of 0.0934, Mars is the planet with the most elliptical orbit after Mercury. Because of this ellipticity, the distance between Mars and Earth can vary between 400 million km and 55 million km. For this reason, the closest conjunction between Mars and Earth is usually every 779 days on average when both are on the same side of the Sun, but the closest conjunction between Earth and Mars is every 17 years (Barlow, 2008).

1.3 Geology of Mars

In the first part of this chapter, we looked at how Mars formed and how its internal structure developed and changed after its formation. We then discussed the geological history of the planet in chronological order, including the leading roles of the main geological processes that have shaped the planet. We have done our best to keep it short, but not superficial.

Formation and internal structure

Mars, along with all the other terrestrial planets, formed at about the same time, 4.5x10’9 years, or about 4.6 Ga, from rocky debris left over from the formation of the outer gas and ice giants beneath the inner nebula (Taylor & McLennan, 2009).
The formation phase for Mars and all other planets is generally divided into 3 phases: planetesimal formation, planetary embryo formation and larger planet formation (Chambers, 2004). Rotating material in the dust cloud collides at certain speeds and sticks together to form objects of greater mass. As objects in inner orbits are more likely to collide, their masses gradually increase and when they reach 1 km in size they are called planetesimals (Barlow, 2008).

Objects that reach 1 kilometre in length, which we now call planetesimals, move orbitally and gravitationally. As we mentioned earlier, because objects of greater mass bend the fabric of space-time more, they attract more objects of lesser mass than themselves, and their masses gradually increase. This process of accumulation and aggregation is called accretion, and the result is the formation of planetary embryos. After the planetary embryos were formed, the mass of Mars was generally formed. However, the final touches to planet formation, which we call the final stage, will occur as a result of large collisions.

Soon after its formation, within the first 10 million years, Mars was divided into 3 parts: core, mantle and crust. The distinction between core, mantle and crust has long been debated. As we mentioned in the first part, the SEIS (Seismic Experiment for Interior Structure) on the InSight rover sent by NASA to the Elysium Planitia region recorded 733 different Martian earthquakes and made observations to understand the size and structure of the ground layers.

Based on the data obtained by InSight, it was understood that the Martian crust, previously estimated to be about 40 to 60 km thick (Taylor & McLennan; Barlow, 2008; Coles et al., 2019), was much thinner, at 20 to 37 km. The mantle was found to extend up to 1,560 km from the surface, and the radius

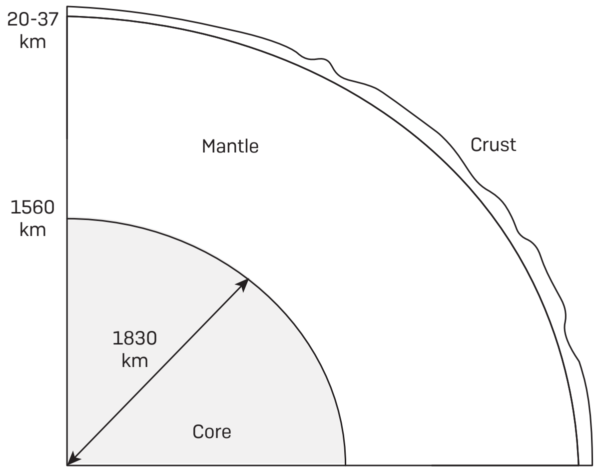


Figure 3: Interior of Mars

of the Martian core was found to be 1,830 km. In addition, the long-running debate about whether the nucleus is liquid or solid was resolved, and it was understood that the nucleus is liquid (Khan et al., 2021).

Geological timeline

As mentioned in the previous section, Mars, which formed about 4.6 Ga ago, is divided into four geological periods: Pre-Noachian, Noachian, Hesperian and Amazonian (Hartmann & Neukum, 2001).

The Pre-Noachian period covers the time between 4.6 Ga and 4.15 Ga. We know that during the first half of this period there was an active dynamo in the inner core of the planet, which generated a magnetic field. The magnetic field naturally kept the atmosphere around the planet and prevented it from escaping into space. The fact that the atmosphere did not escape into space indicates that the pre-Noachian period was hot and humid. During this period, also known as LHB, or Late Heavy Bombardment, there is intense cratering as the planets are subjected to intense collisions.The period between 4.15 Ga and 3.71 Ga on the Neukum scale or 3.56 on the Hartmann scale is called the Noachian and this period is divided into three: Early, Middle and Late. The formation of valley channels was due to the catastrophic floods that occurred during these periods. As we will explain later, volcanic movements such as the formation of the Tharsis region began. During the Late Noachian period, the formation of Valles Marineris and Noctis Labyrinthis began and continued until the Hesperian period.

The period between 3.56 Ga and 3.24 Ga on the Hartmann scale, or 3.71 Ga and 3.37 Ga on the Neukum scale, is called the Hesperian period. This period is divided into two parts: Early Hesperian and Late Hesperian. During this period, outflow channels and south polar ice deposits began to form.

The Amazonian period, which we call the last period, covers the time up to the present with a scale of 3.24 Ga in the Hartmann scale or 3.37 in the Neukum scale. This period is divided into 3 parts: Early, Middle and Late. During this period, the north polar deposits began to form and volcanism continued to be active in certain regions (Coles et al., 2019).

Thus, although Mars has been in a period of silence or very low noise for a long time, its first period of about 1 billion years was very active. The similarities between Mars and Earth, particularly in the pre-Noachian and Noachian periods, have increased our excitement and curiosity about Mars.

Impact Crater

Impact craters are the most common landforms on the surface of Mars and other terrestrial planets. These craters began to form intensively from the time when Mars first formed, and in particular from the LHB,

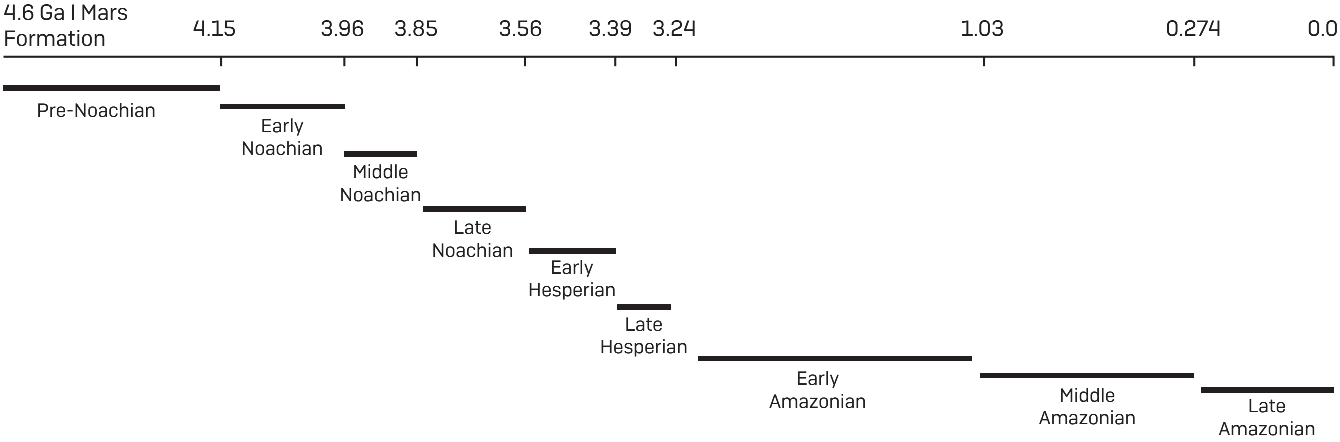


Table 2 : Geological timeline

or Late Heavy Bombardment, period mentioned above. This frozen state of the planet, caused controversially by the lack of plate tectonics, allows us to obtain data from Mars about this period that we cannot obtain from Earth today, because it has managed to preserve its traces from that period to the present day. Mars is therefore a frozen past.

Although earlier scientists thought that these craters were caused by volcanism, later laboratory studies showed that they were caused by high-speed collisions (Barlow, 2008). Craters are divided into three groups based on size and shape: simple, complex and multi-ringed basins, depending on variations such as the volume, mass, density and shape of the impacting body or the surface characteristics of the impact area (Carr, 2007).

The largest impact basin on the surface of Mars is the Hellas basin in the southern highlands. Its diameter reaches about 2,400 km and its deepest point is about 8,200 metres from the surface (Coles et al., 2019). The Hellas Basin is followed by the Isidis Planitia and the Aryrgre Planitia with a diameter of 1,500 km. Although not as large, small and medium-sized impact craters have also been given names such as Schiaparelli, Antoniadi, Cassini and Huygens.

The surface of Mars, exposed to intense high-speed collisions during the LHB period, has produced certain effects: global dichotomy. Global dichotomy manifests itself in several ways: elevation, crustal thickness and crater density. There is a difference in elevation between the southern highlands and the northern lowlands; the northern lowlands are on average 5.5 km lower in elevation than the southern highlands. (Cox & Cohen, 2019). Crustal thickness is thinner in the south and thicker in the north. As expected, crater density is higher in the south and lower in the north. Although the reasons for this dichotomoy include plate tectonics, which we will discuss later, it is known that large impact craters can cause this (Cowley et al., 2016; Watters & Schultz, 2010).

Understanding the importance of impact craters is also important for Martian habitats. As we will discuss in more detail later, there have been designers who have made design proposals for settling in craters using landforms.

Volcanism

The main geological force shaping the planet is volcanism. When Mariner 9 first approached Mars in 1971, the shield volcanoes it observed, changed the impression that the planet was dead (Carr, 2007; Chapman, 2007). Since the planet's middle Noachian period, volcanism has been intense in the Tharsis region and then in the Elyisum region. After these regions, it continued in regions such as Tharsis, Elysium and Hellas for the rest of the planet's history. Today it is debated whether there is still volcanic activity in the Tharsis and Elysium regions.

Although the number of volcanoes on the surface of Mars is less than on Earth and Venus, they outshine other volcanoes in size (Rothery, 2010). Olympus Mons, the largest of the large shield volcanoes in the Tharsis and Elyisum regions, is the largest volcano in the solar system with a height of 21.3 km and a volume of 3x10^6 km^3 (Barlow, 2008). To make a comparison, we would consider Mauna Loa's height of 9 km and its volume of 42.5x10^3 km^3 (Coles et al., 2019) or Pūhāhonu, which comes first and is the largest shield volcano in the world. It's volume was measured to be 148 ± 29 vs. 74.0 × 103 km3 (Garcia et al., 2020). Olympus Mons is followed by the other shield volcanoes of the Tharsis region: Ascraeus Mons, Pavonis Mons and Arsia Mons. The largest shield volcano in the Elysium region is Elysium Mons, which is 14.1 km high.

The answer to the question of why Mars has such large volcanoes is that, as we will explain later, Mars is a probably one plate planet, although this is controversial, and it loses energy quickly and has a thick and cold lithosphere (Carr, 2007; Rothery, 2010). We must say that volcanism is also the main factor in changing atmospheric properties, creating surface shapes and giving surface characteristics. Because of volcanism, which is the main geological element, the surface is covered with volcanic rocks (Cowley et al., 2016). Understanding the movement of lava flows will form the cornerstone of the habitat to be designed on the surface of Mars, as we will see later in the materials section. In this case, proposals have been made for the use of volcanic materials.

On the other hand, settlement within landforms formed as a result of volcanic activity has been proposed by various designers, but we will not discuss the positive or negative aspects of these proposals in this section.

Tectonism

In fact, the first thing that comes to mind when we hear this word is plate tectonics. Plate tectonics is one of the most important elements of Mars that is still being debated. Is Mars a single plate planet, or did it have plate tectonics during certain and particularly early parts of its history?

Plate tectonics has been proposed to explain the global dichotomy (Sleep, 1994) mentioned in the previous section, but both the global dichotomy and other surface features of Mars can be explained without plate tectonics. The thick and cold lithosphere of Mars prevents plate tectonics from occurring, but it is expected that the planet's lithosphere would not be so thick and cold in the Noachian periods, because the thickening of the lithosphere occurs when the planet gradually loses its energy and cools suddenly. From another perspective, features such as mountain chains and subduction zones, which are surface manifestations of plate tectonics, are not visible on the surface (those wishing to explore this topic in more detail should refer to Watters & Schultz, 2010; Carr, 2007).

If we leave the discussion of plate tectonics to geologists, the tectonic process on Mars is manifested in the morphology of the Martian surface. This can be divided into two categories: extensional and compressional. Extensional features include simple grabens, complex grabens, rifts, stress cracks, etc. Compressive ones are wrinkle ridges, lobate scarps and lod belts (Chapman, 2007; Watters & Schultz, 2010).

The largest tectonic feature on the planet is again the Tharsis bulge. Valles Marineis and Noctis Labyrinthus are also large and important tectonic features.

Channels and vallyes in relation to water

As we write this and the next chapter, we feel it will be necessary to talk about the history of water on Mars, because water has played a major role in the formation or morphological change of these landforms. While the pre-Mariner 9 spacecraft led us to see Mars as cold and dry, the Mariner 9 and Viking spacecraft changed this slightly; the doors to warm and wet Mars were opened in the early period. Measurements from MAVEN, Odyssey and Phenix have also provided detailed data on the water history of Mars (Weintraub, 2020).

We do not know exactly how much water by volume there is on Mars today, but we do have estimates. It is clear that liquid water was abundant in the planet’s past, especially during the Noachian period. Over time, Mars gradually lost its previous amount of liquid water, either underground or as Mars lost its magnetic field and atmosphere, and water escaped into space due to ultraviolet rays (Villanueva et al., 2015).

Today, we do not know whether liquid water exists on the surface of Mars, but we do know that there are places that have both the pressure and temperature to support the presence of liquid water. If so, there may still be reserves of liquid water underground (Lasue et al., 2012). We already know that there is water ice in the polar ice caps (Smith et al., 2001; Plaut et al., 2007; Zuber et al., 1998). Water appears to be generally distributed throughout Mars, both above and just below the surface. Even in the equatorial region there is 2-10% water by volume (for details see: Feldman et al., 2004).

The publication of images of the valley networks and outflow channel systems by the Mariner 9 and Viking spacecraft led most researchers to suggest that they were formed by liquid water, but some have argued that Mars is currently a dry planet (Carr, 2007; Barlow, 2008). As we will see later in the section on the atmosphere, the atmosphere during the Noachian period was denser, hotter and more humid, causing some form of rainfall. During the Middle Noachian period, catastrophic floods began to form valley networks. As we entered the Hesperian period, outflow channels began to form (Coles et al., 2019).

On the other hand, some studies show that the formation of valley networks cannot be caused by rainfall. A warm environment was needed for rain to fall, but the amount of energy from the Sun was lower then than it is today. Another point of debate was whether the Martian atmosphere was dense and thick enough to maintain this temperature. For this reason, some researchers have suggested that it may have been due to groundwater seepage (Carr, 2007).

Although the outflow channels vary greatly in shape, the largest is Kasei Vallis, which is up to 400 km long. Based on data from the Pathfinder spacecraft, it has become more certain that the outflow channels (Chapman, 2007) that we frequently encounter in the Utopia, Hellas and Tharsis regions were formed as a result of major floods. Pathfinder's landing site, the Chryse region, was a mixed flow channel and Pathfinder data confirmed past large flood activity (Carr, 2007).
Ancient lakes and possible oceans

A number of geological and atmospheric events would have to come together for a possible ancient lake and ocean on the surface of Mars. The surface of Mars, exposed to intense high-speed collisions during the Late Heavy Bombardment (LHB) mentioned in the earlier chapters, probably created a global dichotomy, as mentioned earlier. One of the most important consequences of this was the separation in elevation between the southern highlands and the northern lowlands, which were exposed to intense bombardment. It seems that catastrophic floods during the Hesperian period, which also created large drainage channels, left some of the water in the northern lowlands because of this difference in elevation.

Another aspect supporting the idea of a possible northern ocean is that, as a result of Mars losing 85% of its water volume to space, it does not seem unreasonable to think that the lowland northern lowlands are covered with water (Villanueva et al., 2015). Sequences of linear features around the northern lowlands are proposed as coastlines. The smallest and youngest of the proposed coastlines are supported by various observations (Carr, 2007).
Similar trajectories have also been followed in impact basins such as Hellas. These palaeo-lakes, which coincided with the formation of valley networks, may have formed channel networks such as Ma'adim Vallis as a result of rapid water discharge. Similarly, valley networks may have supported the formation of palaeo-lakes (Wilson et al., 2016). In some of the palaeo-lakes, horizontally layered sediments within their flat bottoms may be lacustrine, but this was not the case in the Gusev crater (Carr, 2007).

1.4 Atmosphere

Just as we cannot divide the planet into separate parts and evaluate them independently, we cannot consider the atmosphere in isolation from other processes. All tectonic processes have affected the atmosphere, and the atmosphere has affected all geological events. For this reason, in the first section of this chapter, we took a brief look at the historical evolution of the Martian atmosphere and examined its current state. We then looked at wind, which plays a major role in the formation of some of the surface features on Mars.

Characterics of Martian atmosphere

As mentioned above, the Martian atmosphere has been known to have a high CO2 content since the Mariner 4, 6 and 7 missions. The high level of CO2 pumped into the atmosphere was also most likely the result of volcanic activity on Mars. The atmosphere, which is 95% CO2 by volume, also contains some nitrogen, argon and oxygen, and traces of water.

Semimajor axis	2.2792 x 10^8 km 1.52371043 AU
Eccentricity	0.933941
Inclination	1.84969142°
Longitude of ascending node	49.55953891°
Longitude of perihelion	336.0563704°
Sidereal orbital period	686.98 days
Synodic orbital period	779.94 days
Mean orbital velocity	24.13 km s^{-1}
Maximum orbital velocity	26.50 km s^{-1}
Minimum orbital velocity	21.97 km s^{-1}
Obliquity	25.19°

Table 3 : Constituents of the martian atmosphere (by volume)

Because Mars has no magnetic field to hold its atmosphere in place, the density of its atmosphere is very low, with an average pressure of 610 Pascals. As the atmospheric content changes seasonally, these values can vary by an average of 200 Pascals. (Given the 101 kPa to which we are accustomed, these values mean nothing to us).

Temperatures on Mars vary from region to region, but are generally between -153'C and 20'C. These values can be considered normal for a planet with a very thin atmosphere. Mars lacks a layer thick enough to evenly distribute the heat that reaches its surface.

History of the atmosphere

We have said that Mars had a dynamo and produced a magnetic field in the pre-Noachian period. Of course, the magnetic field ensured that the early Martian atmosphere remained on the planet's surface. The formation of valley networks also shows that Mars entered a period that was hot and humid enough for liquid water to exist. The volcanic activity that began around this time, and the uplift of Tharsis, probably contributed to a thickening of the atmosphere and a greenhouse effect by releasing CO2 and H2O into the atmosphere and in fact, during this period, it may have had an atmosphere even denser than the Earth's atmosphere (Cox & Cohen, 2019). The causes of catastrophic floods and the drainage channels formed by rainfall during this period were also examples of this.

But it didn't always stay that way. As Mars' magnetic field disappeared, solar winds swept the Martian atmosphere into space. As the atmospheric density gradually decreased, the planet began to cool. Coinciding with this period, the Late Heavy Bombardment (LHB) also contributed to the decrease in atmospheric density.
After these periods, we think that the atmosphere of Mars also underwent minor changes, but that it reached its current state without any major changes, as we expected.

Wind

Winds have played an active role in shaping the surface of Mars, generally lifting dust particles from one place and moving them to another. This transfer varies depending on dust particle size, atmospheric pressure and wind speed.

Dust devils, which are atmospheric phenomena caused by wind, are generally a mechanism for lifting dust from the ground into the air. Dust devils, most recently seen by Spirit at Gusev Crater, are most common in the southern spring and summer (Greeley et al., 2006).

However, dust storms are not as local as dust devils. Dust storms tend to be more intense in the southern spring and summer (Fisher et al., 2005; Whelley & Greeley, 2006). Although they tend to be regional in low-lying areas such as Hellas, they can also be global under suitable conditions (Zurek & Martin, 1993). As mentioned above, the global dust storm of 1971 caused Mariner 9 to postpone its mission slightly.

When it comes to wind-generated landforms, the most important are ripples and dunes. While megaripples tend to form inside craters, dunes tend to form in mid-latitudes and on the northern polar ice cap. Dunes are classified according to their shape and structure (Greeley et al., 2006), but the most common are barchan dunes. Like much of the Martian surface, they are basaltic.

1.5 Final Look

Summary

In this first part, which we called 'The Uncovering of the Red Planet', we tried to give a brief but detailed explanation of the history of our discovery of Mars and the evolution of the planet since its formation. As you can see, we believe that Mars is not actually a very distant planet from us, as anyone interested in these matters will know. The word we use to mean distance should not be understood as distance; Mars is a planet that is 'familiar' to us, from its atmosphere to its landforms.

Formed at almost the same time as the other terrestrial planets in the inner orbit of the Solar System, an average of 4.6 Ga ago, Mars has gone through processes similar to those of our home planet, Earth. The magnetic field generated by the dynamo, which was active in the pre-Noachian period immediately after its formation, protected the planet from deadly radiation and allowed it to maintain its atmosphere. When the shield volcanoes formed as a result of active volcanic activity on the planet warmed it, a suitable environment was created for liquid water to remain stable on the planet's surface. The ancient valley networks, outflow channels, lakes and possible northern ocean on Mars during the Noachian and Hesperian periods remind us of what a familiar planet we were neighbours with at one time in its history.

However, because Mars is not as large as our home planet Earth, it cannot retain its heat and energy for long. The dynamo of a planet that is gradually losing energy begins to shut down, and so its magnetic field begins to disappear. A planet whose magnetic field has disappeared has no shield to protect it from solar winds and galactic cosmic rays.

As Mars begins to lose its atmosphere, it is deprived of a shield that would distribute heat homogeneously on the planet, and for this reason the planet begins to cool slowly. As the planet begins to cool, it loses much of the liquid water it contains to space. Since the Amazonian period, the remaining part has remained as water ice underground or in the polar regions.

After these short but exciting periods, the planet entered a quieter period, averaging 3.5 Ga, during the Hesperian-Amazonian transition. The surface is now filled with radioactive particles from the Sun and the Universe, and is far from conditions that would support what we call 'life'. But it is not correct to say that it is completely dead. Volcanism is probably still active today, especially in the Tharsis and Elysium regions. Landforms are still formed by wind, and layered sedimentation continues in the polar regions. Polar ice also expands and shrinks seasonally.

Why?

Why do we spend so much money on space exploration? Couldn’t we build a better life on Earth with the money we spend on this research? What is the benefit to society of space exploration that we spend so much effort, money and time on? All these questions are valuable for society to understand space and its importance, rather than being pushed into a corner as is commonly perceived. The answers to these questions are more than superficial, they are questions that need to be answered with a scientific approach. Since, of course, the budget for space research comes from society, we believe that it is very important for society to look objectively at space and the importance of space research and to know its positive and negative aspects. After all, we all know that after the Challenger and Columbia disasters, society’s support for space research decreased, perhaps rightly so.

In general, claims have long been made that space exploration will help us build a civilisation that is more inclined to international cooperation, or that space exploration will make us a more peaceful species, or that our society will live a wealthier life because of the rare minerals we can access through space exploration. There are also reasons such as the technological developments that space exploration will bring, or that going into space is the only way to save the Earth’s ecosystem, because the population, which is now so overpopulated that it is out of control, is constantly having to deal with new epidemics and wars. From another perspective, there are those who say that our instinct to explore space stems from our natural human curiosity and that we cannot resist embarking on this adventure.

The events of the Cold War period after the World War II have shown us that space exploration is not just a matter of curiosity (we know from human history that curiosity has not always spread throughout society). It is true that international cooperation in space exploration, and of course in many fields such as science, art and sport, brings different societies closer, but recent changes show us that international cooperation is not always forward looking. In our opinion, reasons such as going to another planet because the already collapsing society needs a new start are not even worth discussion and are only the fantasy of billionaires. Even if Mars is colonised, there will never be an El Dorado, especially given the tragic events resulting from the irresponsible exploitation of our planet’s resources, out-of-control pollution and our impact on global warming (Rocard, 2020). Moreover, while the agreements in the field of space are still not fully clarified, it is also debatable what the hierarchical relationship will be between the pioneers who will go to another planet, or the states or institutions that will lead them, and the society that remains on Earth.

As this is academic research, what it has to say about our exploration of space and Mars is, of course, scientific. Yes, we are going to explore space and we want to create a multi-planetary society, so why are we targeting Mars when the Moon is so close? While everything would be much easier on the Moon, why go to Mars after a 6-month journey with rockets that we can launch almost every 2 years?

Before we can answer that question, we need to know what the Moon is and how it was formed. We have never mentioned the Moon in this research, but to answer this question we are familiar with the theory that the Moon was formed as a result of a planet called Thea colliding with the Earth and tearing off a piece of the Earth as a possible reason for its formation. Over time, this piece of the Earth reaches a position of equilibrium in the fabric of space-time, bending due to the mass of the planet and collecting the small pieces around it due to its mass.

In our view, the Moon can be used for this comparison because of its proximity to the Earth. The Moon, which has little scientific promise compared to Mars, could perhaps be used as a test bed for engineering and space technology. There are a considerable number of scientists and space researchers who defend this. They have repeatedly argued in publications and at conferences why we should not go straight to Mars when we can test all sorts of technologies on the Moon, which is close by, and it is not unreasonable to say that in a sense they are right.

Mars tells us a lot about our own past and future, as we explained in the previous section. When life began on Earth 4 billion years ago, Mars was an Earth-like planet (Cox & Cohen, 2019). Mars, which has had favourable conditions for life since pre-Naissance times, can give us an insight into how life began on Earth. We do not know whether life on Earth really began on Earth or was transferred from another celestial body, but we believe that the independent discovery of past or present life on Mars would be both a social and scientific revolution. Or, in Sagan’s words, the gates of the wonder world may open.

In another sense, Mars is a frozen laboratory for us (Cox & Cohen, 2019). Traces of the Late Heavy Bombardment period that took place after its formation are still present in an unchanging landform due to the absence of plate tectonics. It is much harder to understand what happened in the inner Solar System after the planets formed by looking at Earth than it is to look at Mars. This is because rock records on Earth begin in the Archean, and there are no significant rock records from the Hadean world for the first 0.6 billion years (Zalasiewicz, 2018). For this reason, we can better understand the stages that our Hadean Earth went through from its formation by looking at Mars Pre-Noachian and Noachian stages.

Mars is also a very similar planet to Earth. Although Mars has been quiet for a long time, it is still an active planet and contains all the materials we need to build a sustainable settlement. Yes, its atmosphere is not conducive to breathing, yes, the pressure is too low, yes, it is often too cold, yes, it is exposed to excessive doses of radiation, yes, it is far enough to travel for 6 months after waiting 2 years, and yes, the production of materials for any kind of campus is complicated and complex. But none of this stops us from giving up on Mars settlements. In spite of all the hostile environment we explained in the first section, Mars is the planet closest to where we can go and the friendliest planet in terms of environmental conditions.

As for us, why are we doing this research on Mars and not on the Moon or some other celestial body? All the scientific reasons mentioned above have helped us to make this decision, but we can say that it was not direct scientific reasons that drove us to this decision. In the first few paragraphs of this section, we actually have an answer that we disagree with, which is commonly referred to as space myths.

We wondered too.

Part 2
Martian Habitats

1.1 I Martian Structures

In 2002, space architecture was defined in the ‘Millennium Charter’, prepared by space architects and published with the participation of dozens of scientists, designers and researchers from different countries and different fields: ‘Space architecture is the theory and practice of designing and building inhabited environments in space’ (Adams et al., n.d.). As stated in the publication, the main goals of space architecture were revealed by considering its relationship with other fields. Space architects need to build on terrestrial architecture (and must to learn from the past: Ozdemir, 2013) and other space sciences, just as they benefit from all other human and social sciences.

As mentioned in the introduction, the way space architecture approaches problems are no different from terrestrial architecture. It starts by asking similar questions to terrestrial architecture and tries to understand the context first. But this is where the difference begins. Terrestrial architecture creates a series of intersections between the desired programme, the design principles and the context. In space architecture, context is almost everything. In terrestrial architecture, architecture that does not take context into account is, at best, architecture that does not work well or does not relate well to its environment. The primary requirement for space architecture is to design a safe ‘habitat’ for its users within its context. The mistake made when the necessary care is not taken, taking into account the binding, scientific and engineering disciplines, is irreversible. The importance of this is that ‘habitats’, which have different definitions (for further details, see White and Ree, 1963; Kubis, 1967; Wise, 1985; Connors et al, 1985; Stuster, 2011), are always designed for extreme environments.

Designing a habitat in extreme environments requires adaptation to extreme environments. These extreme environments, which we abbreviate as ‘outer space environments’ (for more detail, see: Manzey &

Lorenz, 1998; Barnett & Kring, 2003), have conditions that are completely different from the Earth to which we are accustomed and on which we have naturally evolved, and these are lethal to us.

In order to realise a safe and functional design, a number of mechanisms are implemented to protect against extreme environmental conditions. Whether these mechanisms are orbital architecture or an architecture on the surface of another planet, almost similar problems are encountered. While orbital architecture designs and builds shielding against environmental conditions, this is usually done on Earth, using Earth materials. But for a sustainable Mars settlement, these shielding must be made on Mars, with Martian materials.

Mars settlements, which we will be classifying and detailing in the next sections, are naturally expected to be resistant to the extreme environment of Mars. To ensure this durability, it is essential to protect the habitat. The habitat needs a barrier, or in other words a 'shell', to protect it from all kinds of extreme conditions coming from outside. In this research, we have called these shell alternatives 'structure' as a more general definition. Martian structures must support and protect the habitat from all kinds of extreme conditions, both internal and external.

In the following sections, we examined the conditions of extreme environments that Martian structures must withstand, and the shield structures that are designed and fabricated differently according to the classification of Martian habitats. We then posed a design problem by looking at the environmental conditions, which we consider to be the most important element to consider when designing these structures.

1.2 I Form Giving Factors

What we call extreme is relative, as Bannova (2021) said. Answers vary depending on who is asking the question, where they are asking it, and for whom and what is being done there. When we talk about extreme places on Earth, the first things that come to mind are the poles, mountain tops, deserts, etc. In general, the reason for this is that these regions do not offer suitable climatic conditions for urbanisation and therefore it is very difficult to meet the necessary human needs. Of course, there are societies on Earth that live in regions with extreme environmental conditions, and there is an adaptation to these climatic conditions that they have developed over centuries, but we also know that life in Yakutsk is much more difficult than in a Mediterranean city with a temperate climate.

Structures on Mars will have to be designed differently from those on Earth. Earth-centred life, which has evolved over billions of years, evolves according to the physical conditions of the Earth. However, the physical conditions on the surface of Mars make it difficult for us to live on the surface of the planet without shelter or a spacesuit. Things we don't take into account when designing buildings on Earth, namely radiation, temperature fluctuations, pressure differences, gravity, micro-meteorites, global dust storms. Environmental factors such as these have become the main design guidelines or obstacles for Martian structures.

In addition, human psychology plays a very important role in design decisions. (Häuplik-Meusburger & Bishop, 2021) Many analogue habitats have been designed and experiments have been conducted to study the reactions of human psychology when

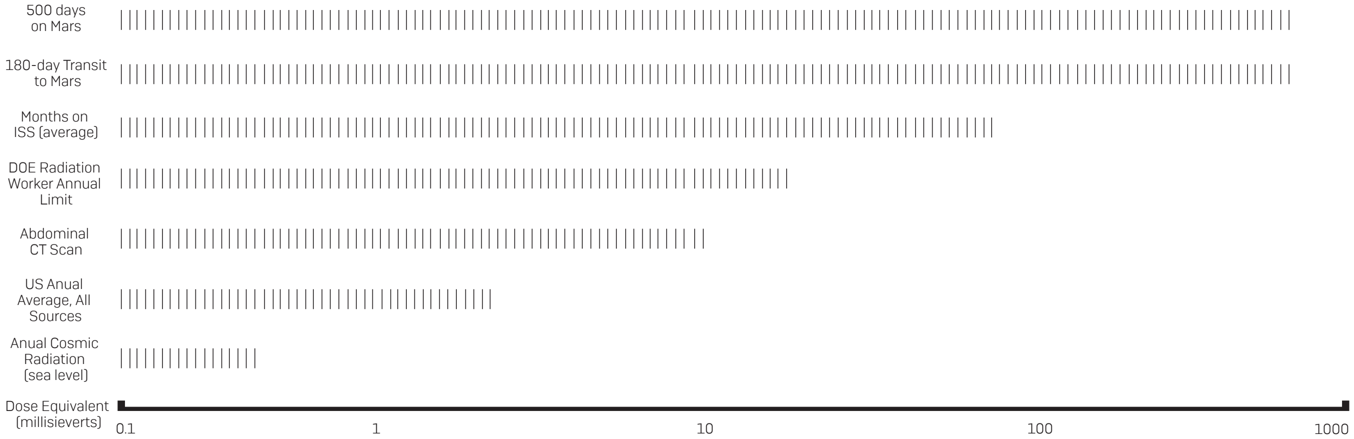


Table 4 : Radiation exposure comparisons with Mars trip calculation

exposed to isolated environments for long periods of time. In addition to that, human psychology also plays an important role in design decisions. For a long time now, it has been proven that enclosed spaces that do not allow visual con- tact with the outside world have a very negative effect on the crew. (for more: Häuplik-Meusburger & Bishop, 2021) However, as this study is concerned with environmental factors directly affecting structure, psychology is not taken into account.

Some of the key environmental factors relevant to a fundamental understanding of space structures are discussed in the following sections.

Radiation

The magnetic field generated by the Earth's working dynamo and its sufficiently thick atmosphere protect it from dangerous radiation (Meusburger-Häuplik, 2011). However, as we have seen in previous sections, the same cannot be said for Mars. The surface of Mars is unprotected due to its thin atmosphere and lack of magnetic field, exposing the surface to deadly radiation. (Hollander, 2023) Humans are exposed to both ionising and non-ionising radiation outside the Earth's atmosphere and magnetic shield (Meusburger-Häuplik and Bannova, 2016). This radiation generally falls into two categories. Solar flare products, also known as solar particle events (SPEs), are streams of energetic protons produced by solar flares. On the other hand, and more dangerously, there are high-energy galactic cosmic rays (GCRs), which consist of heavy nuclei, protons and alpha particles. But there is another type: X-rays, which are produced by the collision of high-energy electrons with metal conductors or passive radiation shields, also constitute the third type of radiation (Benaroya, 2018). Without the magnetosphere or Van Allen belts, it is almost impossible for humans and natural life to survive for long under these radiation levels. This level of radiation would threaten all life in a Martian habitat and would also have a negative effect on electronic materials (Cohen, 1996).

Although the design of habitats to protect against many sources of radiation from the Sun and deep space is complicated by Mars' lack of atmosphere and weak magnetic field, some precautions can be taken. Materials

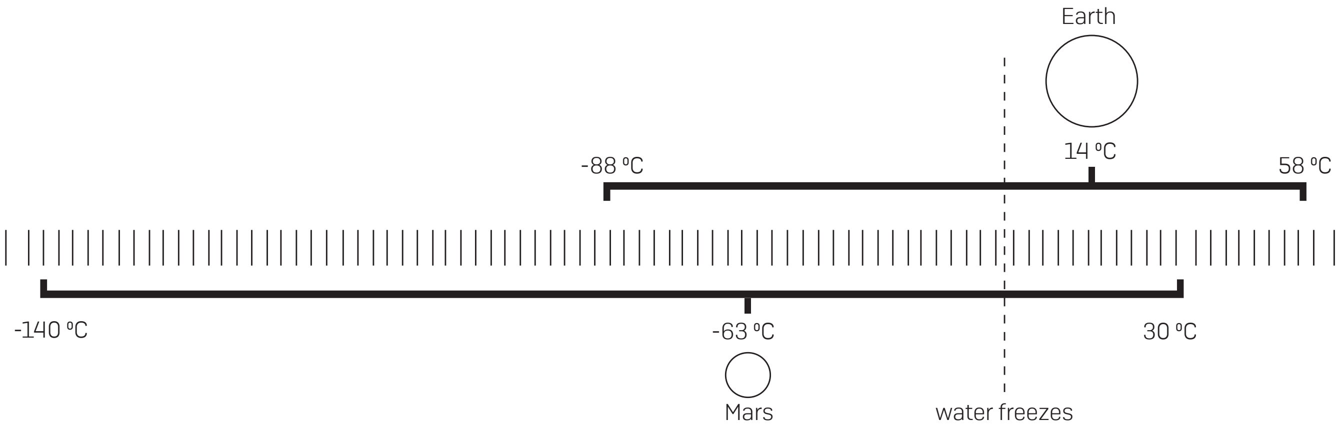


Table 5: Mars and Earth temperature comparision

with high hydrogen content (such as using water or ice as shielding: Hinterman et al., 2022; Morris et al., 2016) generally perform well against radiation. Other options include covering the Martian habitat with a thick layer of soil, or using Martian landforms to place the Martian habitat underground.

Temperature

The changes in temperature that we normally experience in desert environments with arid climates on Earth, are unbelievable on Mars. The fact that Mars has had a very thin atmosphere since the Hesperian-Amazonian transition means that it is unable to evenly distribute the temperatures it already has. This means that a planet without a blanket feels warm when you blow it with a hairdryer, and cold when you don't. If we call the hairdryer the sun, it is day and night whether the hairdryer is working or not.

Without proper protection, temperature fluctuations on Mars are too high for living things to survive (Häuplik-Meusburger, 2011; Häuplik-Meusburger, S. and Bannova, O. 2016). Temperatures on Mars can be as high as 20 degrees Celsius or as low as -153 degrees Celsius, but average daily temperatures vary between -120 C and -20 C (Howe and Sherwood, 2009). The average surface temperature is around -60°C (Hollander, J. B. 2023).

These changes naturally place thermal loads on the structure and good insulation is essential to protect the habitat from these extreme cold temperatures.

Gravity

The invisible force of nature known as gravity shapes our existence on Earth. Since mass is a property of an object, it is the same everywhere in the universe. However, the cause of mass is gravity. But it is the gravitational force between the object and the Earth. This acceleration, known as 1G, is about 9.8 m/s^2 on Earth. (Häuplik-Meusburger, 2011).

Mars' gravity is lower than Earth's, objects with mass will fall to the Martian surface at a slower rate. The gravitational force on Mars is on average 38% of that on Earth, or 3.71 m/s^2.

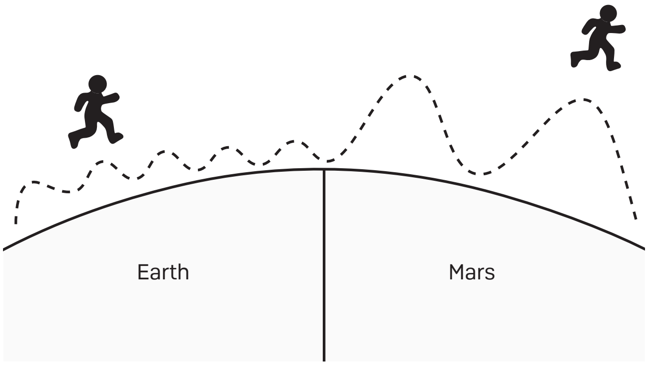


Figure 4 : Mars and Earth Gravity comparision

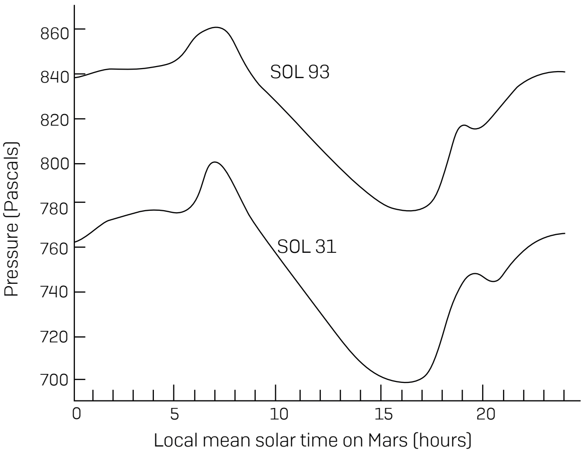


Table 6: Pressure on the surface of Mars

In this case, 10 kg on Earth will correspond to 38 kg on Mars on average, and this will play an important role in calculating the weight of the structure when designing Martian structures.

Pressure

Another important value is the atmospheric pressure of Mars. An atmosphere that has been very thin and low density for a long time cannot be expected to have a high pressure. However, the atmospheric pressure on Mars varies seasonally and geographically by 20% throughout the year (Barlow, 2008), but is nowhere near the desired values. Data recorded by the Rover Environmental Monitoring Station on NASA's Curiosity rover show that atmospheric pressure averaged between 0.9 kPa and 0.007 kPa over 62 Martian days (Pressure Cycles on Mars - NASA Science, n.d.).

These values are far from the pressures we are used to. As we explained in the previous section, the microgravity environment eliminates the physical comfort of the normal 'up-down' orientation and makes the traditional method of space allocation obsolete. It is clear that artificial gravity, i.e. pressure, will have to be applied to any area where people will live. Since, the atmospheric pressure on Earth is 101 kPa, the atmospheric conditions we are used to will require a pressure of 101 kPa inside the habitat. While the outside of the habitat is generally 0.7 kPa, the inside will be 101 kPa. This will, of course, put incredible stress on the structure.

Micrometeorites

Similar to the other environmental factors mentioned above, the reason for this problem is that the Martian atmosphere is not thick enough. The Earth's atmosphere burns meteoroids and micrometeorites up to a certain size, preventing them from reaching the surface. (It cannot completely destroy anything larger than a certain size: for example, it fell on the Yucatan peninsula 66 million years ago, forming the Chicxulub crater). However, the same cannot be said for Mars. Mars is vulnerable to micrometeoroids because of its thin atmosphere.

Small meteoroids or micrometeoroids are very small pieces of rock or debris that have the ability to travel very quickly in deep

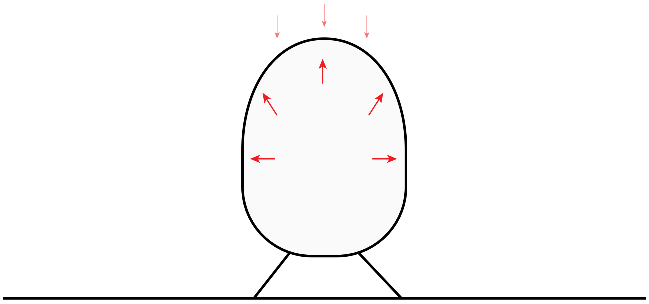


Figure 5: Class I Habitat

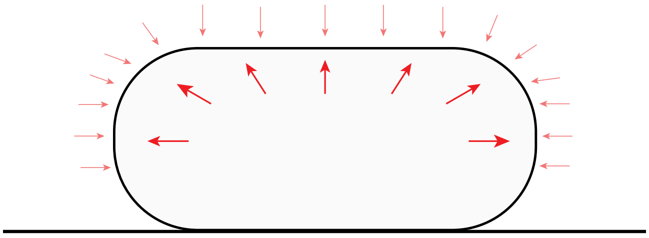


Figure 6: Class II Habitat

space, posing a serious risk of damaging the surface of the space habitat (Häuplik-Meusburger, S. 2011). Micrometeorites pose a major threat to planned habitats as they will cause deformation in the habitat as a result of possible impacts. For this reason, the outer surfaces of habitat designs must be resistant to these future micrometeorite impacts.

Global dust storms

We think some people will wonder why we haven't included wind in this section. This is because in the low atmospheric pressure of Mars, wind is not such an important factor for structures. But the same cannot be said for the global sandstorms caused by winds that we explained in the first section.

Global sandstorms can start locally, especially in summer and spring, and cover all parts of the planet for a long time. If these grains of sand, which vary in size, penetrate the habitat, the result will be catastrophic. As the Martian soil is prone to radon exhalation, it is important to completely seal habitats (Lévy & Fardal, 2010). In addition, this is a very important issue for the operation of equipment planned to be semi-exposed outdoors. If the solar panels installed in the habitat are covered with dust, this will obviously lead to energy problems, which is a very dangerous situation on a planet like Mars.

For this and similar reasons, it is very important to design structures that are resistant to dust and sand-like particles brought by global sandstorms.

1.3 I Structure Types

Space mission classifications for human space missions to Mars occupy an important place in the classification in this section. Classifying space structures according to this classification allows the structures to be understood according to the purpose of the space mission (Kennedy, 2002).

There are different alternatives with different technologies as a solution to the extreme environmental conditions on Mars that we mentioned in the previous section, and they all have positive and negative aspects. They all differ according to the purpose, duration

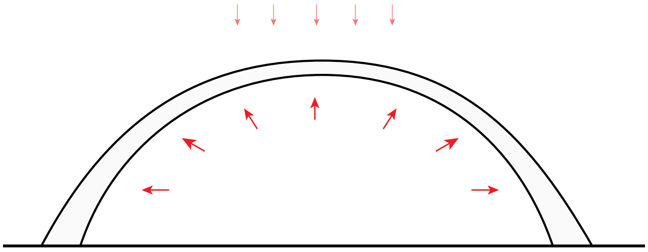


Figure 7: Class III Habitat

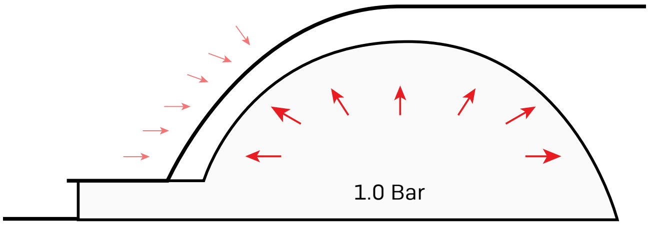


Figure 8: Habitat inside the lava-tubes

and budget of the human mission to Mars. The only thing that does not change is the steps that need to be taken to establish a colony on Mars and, ultimately, the scenario of establishing a Mars settlement independent of Earth or any other celestial body.

Class I

The early spacecraft engineers and designers did not use the term "habitability" or any other notion that might be used to characterize how suitable the environment was for everyday human living. Their frequently employed phrase "man in a can" emphasizes this mindset. (Häuplik-Meusburger, 2011) Most likely, the first Mars travellers will be part of a short-term mission in a tin-can landing on the surface of Mars. These structures, known as Class-1 as pre-integrated (Kennedy, 2002), are hard-shell structures (Fig.5) made from Earth materials and are completely dependent on Earth.

Class I habitats are pre-integrated - fully assembled, integrated, function-tested and ready for use on delivery (Howe & Sherwood, 2009). The pre-integrated "Tuna Can" rigid module designed by John Frassinito and Associates in 1993 is one such example (Cohen, 2002). On the other hand, given the difficulty of transportation costs, these are the buildings that do not offer us the possibility of a large settlement area, which we will only consider in our first step.

The International Space Station (ISS), whose individual modules are pre-built on Earth before being launched and integrated in orbit, is the best example of the tin-can approach to space habitat design. The ISS's modular tin-can design, which permits gradual expansion and alterations, has allowed for the continuous presence of humans in space for more than 20 years. But it is important to remember that this is not a planetary habitat, the ISS is an orbital habitat.

For this reason, it is relatively easier to grow, shrink and change its configuration over time than a structure to be built on the surface of Mars. It goes without saying that the ISS wasn't the first orbital home; in fact, it would be unthinkable without its predecessors, such as MIR and Skylab, which allowed it to function for more than 20 years despite numerous repairs and modifications. In addition to promoting international cooperation

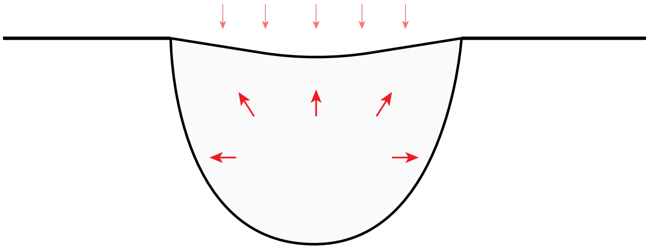


Figure 9: Habitat inside burying in the inner walls of the crater

in space exploration, the International Space Station (ISS) acts as a testing ground for research and technology essential to deep space missions in the future. Although it facilitates the gradual upgrades and expansion, it is always made on Earth.
Now let's take a hard-shell space habitat like the ISS to the surface of Mars. As mentioned above, the spacecraft, which will be connected to the Mars Transfer Spacecraft (in-space habitat), which is also part of NASA's Mars plans and will orbit Mars, will land on the surface of Mars together with the lander on the Mars Transfer Spacecraft. It is likely that this lander will also serve as their habitat for the limited time they remain on the surface of Mars.

We haven't mentioned it here before, but since the launch window for Mars missions opens on average every 2 years and the journey takes 6 months, it will be necessary to either stay on the surface of Mars for a very short time and return, or we can build structures as explained in the next sections and predict the launch time on the surface of Mars 2 years later.

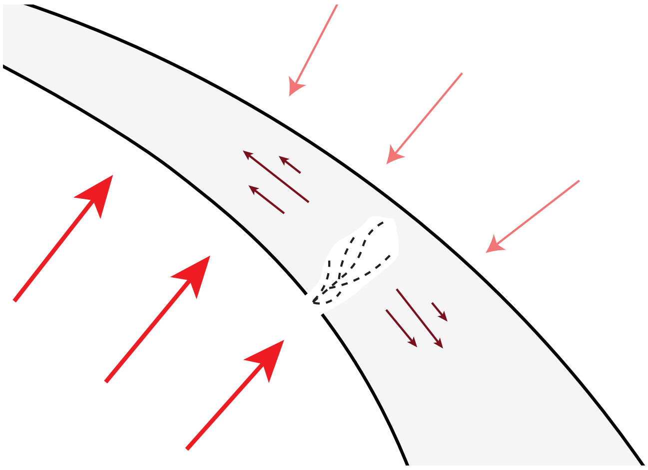


Figure 10: The internal pressure pushing the structure

Class II

Prefabricated habitats will be Class II. However, when deployed in space or on the surface of a planet, they will need to be expanded, equipped or assembled (Howe and Sherwood, 2009). Inflatable and deployable modules to be placed on the surface of Mars are a good example of this. (Fig. 6)

Inflatable modules often offer a major advantage in terms of volume. While they take up very little volume when transported to their destination, their volume increases significantly before reaching their destination (Häuplik-Meusburger and Bannova, 2016). One of the pioneering designs in this category was the inflatable wheel-shaped space station developed by Goodyear Aerospace Corporation in the early 1960s (Haeuplik-Meusburger & Ozdemir, 2012; Häuplik-Meusburger & Griffin, 2021). Then NASA's TransHab module or the Inflatable Lunar Habitat model at Langley Research Center are some good examples of inflatable structures that are often designed with rigid sections for space applications. Rigid sections often house life support systems or other necessary equipment and act as a foundation for other structures, while the inflatable section significantly increases the volume inside.

These lightweight, low-cost, box-packable structures are made of woven, reinforced polypropylene fabric. They are easier to transport than tin cans for field installation (Zubrin, 2008).

These Earth-like structures eliminate some extreme hazards using the techniques we are used to and, of course, more familiar with, but their sealing against pressure has always been a matter of debate, and their long-term radiation protection is also questionable and, unfortunately, the most negative aspect for a long-term, sustainable Mars settlement. They are dependent on Earth.

Class III

A sustainable, long-term, permanent Mars settlement should be built with Martian materials as the dominant majority and as independent of Earth as possible. These are referred to as Class III structures (Fig. 8), an in-situ derived habitat where the structure is fabricated using locally available resources (Kennedy, 2002). Class III habitats would be produced in situ, with the structure fabricated using local resources developed on Mars (Howe & Sherwood, 2009).

Building structures from Martian soil is well documented in the literature, but designing a structure that can withstand the extreme environmental conditions of Mars and the loads created by the structural differential caused by the internal air pressure being much higher than the external air pressure is a very difficult process, but the aim is to design a durable structure using Martian soil without transferring any material from Earth.

One of the class III examples, Lava Hive, is a modular, additively manufactured Mars habitat concept using recycled spacecraft materials and structures, using a proposed new ‘lava casting’ construction technique (Cowley et al., 2016). The existing surface material on Mars, called regolith, uses the abundant energy of the Sun to power the construction of structural elements for habitats. The Lava Hive is a good example of a self-contained habitat that is independent of Earth. It is fabricated in-situ using space resources, with all internal finishes made in space, and is space-built and space-tested, allowing large volumes to be built.

1.4 I Main Structural Problem

All the form-giving factors that we have tried to explain above must be solved by different mechanisms because of the categorisation of the structures. Classes I, II and III have different and similar techniques for dealing with these problems. However, the address for a sustainable Mars settlement is clear in every respect. Metal rocket ships and inflatable habitats are not a permanent solution to dealing with the harsh environment of Mars (Petranek, 2015).

If one tries to design a structure with Martian materials that tries to be as independent from Earth as possible, which is the main subject of this research, some form-giving factors become more important. For this, it is important to know the limits of the available Martian materials and construction techniques. As we have not yet reached the section on Martian materials, we will have a preliminary introduction.

How can we design a structure that can withstand the factors mentioned above, such as radiation, pressure difference and temperature difference, using only Martian materials? As we mentioned in the first part, Mars is a planet whose surface is made up of volcanic rocks, and therefore materials such as sulphur and basalt are most abundant on its surface. However, those familiar with materials will know that although the compressive strength of these two materials is satisfactory for certain applications, their tensile strength is not.

Form giving factors such as radiation, temperature difference or micrometeroid can be overcome by certain techniques, but how can a structure be designed to resist pressure without introducing an inflatable or pre-integrated hard shell into the habitat? The answer to this question is the approach that has been gaining ground recently and is the right one. When designing a Class III structure for a sustainable and permanent Mars settlement using only Martian materials, the dominant load and therefore the dominant form-giving factor is pressure (Järvstråt & Toklu, 2004; Yashar et al., 2019).

As we all know, the human body needs an atmosphere of the right composition and pressure to sustain life processes (A & O'Neill, 2004). On the other hand, the pressure of 101 kPa - to which the pioneer 'Martians' in the Mars Settlement are accustomed - will push the outer shell of the settlement towards the pressure of 0.6 kPa on the surface of Mars, creating a load and stress on the shell structure (Fig.10). It is clear that for these structures to be stable, the mass on top of the structure must be greater than the mass underneath. Although settlements within craters (Fig.9) or within suitable lava tubes (Fig.8) seem to come close to solving this problem, they have many operational problems.

Apart from the problem of not being on the surface, the stabilisation of lava tubes on the surface of Mars has not been the subject of much research. Obviously, the living area should be located in a place that more or less meets all the requirements. There will be sites close to scientific research areas and water, where there is suitable Martian soil to produce Martian material of sufficient strength, where the energy from the Sun is maximised, where the least amount of fuel is required to return to Earth, etc. There are many requirements to be considered and, in principle, subsurface settlements will exacerbate these operational problems. These reasons again emphasise the importance of being able to build structures that can stand alone and are completely independent of the Earth, but these structures currently face some engineering problems.

The fact that the internal pressure is greater than the external pressure is the exact opposite of the structural principles we are used to on Earth, where structures are designed to resist lateral and vertical loads as well as their own weight under the influence of gravity. Whereas on Earth structures deteriorate towards the ground, on Mars they will deteriorate towards the atmosphere.

It has been shown that concave structures such as domes, which we are accustomed to on Earth and which are designed to resist loads from their own weight alone under the influence of gravity, will have to work by the opposite logic on the Martian surface and have a convex shape, which will better distribute the stresses resulting from internal pressure within the structure (Soureshjani et al., 2023; Pavese et al., 2023).

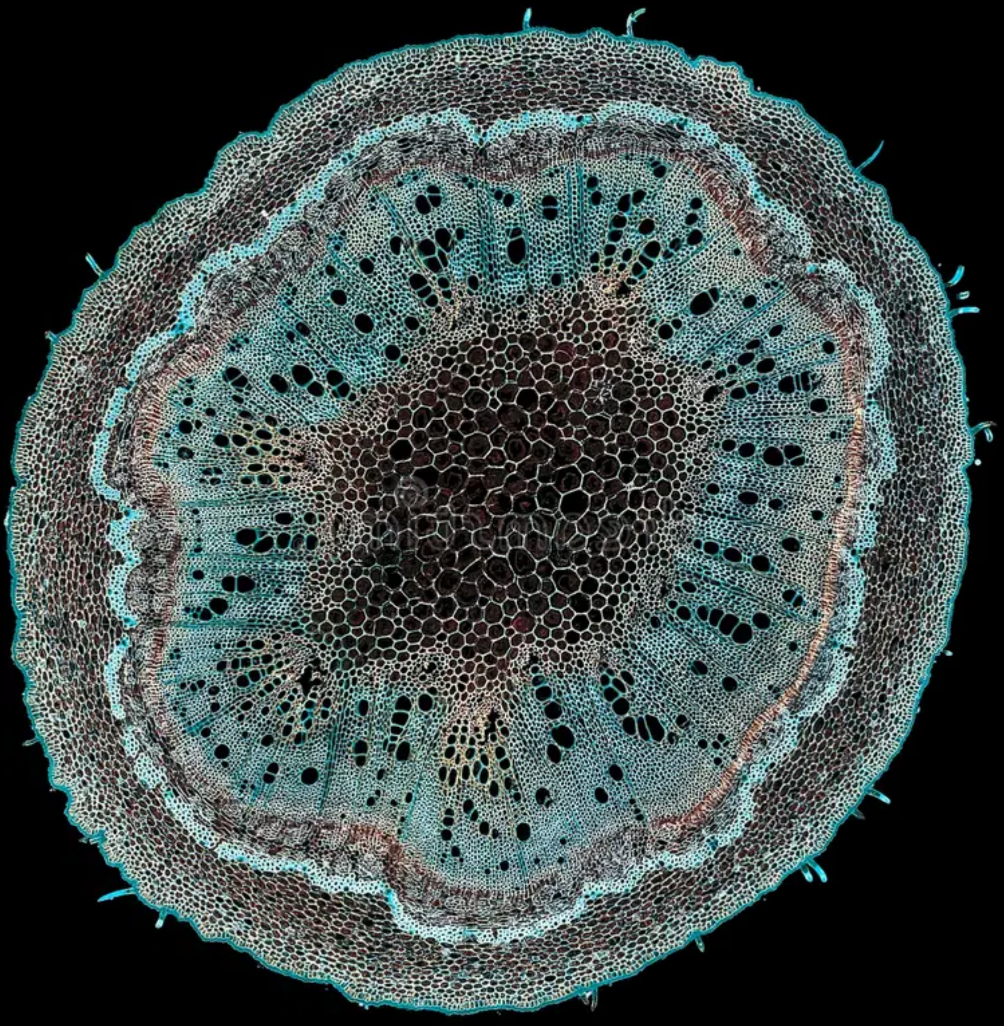
Even if the shape of these structures becomes more suitable for distributing internal pressure loads, they will still need to be supported by high-strength materials. At present, it appears that only Martian materials will be able to withstand the loads and stresses that occur when the internal pressure is much higher than the external pressure. In fact, although the compressive strength of the Martian soil materials is good, their tensile strength is much lower than expected. However, it is possible that problems could arise during the production phase of these structures if the pressure balance cannot be achieved during the layer-by-layer construction process of 3D printing, with risks such as collapse or cracking. Designers have also been tackling this issue recently, with the 3D Printed Habitat Challenge organised by NASA providing valuable input.

Studio Hassel placed an inflatable underneath the shield structure, which only protects against radiation from factors such as micrometeorites, as a shelter made from Martian soil would crack due to the difference in internal and external pressure and would lose its sealing environment over time. In the same challenge, Mars X-House 2, another valuable proposal from SEArch+, approached the problem of pressure in a more complex way, both by designing the walls of the structure inspired by dams, and by using layered options to increase the tensile strength of the structure (Yashar et al., 2019).

AI Space Factory also turned its attention to solving the pressure differential problem for the Marsha project, winning the NASA 3D Printed Habitat Challenge. Marsha's distinctive egg-shaped design with vertical orientation minimises mechanical loads at the top and bottom, which increase with diameter, while maintaining a small footprint (MARSHA - AI Spacefactory, n.d.). Marsha uses a novel double-shell design to protect habitable areas from structural stresses caused by the wild temperature swings of Mars. AI Space Factory used polylactic acid (PLA) and basalt fibre in pelletized polymer composite concrete. PLA, basalt fibre and the blend can reach their maximum strength and have a low coefficient of thermal expansion while providing radiation protection, an advantage given Mars' temperature swings (Mueller et al., 2019).

Both are prime examples of Class III habitat, focused on printing in both form and use of materials, and produced on-site with space resources. But on the downside, we have legitimate doubts about how detached Marsha is from Earth, especially when it comes to materials.

As we can see, there are currently many engineering problems involved in building a sustainable, self-sustaining structure on Mars that is independent of Earth and made only with materials from the Martian soil. To design in extreme conditions such as the Martian surface, it is necessary to know how nature works and to consider the efficient and optimal structures that nature offers. It is necessary to look at the realistic solutions that nature has created for these extreme conditions and the biological harmony it has developed. This is where biomimicry comes in, which we will explore in the next chapter, inspired by living organisms that for millions of years have tried to build the most suitable and efficient structures for the environmental conditions in which they live. Of course, biomimetic approaches to solving this problem can face the problem of scale transfer (Gruber et al., 2007), but this problem will be overcome by using the form-finding method in later chapters.



Part 3
Nature as a Guideline

The biomimetic approach on the surface of Mars aims to harness the creativity of nature's designs to meet the unique challenges of survival on Mars. By studying organisms and ecosystems that thrive in harsh environments on Earth, they can develop innovative solutions to build sustainable habitats, produce resources and protect human health in the harsh Martian climate. Biomimicry not only provides a blueprint for building habitats that can withstand the harsh weather and radiation of Mars, but also inspires sustainable practices. In this chapter, we will examine biomimicry and which organism we are using as a model for structure on the Martian surface.

3.1 I Billions of Years of Optimized Design

''There is no extra or coincidental development in nature.''

Janine Benyus

Nature, a self-regulating system of matter and energy, continually improves itself by solving problems and eliminating those that cannot adapt to changing conditions. The living things in nature are the result of 3.8 billion years of biological evolution, a process that shapes and influences all aspects of life. This evolution, driven by the competition for limited resources, ensures that the best-adapted individuals have the best chance of survival and reproduction. Nature, characterized by biological evolution, does not follow an anthropocentric perspective, cannot think and act teleologically (Knippers, 2019).

Being curious about nature is an element that has existed since ancient times. Many philosphers have worked on understanding nature and the universe. Thales, one of the pioneers of this curiosity, argued that the basic substance of the universe was water and tried to understand the components of nature with this view. Anaximander put forward his thoughts on the origin of the universe and the basic elements of nature. Aristotle, on the other hand, developed a systematic scientific approach by making detailed observations to understand the functioning of nature. While Heraclitus argued that nature was in constant change and flow, Empedocles defined the four basic elements (earth, water, air and fire) as the basic components of nature. These thinkers not only tried to explain nature, but also formed the cornerstones of philosophical and scientific knowledge by taking inspiration from its order and functioning. The tradition of drawing inspiration from nature was shaped by the works of these great thinkers and nourished humanity's hunger for knowledge.

Although Darwin put forward the theory of evolution, this process's foundations were laid by a body of knowledge from ancient times. Carl Linnaeus developed a classification system (taxonomy) for living things in the

18th century. Jean-Baptiste Lamarck suggested in 1809 that living things evolved by adapting to their environment and that these characteristics were hereditary. By examining the fossil record, Georges Cuvier argued that species became extinct and were replaced by new species. James Hutton and Charles Lyell stated that geological processes are slow and continuous and that these ideas can also be applied to biological changes. Alfred Russel Wallace independently discovered evolution by natural selection and shared his findings with Charles Darwin. Gregor Mendel's works, published in 1866, provided the genetic basis for the theory of evolution by explaining the laws of inheritance and genetic variation. In his work "The Origin of Species," published in 1859, Darwin established the theory of evolution on a solid basis by supporting scientific evidence that species change and evolve through natural selection. Darwin's book changed the world's view of living nature. Within a few years, his theory was accepted by the scientific world for its logic and provability (Gruber, 2011).

Life evolves as organisms interact with their environment. Organisms have transformed rocks and the sea into a life-friendly home with constant temperatures and smoothly floating cycles. In short, living things have done everything we want to do without consuming fossil fuels, polluting the planet, or mortgaging their future (Benyus, 2002).

Self-organization is characteristic for all processes in nature, and is important for the creation of living forms as well (Gruber, 2008). An organism needs minimum resources to survive and reproduce, and the resources that any population can use in the long term are limited. We couldn't ask for better systems to compare nature's designs with human inventions. Nature's technology occurs on the surface of the same planet as human culture, so it relies on the same physical and chemical limitations and must use the same materials.

Life has been able to survive on its own for millions of years thanks to the process of evolution and the ensuing adaptations (Mazzoleni,2013). A fundamental feature of evolutionary processes is the power of innovation, which constantly produces surprising new results. However, the expanded scope and speed of human activity has unidentified effects on the delicate systems that support the survival of all species, including our own.

Currently, there is a growing and pressing need to reduce the environmental impact of human activity (Myers, 2018). This suggests that evolutionary approaches to design may also lead to the search for new solutions (Knippers, 2019). Sustainable design, a way to harmonize manufactured structures with the natural environment, is becoming increasingly important in the field of architecture. Biomimicry, by seeing nature as a source of functional and aesthetic solutions, can help us change our perception and design more sustainably (Mazzoleni,2013).

3.2 I A Brief History of Biomimicry

Derived from the ancient Greek words mimesis, meaning imitation, and bios, meaning life, biomimicry is the study of biological processes and mechanisms, as well as the formation, structure, and function of biologically produced materials and substances. It focuses on artificially mimicking natural mechanisms to synthesize similar products. The term 'biomimicry,' which first entered the scientific literature in 1962, gained popularity, especially among materials scientists in the 1980s. It involves studying

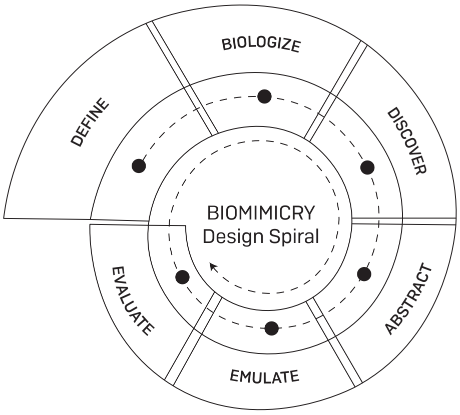


Table 7: Biomimicry Design Spiral

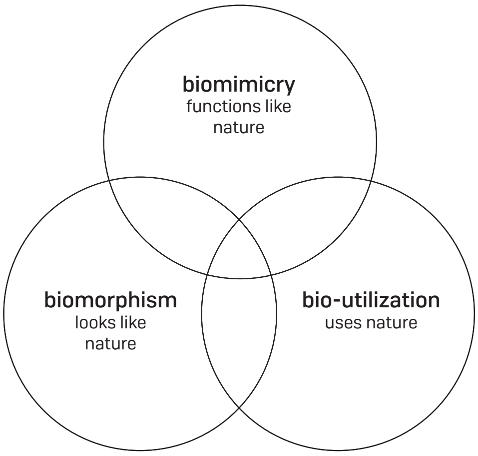


Table 8: Antoni Gaudi hanging chains

and imitating solutions that have evolved in nature over millions of years to solve human problems, improve technology, and create sustainable designs. Even in Greek myths, we see Deadlus, inspired by birds, making wings using feathers and wax to save his son. When we look at Egypt, we see that the column capitals of the Luxor Temple are made of sandstone and imitate the bud of the papyrus tree. This historical context connects us to a long tradition of innovation always inspired by nature.

Collectively, creatures have transformed the sea and rocks into a home for life, with stable temperatures and easy-floating cycles. In short, life has achieved everything we could ask of it, without over consuming fossil fuels, destroying the environment, or endangering its future (Benyus, 2002). This brings us to the question of what superior models might be available? The question must not be what we can extract from nature, it must be what we can learn from nature. (Table7)

Biomimicry, Biomorphism, Biometics

While Julian Vincent defines the discipline as 'the application of good design based on nature', for Janine Benyus it is defined as 'the conscious imitation of nature's genius'. 'Biodesign' is a term that originated partly in the medical world (the invention and application of new biomedical technologies), partly in the field of robotics, and partly as a broad definition. The point made in adopting a new term is that both 'biomimicry' and 'biomimetics' imply replication, while 'bio-inspired' is intended to include the potential to develop something beyond what exists in biology. Michael Pawlyn explains his adoption of the term biomimicry by seeing 'bio-inspired architecture' as a very broad definition that includes everything from superficial imitation of form to scientific understanding of function and how this can inspire innovation. Biomimicry and biomimetics are now widely understood as functionally based approaches (Pawlyn,2016).(Table8)

Biomimetic discipline evolved in the intersection between the life sciences and engineering (Gruber & Benti, 2013). Biomimicry, which is also referred to as biomimetic, bionic, bio-inspirations, and biognosis, is a scientific term that refers to the process of modifying natural systems and industrial design in order to produce new types of products (Khoshtinat, 2015). There are other terms worth clarifying, such as 'biophilia,' 'biomorphic,' 'bio-use,' and 'bioinspiration.' 'Biophilia' is a term popularized by biologist E. O. Wilson and refers to an instinctive relationship between humans and other living organisms. It expresses the hypothesis that there is a connection. 'Biomorphic' The study of how living things, including their organs, tissues and cells, are assembled and arranged (Gruber,2011).

'Bio-use' refers to the direct use of nature for beneficial purposes, such as using vegetation in and around buildings to produce evaporative cooling. Bioinspiratin, on the other hand, is the most general expression of design inspired by natural role models, including all levels of abstraction as well as purely morphological interpretations (Gruber,2011).

There is a very thin line separating the concepts stated above, therefore no single term can adequately capture what we accomplish (Pawlyn, 2016). Instead of arguing over the issue, as in any negotiations, it is preferable to reach an understanding on points of agreement that bring the disciplines together, such as being interdisciplinary, evidence-based, functionally focused, and dedicated to bringing about transformative change. It is crucial. The study and emulation of functional strategies to produce sustainable solutions is the hallmark of biomimicry.

As Steven Vogel points out, this interdisciplinary field covers a wide range of disciplines, from engineering to architecture, materials science, and medicine. It establishes a deep connection between the genius of nature and human creativity. Additionally, as Vogel points out, natural structures also have other critical architectural features. They are sturdy; They can survive unpredictable events without losing their balance. They can repair themselves when damage occurs. In the context of evolutionary adaptation, they can adapt to changing mechanical forces and climatic conditions both day, year, and throughout their lives (Vogel, 2000).

3.3 I Biomimicry in Architecture

Why has humankind felt the need to protect nature since ancient times? The beauty, power and immensity of nature are an inexhaustible source of inspiration (Hoornaert et al., 2020). Natural life forms distinguish themselves by the multifunctional design of structural elements and functional groups for various needs (shelter, temperature, thermoregulation, energy processes, transportation, movement, and growth). There are countless examples and varieties of tasks performed by nature. There is a deep connection between the genius of nature and human creativity.

Providing a new perspective on innovation by harnessing biodiversity and promoting a healthy coexistence between human progress and the wonders of the natural world allows designers to gain new insights and apply their techniques more successfully by carefully observing nature and using it in their creative processes. Although human needs and problems change over time, people have always learned problem-solving techniques from nature. Many models of human problem-solving in nature have been used as teaching tools for many years.

Looking into nature's eyes takes our breath away and bursts our bubble (Benyus, 2002). We know that all our inventions already exist in nature, but in much more elegant forms and with much lower environmental costs. As Steven Vogel points out, this interdisciplinary field covers a variety of disciplines, from engineering to architecture, from materials science to medicine (Vogel,1998).

The relationship between biology and architecture and the origins of biomimetics in architecture lie in the design of innovative initiatives (Gruber,2011). Structures seen in nature nearly immediately satisfy the fundamental requirements of future architecture (Pohl, 2015). Our most ingeniously designed architectural beams and columns are already embedded in bamboo stems and lotus leaves. Once considered a uniquely human invention, our central heating system was discovered in the microscopic rotating engine that powered the flagella of the first bacteria on the planet.

Nature provides an endless source of 'living structures' that resemble architecture in form and function. These structures have influenced architects throughout history and today. Additionally, as Steven Vogel mentioned, natural structures have other critical architectural features such as they are sturdy; They can survive unexpected events without losing their balance. They can repair themselves when damage occurs. In the context of evolutionary adaptation, they can adapt to changing mechanical forces and climatic conditions both day, year, and throughout their lives (Vogel,2000).

Pioneers of Biomimicry

This adaptability of natural structures, their ability to withstand and even thrive in changing conditions, is a testament to the resilience of nature give inspire to designer and especially architects.

Utilizing instruments taken from the art world, science advanced. The finest naturalists in history, including Ulisse Aldrovandi (1522–1605), Konrad Gessner (1516–1565), and Leonardo da Vinci (1452–1519), created incredibly insightful drawings (Mazolleni, 2013).

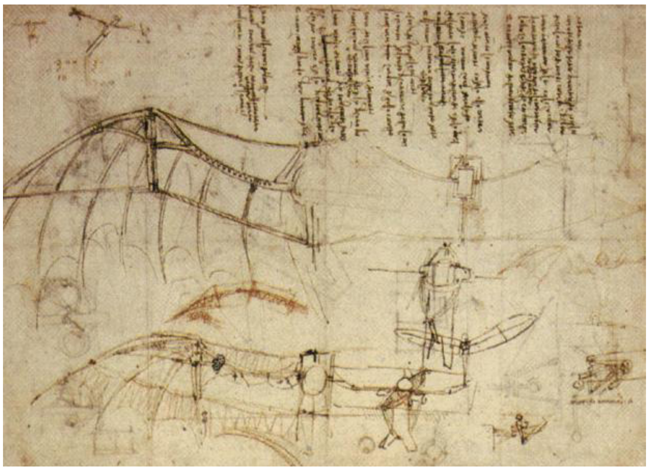


Figure 11: Leonardo da Vinci's drawings

In the modern era, biomimetics or "learning from living nature for technical solutions" began with Leonardo da Vinci (1452–1519) (Knippers et al., 2019). (Fig.11) His philosophy of biomimicry was based on a profound respect for the engineering of nature, as he felt that a better understanding of natural shapes and processes may result in better human-made solutions. Leonardo da Vinci, a genius of his time, studied how birds fly and proposed designs of flying machines (Bhushan,2016). Da Vinci's works established the foundation for contemporary biomimetic design, exemplifying how a close study of nature can lead to breakthroughs in both art and technology.

We should also mention Otto Lilienthal and the brothers Wilbur and Orville Wright, who followed Leonardo's footsteps. Lilienthal was one of the most famous pioneers of human flight and studied the flight of storks in particular to improve his devices (Gruber, 2011). By combining this knowledge with their own skills, Wilbur and Orville Wright brothers managed to achieve the first powered human flight at Kitty Hawk, North Carolina, in 1903. Their accomplishments spurred the swift advancement of powered flight.

Simon Schwendener inspired structural biomimicry by analyzing the mechanical structure of plants; Ernst Haeckel brought an aesthetic dimension to biomimicry by depicting forms in nature in an artistic and scientific way (Gruber,2011). While Haeckel marveled at the variety of forms found in marine organisms, especially the skeletons of radiolarians, which are composed of silica and strontium sulfate and form deposits several meters thick on the sea floor, his aim was actually a general classification of all life forms. He was not successful for many reasons, but his research and drawings had a huge impact, including on architects and designers.

Karl Blossfeldt pioneered the use of natural forms in design by photographing the microscopic structure of plants; Johann Gerhard Helmcke and Werner Nachtigall explored nature-inspired structures in biomimetic engineering. It is also worth mentioning "On Growth and Form", which discusses questions about how form develops in organisms, of which radiolarians and some higher animals and plants are examples. Published in 1942 by D'Arcy Thompson (Gruber,2011). While still considered a bible for the development of the form and structure of living organisms, his work is an inspirational resource that is carried forward through the discipline of mathematical biology, which investigates spatiotemporal pattern formation in biology.

Fuller, who designed innovative structures such as the geodesic dome, inspired by the principles of efficiency and durability in nature, demonstrated the applicability of geometric shapes and structural principles in nature in architecture. (Fig.) His geodesic domes are optimal for the relationships between volume and weight, efficient use of material and floor area, and as a demonstration of liberation from the ubiquitous right angle (Gruber,2011). In particular, geodesic domes are known for being lightweight yet extremely strong and durable, similar to cell structures in nature. Fuller's work has shown how more sustainable and efficient structures can be created by integrating optimized forms and processes of natural systems into human-made designs. Through this dome, Fuller was the first to explain the tensegrity principle, and we will talk about the tensegrity principle in detail in the following sections.

Figure 12: Gaudi

Pier Luigi Nervi designed innovative reinforced concrete structures, inspired by the aesthetics and functionality of natural forms and structures. Integrating the efficiency and durability of organic shapes in nature into engineering projects, Nervi used the tensile strength of concrete in his work to create thin-shelled structures and ribbed plates that can spread over large areas without the need for internal supports. These

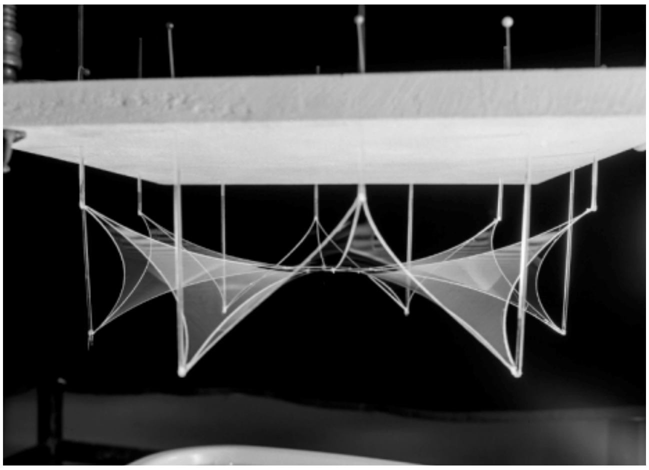


Figure 13: Frei Otto soap bubble

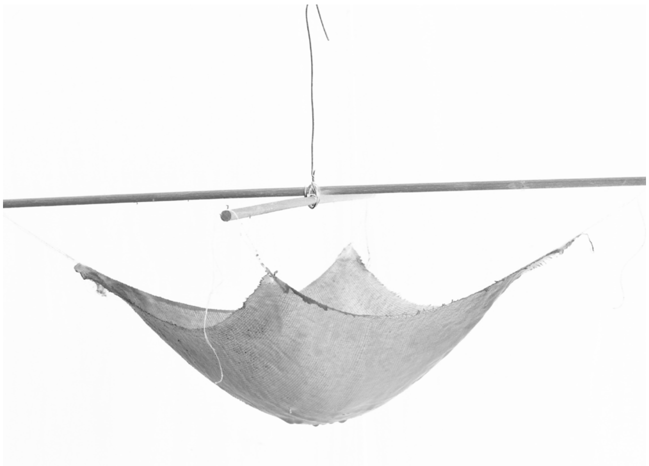


Figure 14: Heinz Isler

designs maximized the material’s ability to cope with tensile stresses, allowing for lighter, more elegant structures that maintained its strength and stability. Nervi’s designs carefully consider how natural forms distribute and balance tensile and compressive forces. He created remarkable works, both aesthetically and structurally, using design principles inspired by nature, especially in his buildings such as the Palazzetto dello Sport in Rome and the Palazzo del Lavoro in Turin. Nervi’s success in adapting structural systems in nature to modern architecture demonstrated the applicability and potential of biomimicry in architecture.

Antoni Gaudí has been recognized as one of the best practitioners of biomimicry, applying nature’s principles of efficiency and durability to architecture, creating structures that are both aesthetically and structurally innovative and sustainable. Gaudí took an experimental approach and suspended defined weights on a network of cables to define the shape of the beams and vaults and used the deformed model as the basis for the building’s design. (Knippers et al., 2019) Gaudí’s vine model is an innovative method he used to develop nature-inspired architectural solutions. To create this model, Gaudí created a weight net using ropes or chains. (Fig.12) When he reversed this network, it naturally reached the optimal structural form. With this method, he created forms that naturally distributed weights and tensile forces in his architectural design. The hanging model reflects the naturally occurring curvilinear and organic forms by balancing the forces at every point of this network shaped by the effect of gravity. The most famous application of this model is the design of the Colonia Güell Church in the Sagrada Familia. Here, Gaudí combined complex structural forms with a natural balance, creating a structure that is aesthetically and functionally superior. The vine model clearly demonstrates Gaudí’s ability to innovate in nature-inspired architecture and his contributions to biomimicry, and will be revisited in terms of tensegrity in the following chapters.

Striving to understand the functional foundations of natural forms and construction processes in collaboration with biologists such as the botanist Johann-Gerhard Helmcke or the zoologist Werner Nachtigall and other experts, Frei Otto studied the principles of lightweight and durable structures in nature and applied tensile structures and membrane systems in architecture (Pohl & Nachtigall, 2015). Working with minimal energy surfaces (soap film models), Otto's group employed an experimental approach to understand natural structures and processes, and then apply proven physical laws to create new structures. The result was the invention of membrane structures (Gruber,2011).

A similar strategy was used much earlier by Antoni Gaudi, as mentioned above. Otto's hanging model is an important method he used to discover the architectural counterparts of light and durable structures in nature. Otto experimented with flexible materials such as ropes, fabrics, and soap films to study the natural distribution of tensile forces. (Fig.13) The models he created using these materials were suspended under the influence of gravity, and the most efficient structural forms were created by assuming minimum energy configurations. This method allowed Otto to develop optimal designs both aesthetically and structurally.

The transition from lightweight structures, which Frei Otto described as "natural structures," to integral buildings is seamless. The more complex the solution to meet many demands on a single structural element, part or building, the more one can speak of "integrative biomimetic principles". This approach has made it possible to develop sustainable and innovative architectural solutions inspired by nature. It is still used by Heinz Isler, who has been developing experimental form-finding methods for decades using suspended models made of various materials to build temporary shell structures (Gruber,2011).

Antoni Gaudi, Frei Otto and Heinz Isler discovered an easy method to take advantage of the catenary phenomena. A chain linking two locations will follow the minimal energy state of the system, known as the catenary curve, under the continuous force of its own weight. The ideal load transfer curve can be found by reversing this. In this approach, suspended models can be used to identify organic shapes in situations involving only normal forces (Gruber,2011). In the case of Heinz İşler, the form is even produced with hanging chains; the catenary curves' perpendicular coordinates were marked. In the thought experiment, "welding" and "reversing" the dangling chains together at their intersections creates a shell like that. This procedure produces a shell that can support itself. It might be the only option to build the structure so that compressive pressures are concentrated at the supports. Of course, function ultimately determines the layout's form and design (Nachtigall and Pohl, 2015).

Heinz Isler also created textile hanger models along with Frei Otto's creations (Gruber,2011). (Fig.14) Isler was inspired by forms in nature in the design of thin-shelled concrete structures and used textile fabrics to obtain shapes that naturally distribute tensile forces. In this method, he suspended flexible textile materials, allowed them to take shape under the influence of natural gravity, and created concrete shells by using these shapes as moulds. This process mimicked minimal surface principles in nature, resulting in lightweight yet extremely durable structures. Among Isler's most famous works are thin-shelled concrete structures built based on these naturally occurring forms. These structures are organic forms that provide maximum durability and aesthetics with minimum materials. Isler's textile hanger models are an important example of how biomimicry can be used effectively in modern engineering and design by applying the principles of efficiency and structural

Figure 15: Neri Oxman, The Aguahoja

Figure 16: Achim Menges, ICD/ITKE Elytra Filament Pavilion

optimization in nature to architecture.
As we approach today, biomimicry is still very popular among designers. Among these, Calatrava is one of the first ones that comes to mind, but it is also obvious that Calatrava approaches his designs not as biomimicry, but as biomorphic, and approaches designs only in terms of form. Two of the prominent names among young designers, Achim Menges and Neri Oxman, impress with their use of nature in terms of its functions and forms.

Achim Menges is one of the important names who brought biomimicry to the fore in modern architecture and engineering practices. While Menges was a pioneer in developing complex structures and systems inspired by nature, Neri Oxman is someone who designs by considering nature and technology; He thinks of the limitations of the natural world as "limits considered new beginnings." (Tavşan et al., 2021).

It is especially known for its biological systems-inspired approaches to thermal regulation, material optimization, and improvement of structural performance. His work succeeds in integrating the adaptive, autonomous and sustainable properties of biological processes and organisms into architectural and engineering problems.

Oxman works at the intersection of science, engineering, and art to understand the complexity and adaptive properties of biological systems. Known especially for his work titled "Biological Design and Integrative Structures", Oxman offers new perspectives on combining sustainable material use, structural performance and aesthetic values using biomimicry. Neri oxman's Silk Pavilion was derived from the study of how silk is affected by the spatial and temperature conditions of the spinning insect; This directs the movement of the silk to spin two-dimensional sheets rather than three-dimensional cocoons. It was built over three weeks with a swarm of 6,500 live silkworms with the help of a robotic arm, resulting in this impressive structure.

Aguahoja is an architectural pavilion composed of the most abundant biopolymers on the planet. (Fig.15) Its layered structure, known as a biocomposite, was designed as a hierarchical network of patterns optimized for structural stability, flexibility and visual connectivity. Combining shell-like and skin-like elements, the pavilion's overall rigidity and strength was designed to withstand changing environmental conditions such as heat and humidity while maintaining its flexibility. This allows control over certain physical characteristics and environmental adaptation to changing weather conditions.

Menges' research at the ICD (Institute for Computational Design and Construction) and SBIT (Intelligent Bio-Interface Technologies) laboratories at the University of Stuttgart encourages the adoption of an interdisciplinary approach in the field of biomimicry. According to Achim Menges, the computational design method used to produce performance-oriented architectural morphology was later guided by reflections between material behavior, robotic production limitations and structural differentiation principles (Material Synthesis, 2015).

Menges also creates structures inspired by nature and displays them by combining them with technology. It is quite successful in its field. Elyron was taken as inspiration for the structure he made in the ICD/ITKE Research Pavilion 2013-14. (Fig. 16) Cross-sections of morphological models based on micro-computed tomography scans show the elytron's complex, lightweight but tough bilayer shell with internal column-like features (trabeculae). It reveals a high level of correlation between fiber arrangement and structural morphology. The inspiration for the ICD/ITKE Research Pavilion 2014-15 was the diving bell water spider (Argyroneta aquatica).

Although the diving bell spider is derived from terrestrial arthropods, it spends almost all of its life underwater. As a result, he developed a clever method to create a submerged fiber-reinforced pneumatic habitat. First, a series of fibers are laid down to trap an air pocket, and then the spider silk is selectively reinforced inside the pocket to stabilize the dynamic structure. The hierarchical fiber patterns of the composite structure can be seen in microscopic photographs of the water spider building its nest (2015, Material Synthesis). Surface-filling fiber arrangements strengthen the shell locally, branching fibers form a cross-linking composite structure, and thicker structural fiber bundles form a network of layers to trap the air pocket. In the context of the ICD/ITKE pavilion, the biological processes used by the water spider can be abstracted and transferred into robotic processes for the fabrication of a fiber-reinforced pneumatic shell. This concept not only creates an integrated fibrous system on the minimal mold of the air bubble.

Architects are naturally drawn to nature for its innate resilience, efficiency, and elegance of form and process. Nature offers many sustainable solutions tailored to various problems, refined over millions of years of evolution. Biology offers direction for methodological approaches as well as for the creation of unique bio-inspired technology features and solutions. Both biological evolution and architectural design are open-ended processes that constantly shift and provide new developmental goals and evaluation standards. Through the processes of mutation, recombination, and selection, biological organisms evolve to become multifunctional and (self-)adaptive (Knippers et al., 2016).

Architects such as Da Vinci, Gaudi, Isler, Menges, and Oxman, mentioned above, have used biological concepts to create and revolutionize the field of architecture. Through their work, biomimicry has the potential to significantly close the gap between human creativity and natural brilliance. This will help create a future in which architectural design and the natural world coexist harmoniously, enhancing the resilience and sustainability of built environments. This multidisciplinary approach emphasizes the importance of nature as an inexhaustible source of inspiration and practical answers to the problems facing modern architecture on the surface of Mars.

3.4 I Biomimicry in Space

Although human beings' needs and problems change, they have always looked to nature to solve their challenges. Various natural models for solving human problems have been around for decades. While further space exploration is planned to include increased human missions, biomimicry will continue to play a vital role in space. The success of biological organisms in solving problems they encounter in their environment, the adaptability, reliability, etc., found in natural systems. The features must be examined and reflected in the designs.

A joint statement supporting the usefulness of biomimetics in engineering is that biological organisms face many of the same challenges as engineered systems. Space presents an environment radically different from that encountered by all known organisms, So much so that, at first glance, one might think biomimetics is infeasible. However, although direct similarities between space systems and biological organisms are less common, many species can be seen to exhibit qualities such as adaptation, robustness, lightness, low volume, and strength that are highly desirable in space system design. In some cases, biomimetic solutions can even exploit the properties of extraterrestrial environments in new ways. This broad interest in biomimetics in space motivates the continued growth of biomimetics as an increasingly systematic and distinct discipline for the design of new, high-performance space systems.

Humans will be a significant future system component for long-term space travel and research. Therefore, the whole mission architecture and spaceship design must consider human needs and requirements. Humans are not considered “elements” of the system but change agents and innovators. As such, human considerations must be included at every stage of the design process. As first Space architect Galina Balashova has said, “Architecture always relies on the same rules, and it doesn't matter what it's about a house or a spaceship.” (Häuplik-Meusburger and Bannova,). Similarly, Melodie Yashar emphasizes that, apart from environmental conditions, architectural concerns remain the same from a human perspective (Yashar, 2019).

Given the harsh conditions on Mars, such as its thin atmosphere, low gravity, and frequent sandstorms, future missions must combine human-centered design with innovative, adaptable architectural solutions. This will involve leveraging the principles of biomimicry to develop sustainable habitats that can withstand Martian conditions. It makes reasonable to transfer concepts from living things because natural models have evolved through many different processes and environments (Gruber,2011). By studying the adaptive strategies and resilience of diverse ecosystems on Earth, we can create designs that ensure the productivity and well-being of future space explorers.

Biomimetic Apprach on the surface of Mars

When we started looking at nature to take it as a role model, we first started by looking

Figure 17: Tartigrade microscope image

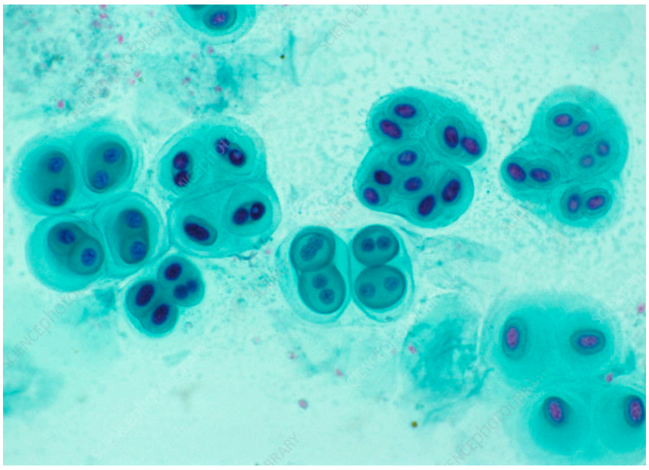


Figure 18: Cyanobacteria SEM image

at all the extreme conditions of Mars and examining the extremophiles (Thermophiles, hyperthermophiles, psychrophiles, barophiles and radiophiles). As a second way, considering the conditions, shelled creatures (Clam, Mussel, Abalone, Oyster, Nautilus, Glyptodon, Turtle) were examined with the logic of creating a shell to protect the habitat from external factors. Since it is considered very important for the material to be light and durable for the habitat to be built, these types of creatures (Spider web, Water Lily, Foraminifera, Diatom, Honeycomb, Bird Skull, Sea Urchin, Bamboo) were put under the spotlight and lastly, they were the main problem of this thesis. Based on the pressure difference discussed, living things (Walnut, Bone, Plant Cell) were examined and a conclusion was reached.

To address the extreme conditions on Mars, such as intense radiation, high temperatures, and significant pressure variations, researchers have studied extremophiles. Extremophiles are a class of organisms that are able to exist in situations that most other living forms find difficult to endure, such as extremes in temperature, salinity, pH, pressure, and so forth (Zhu et al., 2020). Understanding the physicochemical characteristics of life on Earth and possibly gaining insight into its origins can be gained through studying extremophiles (Niederberger, 2009). These organisms, which thrive in harsh environments, can inspire the development of durable materials and structural designs for habitats on Mars. For instance, the metabolic and structural adaptations of these extremophiles can lead to advancements in self-healing materials, effective thermal insulation, and other resilient construction methods essential for long-term human habitation on Mars. (Fig.17 & Fig.18)

In this research process, the structures of radiophiles, one of the extremophiles, were examined, and whether a protective layer against radiation could be built with a living organism inside the structure in material production was studied. Although integrating these and similar creatures into the structure has been tried on Earth, we have yet to determine what the effects will be on an extraterrestrial planet, Mars.

Since we are in an environment where the risk of adverse consequences cannot be taken, these researches seem to be a situa-

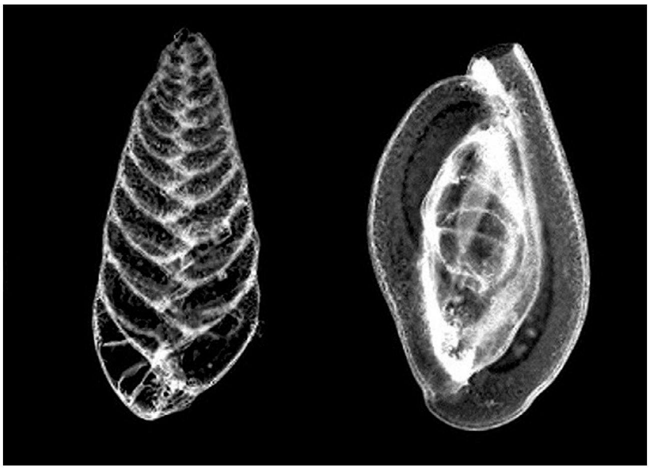


Figure 19: Molluscs microscope image

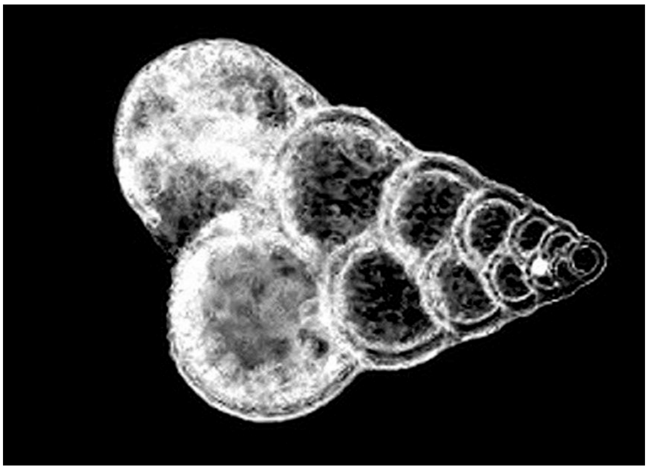


Figure 20: Molluscs microscope image

tion that will be understood through on-site experiments in the future, perhaps with the beginning of life on the surface of Mars.

When thinking about Martian environments, another strategy that arises is to shield the habitation region from harsh environmental conditions by creating a top cover based on shell. Nature is an accomplished maker of shells and domes (Pawlyn, 2016). We include empty shells, shell fragments and live molluscs under the umbrella term 'shell'. Nevertheless, the diversity of shell characteristics and the environments in which molluscs live suggest an extreme degree of idiosyncrasy and contingency in any engineering consequences (Gutiérrez et al., 2003). As Michael Pawlyn points out, we can look to mollusks for guidance on creating undulations and increasing openings using the least amount of material (Pawlyn, 2016). The standard features of clams, oysters, mussels, nautilus, and abalone shells will likely inspire habitats on Mars. (Fig.19&20)

The primary material of these shells is calcium carbonate, which is layered hierarchically with aragonite or calcite to create a strong but lightweight structure. The shells' exceptional mechanical strength and durability resulting from their layered architecture make them highly resistant to impacts and mechanical stress. Additionally, these shells contain complex, often spiral or radiating patterns that increase their structural strength. The organisms inside them can repair the damage by secreting new layers. These properties can be used as inspiration to develop material and structural designs for a Martian dwelling that is light and strong enough to withstand the planet's harsh climate. At the same time, the safety and sustainability of human life on Mars include layered construction techniques to build sturdy, durable habitats that can maintain their integrity over time. They can be achieved using self-healing materials and biomineralization-inspired processes.

Shell structures were the first efforts at Martian architecture by various architectural firms. Among the projects mentioned in the previous section, Foster & Partners' Mars Habitat (Figure) and Hassel's NASA 3D Printer Habitat (Figure) are examples of this. Since both projects aimed to protect the interior living space from severe external effects, an inflatable living space, a flexible and expan-

Figure 21: Seaurchin SEM image

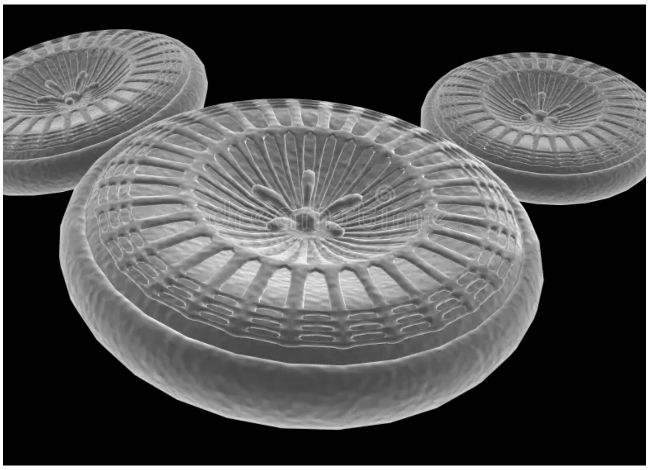


Figure 22: Diatoms SEM image

dable structure that can be inflated to create a living space, was placed inside and covered with a shell to create a Class 2 living space. In this case, we cannot discuss a sustainable existence outside Earth. The pressure difference problem we mentioned before was solved with inflatable and shell systems, but both projects could not be independent from the Earth.

The principle of "less material, more design" (Pawlyn,2016) is evident in nature, where organisms achieve maximum impact with minimal material use. While examining these creatures, it was seen that nature creates maximum impact with minimum material. Many examples in nature demonstrate this structural principle, such as Spider Webs, Water Lilies, Sea Urchins (Fig.21), Foraminifera, Diatoms (Fig.22), Honeycombs, Bird Skulls, and Glass Sponge (Fig.23).

When we look at the giant water lily of the Amazon, Victoria Amazonica, it is remarkable how to strengthen a thin surface (Pawlyn,2016). The smooth upper surfaces and undersides of the leaves, up to 3 m in diameter, are reinforced with a radial, branching network of ribs large enough to support the weight of a small child. In the case of sea urchins, the skeleton of the urchins consists of interlocking plates, each with a single calcite crystal structure. If calcite were solid, it would be heavy, but ossicles have a porous, light, and rigid spongy structure due to their increased adequate thickness. The interlocking structure of sea urchin ossicles served as the model for the Landesgartenschau Exhibition Hall from Achim Menges. A significant amount of strength is required to protect against impacts to the ends of the keels, or an engineer would call "axial load." They are solid and flexible due to the composite effect of the material and have a porous form that combines proteins and calcite.
On the other hand, Argyroneta aquatica, the diving bell spider, uses a series of fibre-laying behaviours to build its nest, which in turn shapes, forms and strengthens the underwater bubble from the inside out (Material Synthesis, 2015).

Frei Otto and his colleagues were already fascinated by strategies for optimizing the shell architecture of microorganisms. The focus was on the shells of diatoms and radiolarians, characterized by their strength with little material input. Diatom shells are

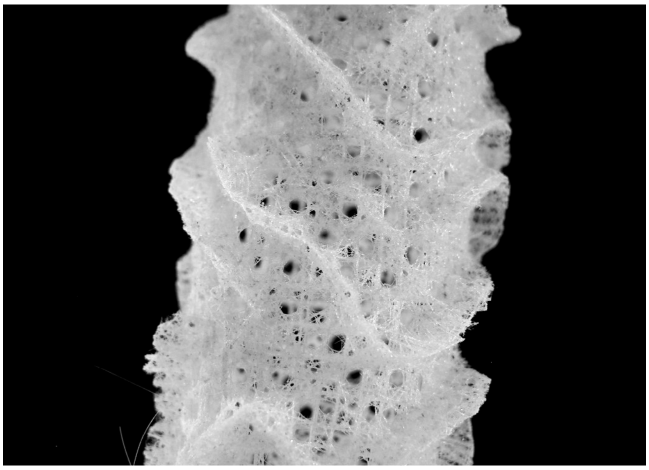


Figure 23: Glass sponge SEM image

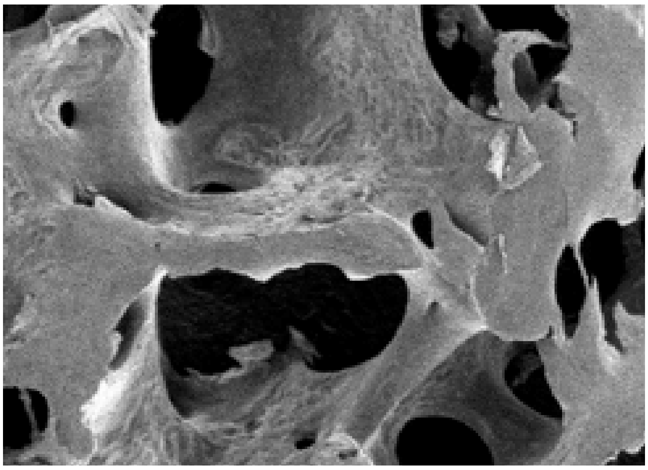


Figure 24: Trabecular Bone microscope image

composedof efficient silicate structures that achieve high durability with minimal material. (Pohl & Nachtigall, 2015) Silicate solids are as flexible as bone and withstand high pressures and stresses.

The complexity of the shell structure is necessary because a significant reduction in hardness has been achieved by simplifying the shell shape while maintaining the same level of material application. Diatoms follow the same principles as existing lightweight structures, achieving maximum durability with the least amount of material.

All the creatures studied are remarkable organisms in their class and respond to particular problems within themselves. It is understood that some creatures do not fully respond to pressure, which is the main problem addressed in this thesis for Mars, while others have a disadvantage against pressure. If our main problem was protection from radiation, dust storms, and meteoroids, mollusks might be outstanding examples to draw inspiration from. Or, if this thesis was all about materials and our only goal was to create lightweight structures, diatoms, water lilies, or sea urchins, it could be very inspiring. However, as we have just mentioned, the search continued for a creature that solved the fundamental problem of pressure. The creature's internal pressure was higher than the external pressure at one stage, but it adapted to it and continued its life. In this search, walnut shells, bones, and plant cell walls came to the forefront.

First of all, if we look at the growth of the walnut shell, we encounter an organism with a light material with high strength and hardening properties (Wang et al., 2023). As the nut matures, internal pressure increases, allowing the shell to grow in layers, each adding strength and durability. As the bark grows in layers, each layer provides additional strength and durability. This layered structure, combined with the complex, interlocking microstructure of the shell, allows the shell to absorb and dissipate energy efficiently, making it highly resistant to cracking and fracture.

The complex, interlocking microstructure helps disperse and dissipate forces, increasing overall durability, but shells are more likely to crack under tension rather than crack under pressure.

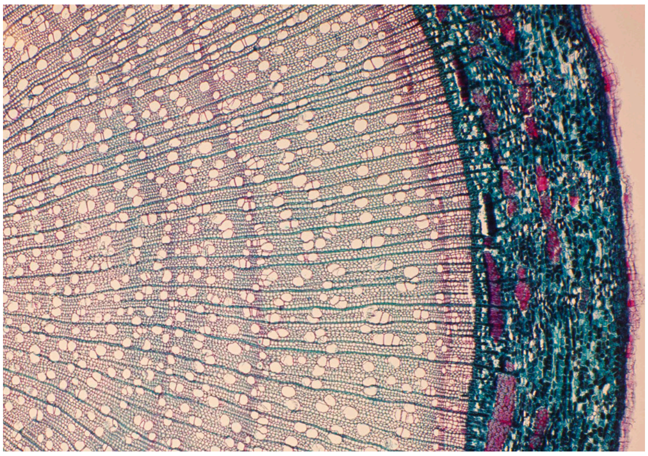


Figure 25: Plant Cell SEM image

Studies have also revealed that walnuts have low energy absorption in the tensile test. (Xiao et al., 2021) Testing has shown that although walnut shells are strong under compressive forces, they are brittle and less capable of absorbing tensile forces, making them less ideal for applications requiring high tensile strength, such as habitats on Mars has shown.

Trabecular bone, also known as spongy bone, trabecular structures combine to form natural biocomposite bone (Mirzaali et al., 2016). (Fig.24) The complex mechanical-biological feature of the functional relationship of the trabecular structure of the body is the result of optimized bone self-adaptation according to the mechanical load situation (Zhang et al., 2023). Optimizing the self-adaptation of bone to a mechanical loading scenario results in a complex mechanobiological property that determines the functional relationship of trabecular structure in the body (Keaveny et al., 1994). The porous structure of bone consists of interconnected rods and plates called trabeculae, which adapt to mechanical loads by aligning according to the direction of the applied force. Following Wolff's Law, this alignment maximizes strength and efficiency under compressive loads (Zhang et al., 2023). The process of bone remodeling involves the resorption of existing bone and the formation of new bone; This allows trabecular bone to maintain its strength and functionality while remaining light and flexible. Although primarily suitable for compression, trabecular bone also provides some resistance to tensile forces, providing flexibility and reducing the risk of fracture (Birnbaum et al., 2002).

Some of the largest organisms on Earth are plants and this achievement is based largely on the growth and mechanics of the plant cell wall (Cosgrove, 2000). Plants have been used as role models ever since man began to use technology. For architecture, plants are especially important as they share some common problems with houses: most of them stay at one place and are dependent on local environmental conditions. Trees and houses are of a similar size, and subjected to similar influences of natural forces (Gruber, p.21).

A Role Model, Arabidopsis

Recent sophisticated models of plant morphogenesis, in which mechanical stresses in developing cell walls drive a dynamic supracellular system involving microtubule reorganization, oriented cellulose deposition, and auxin transport, have significantly increased interest in cell wall mechanics. (Cosgrove, 2015) The adaptation of the cell by changing shape in response to this pressure change due to microfibrils occurs when the internal pressure is higher than the external pressure during the growth process caused by the turgor pressure at the maturation stage of the cell. Before examining this mechanism in more detail, the structure of plant cells was examined. (Fig.25)

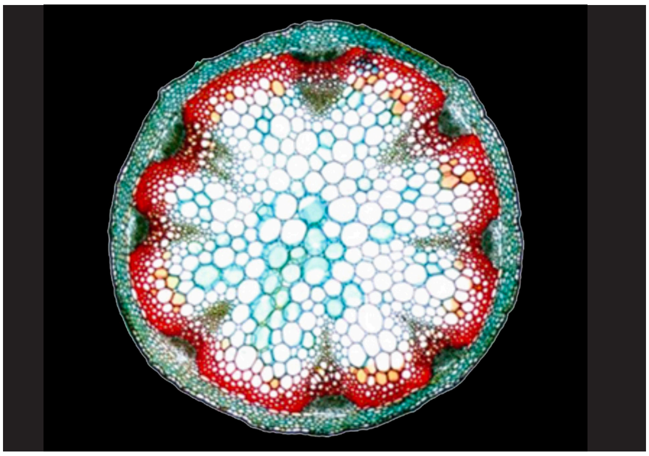


Figure 26: Arabidopsis SEM, ACA triple reagent stains secondary cell walls red and primary cell walls green

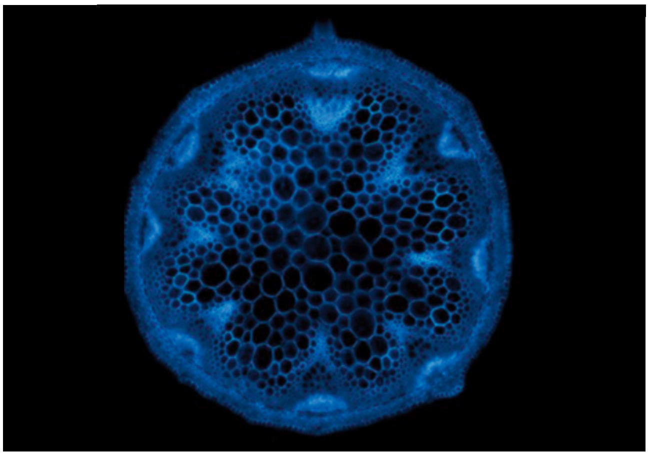
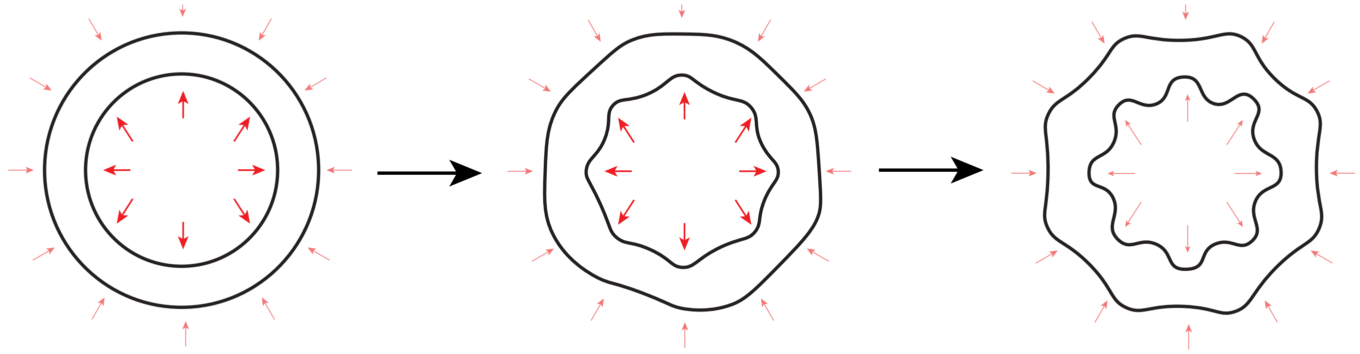


Figure 27: Arabidopsis SEM, all cells walls as blue

The structure of plant cells, particularly their walls, is a crucial aspect of this adaptability. It is agreed that changes in tissue and organ morphology during plant growth and development are largely due to controlled cell division as well as structural modification and rearrangement of wall components and synthesis of new material and addition to the existing wall. (Rose, 2009) Plant cell walls are semirigid composite structures made primarily of cellulose, hemicellulose, and pectin, which provide strength while allowing flexibility for growth. (Sahi & Baluška, 2019) An exoskeleton known as a cell wall covers every plant cell. The cellulose, hemicellulose, and pectin carbohydrates comprise the cell wall. Primary and secondary cell walls are the two main categories into which plant cell walls are often separated. Primary cell walls in all growing cells are extendable and play a crucial role in cell growth.

The main mechanical functions that primary cell walls need to fulfil are to provide sufficient stiffness and strength to the cell but at the same time to allow for cell growth, as well as enabling reversible changes of cell size and shape with regard to pre stressing and organ movements. (Burgert & Keplinger, 2013) Mechanical forces such as tension, compression, and shear stress are essential for the growth and development of plant cells. Growing cell walls are said to be extensible, by which we mean they deform irreversibly in a time-dependent manner under the action of tensile forces in the wall, forces usually generated by cell turgor. This is the most common general meaning of 'wall extensibility' in the literature on plant growth (Cosgrove, 1992).

The internal turgor pressure and the growth of neighboring cells exert constant mechanical tension on plant cells. In physical terms, cell shape and size are governed by the mechanics of the cell wall, which is a thin, fibrous layer strong enough to withstand the high physical stresses generated by cell turgor pressure (P) (Cosgrove, 1997). After cell growth has ceased, secondary walls—often thicker than main cell walls—are deposited inside primary walls. Cellulose, hemicellulose, pectin, and trace amounts of glycosylated proteins make up the primary cell wall. The secondary cell wall, on the other hand, is mainly composed of cellulose, hemicellulose, lignin, and glycoprotein. The secondary cell wall contains essentially no pectin, and



Young Arabidopsis Plant Cell

Arabidopsis Plant Cell Under Turgor Pressure

Mature Arabidopsis Plant Cell

Figure 28 : Arabidopsis Plant Cell Cross Cut Section

it differs from the primary cell wall in terms of the polysaccharide ratio of hemicellulose (Ivakov and Persson 2012). (Table)

The rigid network of secondary cell walls, parallel aligned cellulose fibrils, and matrix substances provides mechanical stability even to dead cells. (Burgert & Keplinger, 2013) The primary cell wall is linked to cell growth because of its different mechanical characteristics. In contrast, the secondary cell wall contributes to the plant's ability to transport water and exert physical force. In addition, even though plant cell walls serve various vital functions, the mechanical characteristics of main cell walls will be the exclusive emphasis of this thesis.

As with most developmental events, it is quite likely that cell growth results from a series of complex chemical and physical interactions. Notable control factors in cell growth include turgor pressure as the primary driving force associated with wall relaxation, transverse orientation of cellulose microfibrils, polymerization of new actin microfilaments. (Beck, 2010) Turgor or hydrostatic pressure occurs in plant cells due to accumulation of water in the cell during growth. This pressure, which is several times the atmospheric pressure, is very important for maintaining the structural integrity of the cells. Plant cells have a tough but flexible barrier called the cell wall that can withstand such high turgor pressures.

The plant cell wall is also critical for the mechanical stability of plant tissues as it is subjected to plane mechanical stress while balancing turgor pressure, significantly affecting water relations and water economy. These stresses cause the cell wall to bend elastically (reversibly) until it exceeds the elastic limit, or yield point, at which plastic deformation (irreversible) occurs. Growth arrest that occurs during cell maturation is usually irreversible and is accompanied by hardening of the cell wall (Kutschera, 1996). When physical stress continues over time, the cell wall undergoes time-dependent viscoelastic or viscoplastic deformation, as opposed to rapid and transient increases in stress. Only plant cell expansion combined with mechanical feedback, biochemical remodeling of the cell wall, and production of new cell wall components can achieve this (Cosgrove 2018).

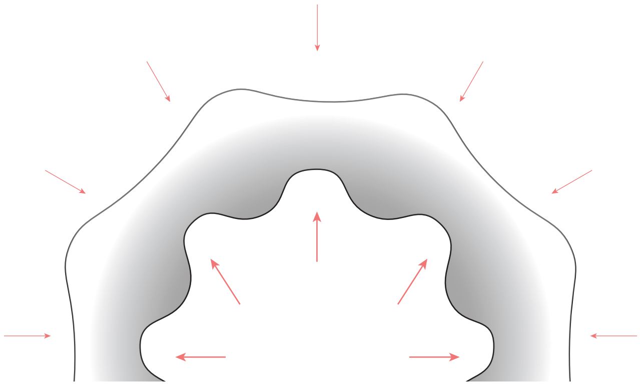


Figure 29 : Plant Cell SEM image

Due to intense turgor pressure in growing cells, the relatively thin plant cell wall is under tremendous mechanical tension or stress or tensile stress. Because matrix polymers interconnect cellulose microfibrils that act as rigid, inextensible reinforcing pieces in the wall, a strong network is formed that can withstand high tensile forces, allowing for such high stresses. This pressure is very important for plants, as it enables cell expansion during growth and contributes significantly to the mechanical stiffness of living plant tissues. Plant cells can withstand this internal pressure thanks to the mechanical strength of their cell walls. (Alberts et al., 2008)

As mentioned above, mechanical forces such as tension, compression, and shear stress are omnipresent and critically important for the growth and development of multicellular organisms. Plant cells are under constant mechanical tension due to their internal turgor pressure and the growth of neighboring cells.

Different cell wall structural elements influence the direction of growth by allowing for and limiting physical stress. The most rigid polymer in the cell wall, cellulose microfibrils, are crucial to this process. They are the primary stress-bearing component of the cell wall.

The microtubule cytoskeleton aligns with the primary direction of anisotropic stress through the cellulose synthesis mechanism, resulting in local anisotropic expansion. Mechanical stresses also affect auxin gradients, intensifying microtubule isotropy and acidifying specific cell wall areas, causing chemical changes in wall stiffness (Sassi et al. 2014). A cell or tissue will undergo shape changes depending on turgor pressure, producing local growth rates that vary spatially. The concept that cellulose microfibrils strengthen regions subjected to higher mechanical stress is supported by the observation of stiffer fiber-like structures in the recessed areas of these cells, as measured by atomic force microscopy (Sahi and Baluška, 2019). A great deal of circumstantial evidence already supports the idea that cells are prestressed stretchable structures with internal molecular supports and cables (Ingber, 1993b).

To briefly summarize, the relationship between turgor pressure, cell growth and cell tension in plant cells is very important to understand how plants maintain their structure and facilitate growth. The turgor pressure created by the water filling the cell's vacuole creates an internal force that pushes the cell wall and hardens the cell. This pressure is necessary for the expansion of the cell as it causes the cell wall to stretch and grow. The secondary cell wall plays an extremely important role in terms of its stiffness, strength and tensile strength, as well as its ability to generate compressive and tensile mechanical stresses (Kepliner, 2013).

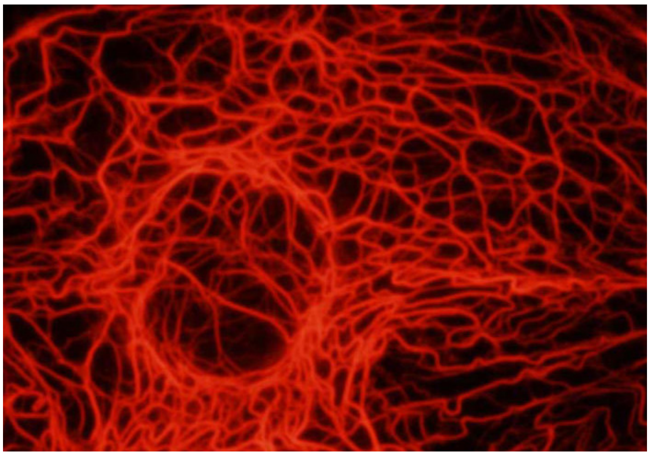


Figure 30 : Arabidopsis microfilaments SEM image

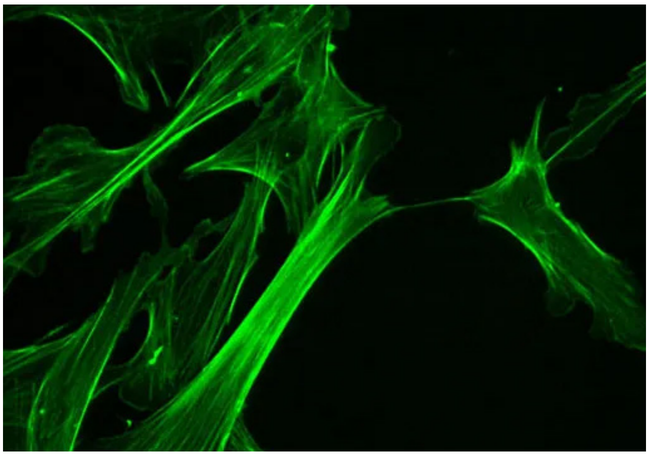


Figure 31 : Arabidopsis microfilaments SEM image

Cellular tension in plant cells refers to the structural organization that allows cells to maintain their shape and stability while being flexible and pliable. This concept is based on integrating tension and compression forces within the cell. In plant cells, the cytoskeleton, consisting of microtubules, actin filaments, and intermediate filaments, acts as a tension network that distributes mechanical stresses throughout the cell. The cell wall, composed mainly of cellulose, hemicellulose and pectin, provides pressure support. Together, these components form a taut structure in which cell wall compression balances the tension of the cytoskeleton. This balance allows plant cells to withstand external stresses, adapt to mechanical stress, and grow effectively. The cellular tension model explains the mechanical stability and flexibility of plant cells and provides insight into their ability to sense and respond to environmental changes.

After the structures and growth processes of plant cells were examined in detail, they began to be examined from general to detail. In line with this research, stem cells, stem cells and leaf cells of many plants were analyzed. As we mentioned in previous sections, one of the most important and necessary conditions for a living space on the Mars surface is that the structure is resistant to tension and pressure. As a result of all these analyses, Arabidopsis stem cells were taken as a role model, in the light of information about how the cell withstands stretching and pressure during the growth process. (Fig.26)

Arabidopsis is a plant species extensively characterized and understood at the genetic, molecular, and cellular levels. Arabidopsis belongs to the Sisymbriae tribe, a member of the Brassicaceae (mustard or crucifer) family (Wilson, 2000). In model plants such as Arabidopsis, the shoot apical meristem (SAM) is essential in studying plant development. Therefore, when examining the apical meristem of the Arabidopsis shoot, a dome-shaped structure, the apical region was found to show intracellular co-alignment between microtubules and the main stress direction. (Fig.27)

The central domain of the SAM contains isotropically aligned microtubules, whereas the peripheral domain has a predominant peripheral orientation of microtubules that come with the same ordered stress patterns. (Sahi and Baluška, 2019) Since the tensile stress experienced by the walls of the cell, on which Sampathkumar conducted more detailed laboratory research, arises from the turgor pressure inside the cells, the three-dimensional geometries of the cells were taken from confocal microscopy images to see whether the cell form affects the anisotropy of the stress on the wall.

The result of the model with mechanically, atomic force microscopy-based measurement of cell wall stiffness in these cells shows stiffer fibril-like structures in recessed areas; this is consistent with the hypothesis that cellulose microfibrils strengthen regions subjected to higher mechanical stress (Sampathkumar et al. 2014a) (Fig.28&27)

In short, turgor pressures and flexible cell walls give them resistance to tensile forces. Cells can withstand tension due to the arrangement of cellulose microfibrils in the cell wall. Therewithal, the structural integrity of the cell wall and the presence of hardening substances such as lignin make them resistant to compressive forces. This combination makes Arabidopsis stem cells resistant to environmental stresses and growth.

Conclusion

To summarize the process Arabidopsis goes through in its cell during maturation, it is briefly as follows. Turgor pressure in Arabidopsis stem cells is crucial for maintaining structural integrity and promoting growth. It is produced when the water filling the cell's vacuole hardens the cell by applying an internal force against the cell wall. This pressure is necessary to expand the cell, stretch the cell wall, and facilitate growth. The process involves a delicate balance between tensile forces from the cytoskeleton, which maintains the cell's shape, and compressive forces from the cell wall, which resists turgor pressure.

Together, these mechanisms allow the cell wall to expand in a controlled manner, ensuring the integrity of the cell and effectively adapting to mechanical stress. In addition, microfibrils are arranged to enable cell growth by resisting the internal forces exerted by turgor pressure and supporting the flexibility of the cell wall. The arrangement of microfibrils makes plant cells resistant to mechanical stress, maintains the stability of the cell wall and regulates the shape change of plant cells. Microfibrils are positioned more or less densely depending on the intensity of the stress.

This process that Arabidopsis goes through in its cell during maturation, especially the shape of the cell at the end of maturation and its resistance to compression and tension thanks to its microfibril structure, inspired this thesis and guided the habitat structure.

Part 4
Designing the Martian Structure

In the first chapter we discussed the history of the exploration of Mars, followed by geological and physical theories based on observations of the planet. In the second chapter, we explained in general what Mars habitats are, how they are categorised and what the main environmental factors are that shape the habitats, and finally we mentioned the pressure differential, which is the main factor that affects the structure, which is the main element that protects Mars habitats from all these environmental factors. Then, in the third chapter, we discussed biomimicry, which is used to find a more resistant form of Martian structure against the stress created by the pressure differential, which is the main problem to be solved for a sustainable Mars settlement. While discussing biomimetic references, we also explained why research has developed historically and why it has come to Arabidopsis Thaliana. In this chapter we have discussed how a Martian structure would behave under Martian environmental conditions, using Arabidopsis as an example. Instead of designing the structure and then going into the structural analysis section, we discussed the structural form finding method and FEA at the same time, and explained step by step how the structure evolved based on local materials on the surface of Mars.

4.1 I Background

In the previous chapters we mentioned that the main design guideline for Martian structures is the pressure difference between the Martian atmospheric pressure of 0.6 kPa and the Earth atmospheric pressure of 101.3 kPA inside the Martian habitat. For this reason, we also mentioned that the pressure difference will push the structure out of the habitat by exerting a pressure, and we also mentioned how much stress will be created on the structure (Özdemir, 2020).

Because of the stress created by this pressure differential, we know that the angular designs we are used to on Earth are not very favourable, and that stress concentrations at weak points will cause problems. We should then look for structures that distribute the stress homogeneously, and these are curved or round designs. Curved or round designs generally distribute stress homogeneously, minimising the risk of material fatigue and cracking.

The design and construction of this type of structure, with which we are very familiar from our own history, dates back to ancient times. Shell structures have been built since pre-historic times, starting with shelters made of clay or mud with rounded corners. In subsequent periods, the gradual growth of building knowledge has introduced important structural forms such as domes, vaults and arches into our lives.

The development of block arches and vaults by the Etruscans in the 4th century BC and

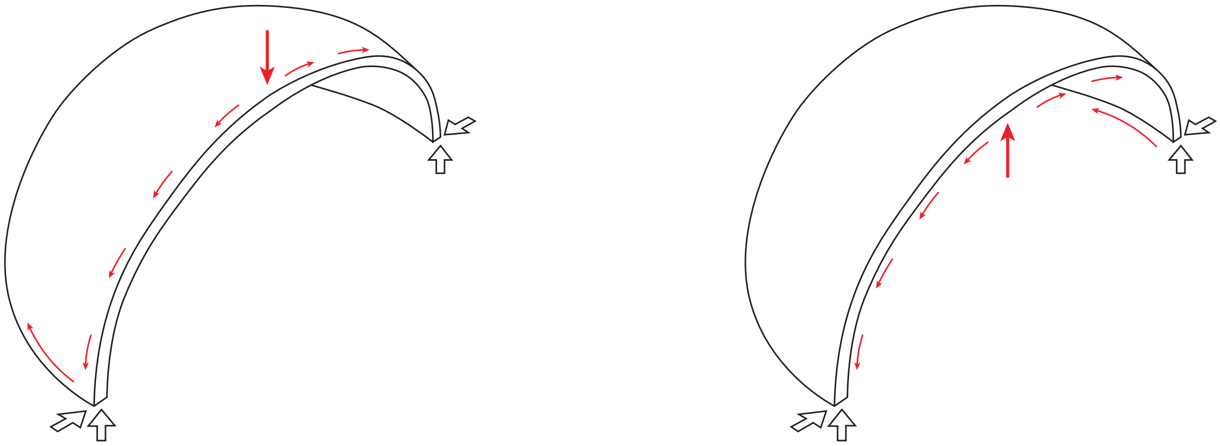


Figure 32: Shell under the loads Earth and Mars

the production of concrete with pozzolanic cement by the Romans in the 3rd century BC may have been the basis for the concrete castellated dome of the Pantheon built in Rome in 125 AD (Ching et al., 2009). Then, in Constaninople (Istanbul), the capital of the Eastern Roman Empire, between 532 and 537 AD, the Hagia Sophia, designed by the mathematicians Isidoros and Anthemios of Miletus (the tradition seems to have continued for some time after Thales, Anaximandros and Anaximenes), had the grandest and largest central dome of the period (Moussavi, 2018).

Notre Dame Cathedral, built between 1163 and 1250, was able to dissipate stress by transferring the downward thrust from the vaults to the external buttresses. The same method was used by Sinan the Architect, the chief architect of Ottoman Empire, who added buttresses to solve the structural problems of Hagia Sophia (Gohnert, 2022), which was repeatedly affected by seismic activity.

Moreover, the architect Sinan took the concept of the central dome to a new level with the Selimiye Mosque, built in 1568 and 1574 in the province of Edirne in present-day Turkey (Kuban, 2010). From Brunelleschi's double dome to St Peter's, the list goes on and on until Pier Luigi Nervi's Palazzo Dello Sport, built in Rome in 1960.

The domes consist of an arch that is turned around its own vertical axis. As this creates a smooth surface, the vertical loads are carried by the combination of bending moments together with the effect of the shell vault (Moussavi, 2018). In this type of structure, the peripheral loads generated are compressive forces near the top and tensile forces at the bottom (Meistermann, 2017; (Ching et al., 2009). These structures, which usually develop thrust where they are supported on the ground, need to be supported from where they are supported. Such dome-like shell structures are successful in transferring their own dead loads homogeneously to the ground and, in the case of large spans, are important curvilinear load-bearing systems for achieving a large static height with the least possible dead load (Fig.32).

Unfortunately, for Class III structures on Mars, dead load is not the most important consideration. As mentioned in the first

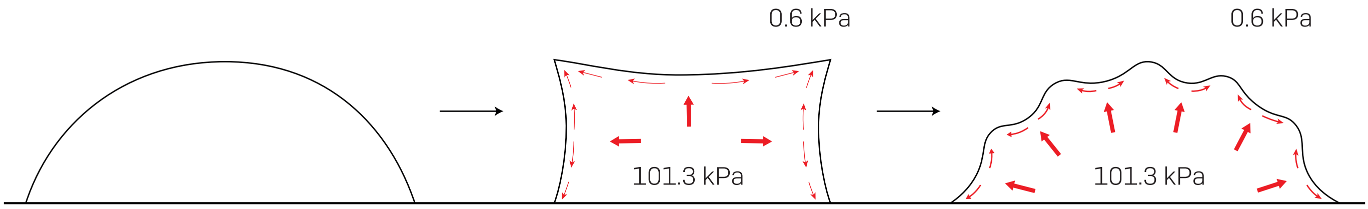


Figure 33: Pressure effect on the structure

paragraph of this section, on a planet with a gravity of 38% of Earth's, the most important factor to consider is the incredible difference between the air pressure of 101.3 kPa inside and the atmospheric pressure of 0.6 kPa outside (Järvstråt & Toklu, 2004; Yashar et al., 2019). For this reason, dome-like shell structures in the Martian environment must function in the opposite way to the shapes we are used to on Earth (Soureshjani et al., 2023; Pavese et al., 2023). (Fig. 33)

We know that any structure built on the surface of Mars cannot be used by directly inverting the dome. However, there are many reasons why these structures (Fig.8,9), which can only be built with an inverted dome cover with the appropriate use of landforms, should not be preferred in a Mars exploration mission, as we have previously reported.

From this point of view, it is important that the structures to be designed for a sustainable human settlement in a Mars exploration mission should be stand-alone structures. Using the example of the shape of Arabiopsids Thaliana under internal pressure, analysed in the previous chapter on biomimicry, the structural form finding method was applied based on this principle.

4.2 I Structural Form Finding

Dimentions

Before applying the form-finding method, we need to apply the basic dimensions of the structure. These measurements are usually based on our previous experience of space missions or Mars analogue missions on Earth.

The ISS, with its predecessors such as the Salyut, Skylab and MIR stations, and its predecessors such as Vostok, Gemini, Mercury, Apollo and Space Shuttle, as well as spacecraft still in service such as Soyuz, Shenzhou, Dragon and Starliner, have provided us with a great deal of volume information. In addition, Mars analogue missions such as the Haughton-Mars Project (HMP) on Devon Island, the Hawaii Space Exploration Analogue and Simulation (HI-SEAS) on Mauna Loa, or the Mars Society's Flasline Mars Arctic Research Station (FMARS) and Mars Desert Research Station (MDRS) have conducted research on habitable volume, which directly affects the psychological state of the crew.

Although the conclusions that can be drawn from these surveys vary, the feedback almost always focuses on certain clusters. Almost all team members asked for larger volumes and more private space for themselves.

After a while, it became uncomfortable for some crew members to see what everyone else was doing in a single volume (for more on this, see Review: Studies and Archiecture of Habitability Mission In In-Situ Environments in Häuplik-Meusburger & Bishop, 2021). Crew members also mentioned the importance of having separate crew quarters and separate hygiene facilities (Bannova, 2021).

Based on these findings, we, as well as AI Space Factory's MARSHA and SEArch+'s X-House 2, envisaged a vertical placement of functions and an organisation in which each function would be located on a different floor, so that the feeling of seeing everyone and everything at the same time under a single space in the team could be eliminated.

We decided that the basic dimensions of the structure should be such that a crew of 6-8 people could stay in the Mars habitat for 780 days, given that the Mars launch window opens in an average of 780 days. (Minimum Acceptable Net Habitable Volume for Long Duration Exploration Missions, 2014). For these reasons, the first step was to determine the dimensions, where the radius is 7.5 m.

Loads

So first we applied the gravitational forces to the structure and determined the draft volume of the shape. (Fig.34) After the first, form-finding, the final height of the simple dome-like shell is 10 m, which is an estimated value based on the goal of reaching the required volumes for the Martian base.

Then, to obtain a structure that takes the shape of the cell wall of Arabidopsis thaliana with the applied internal pressure and gravitational loads, we kept certain extensions of the shell constant and applied the form finding method to the parts in the middle of these regions. (Figure 35). This structure gave us a volume of 891m3. Calculating on the basis of the volume requirement of a crew member (Minimum Acceptable Net Habitable Volume for Long Duration Exploration Missions, 2014), we obtained a volume that could accommodate 6 crew members for 780 days.

The form-finding method takes into account gravity, which is 3.721 m/s2, and internal pressure loads, which are 101.3 kPa (Table 9), but not thermal, micrometeoroid, wind or seismic loads. To accurately calculate and compare thermal loads, it is necessary to determine the area of the Martian surface to be settled. Temperatures on Mars are known to be subject to sudden changes, and temperature data also change depending on the pole, aquator or hemisphere. Wind loads are very low for a planet with a relatively low atmospheric density, and they vary depending on which hemisphere we are in and what time of year it is. For example, global wind-driven sandstorms tend to start in the southern hemisphere. Although the pressure loads vary with location and temperature, the pressure values are 0.2 kPa (Table 6), which is very low compared to the internal pressure of 101.3 kPa. For these reasons, only gravity and pressure loads were included in the form finding method.

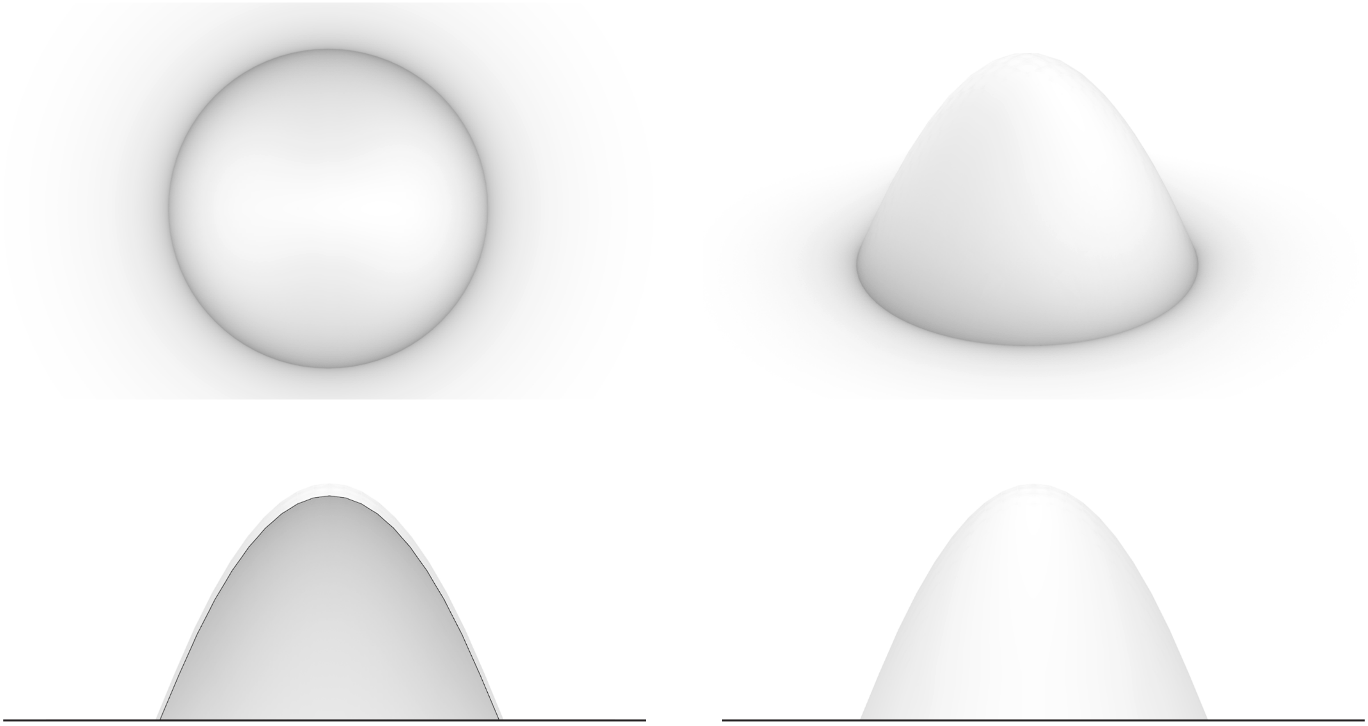


Figure 34: Simple dome form-finding

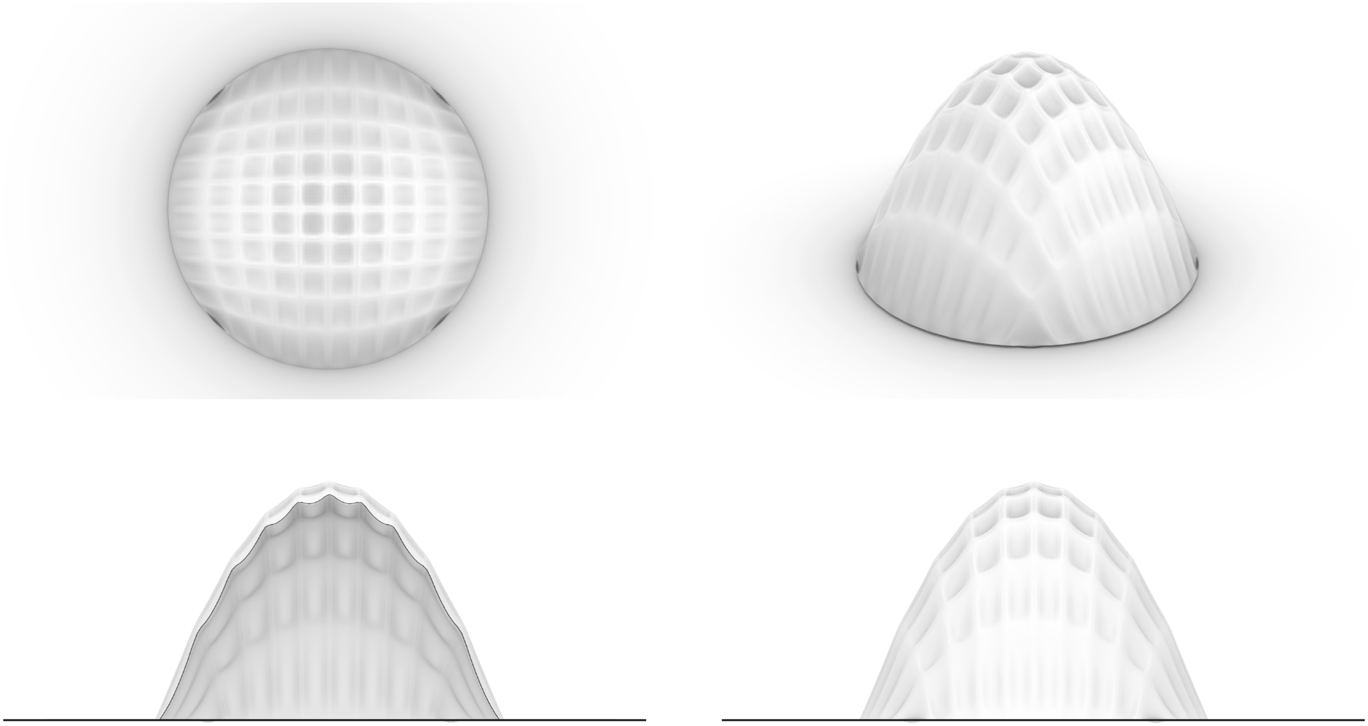


Figure 35: Inner shell of the structure form-finding

	Gravity	Atmospheric Pressure
Mars Surface	3.721 m/s^2	0.6 kPa (6.0 mbar)
Inside of the habitat	9.807 m/s^2	101.3 Kpa (1013 mbar)

Table 9: Environmental conditions at the Mars surface and the inside of the habitat

	Value
Compressive Strength (MPa)	3.66±0.25 MPa
Flexural Strength (MPa)	5.95±0.25
Elastic Modulus (GPa)	9.57±0.32 GPa

Table 10: Mechanical properties of materials used in the analytical solution

4.3 I Structural Analysis

Material

Although the subject of materials is very broad and we are experts in the field, resources are limited when it comes to Mars. For this reason, it is a subject of increasing interest recently, and although there are gaps and incomplete research on Mars materials in the literature, there are also well compiled studies.

We know that high-strength polymers brought from Earth are not very economical or sustainable for a sustainable and permanent Mars settlement. Although these materials are much more resistant to compressive and tensile forces than local materials on Mars, bringing materials from Earth for each structure is outside the boundaries of the Mars settlement, which is defined as Class-III (Kennedy, 2002) and must be made only with Martian materials. In addition, during the production phase in a vacuum environment, they will be subject to complex processes and require high energy, which are methods we do not favour. As for biopolymers, although they have all the above problems, there is also some risk of contamination, and how they will react to the Martian regolith, which does contain toxic materials, needs to be studied further.

On the other hand, AI Space Factory's Marsha project, which came first in the NASA 3D Printed Habitat Challenge, proposed adding natural polymers from greenhouse plants to the dough as a reinforcement. While this is a significant step forward, it is also questionable whether a Mars colony would be able to produce this mix in a space environment. But we should also add that they are very promising for the future, and that detailed research into the possible applications of biopolymers such as mycelium (Lipińska et al., 2022) has now begun (we also think that the biopolymers such as pectin, cellulose and chitin used in Studio Oxman's structures are very inspiring for the future).

Leaving aside the issue of biopolymers and focusing mainly on materials derived from Martian materials, SEArch+ has constructed the structure of the Mars Ice House from ice (Morris et al., 2016), as the Martian surface is generally cold and high-hydrogen materials generally have high radiation shielding.

However, the tensile and tear strength of a structure made of ice in different temperature environments is questionable (for other design alternatives see: Hinterman et al., 2022).

Concreting the Martian soil with a binder, as in the Mars X-House 2 proposal by SEArch+, one of the competitors in the NASA 3D Printed Habitat Challenge, is one of the alternatives (Yashar et al., 2019). However, since the direct contact of the habitat with the regolith would lead to the possibility of radon exhalation as mentioned above (Lévy & Fardal, 2010), they had to add a high-density polyethylene (HDPE) layer inside the habitat. It should also be noted that a certain amount of water is required to mix the concrete obtained from the Martian regolith.

For those reasons, we have based our structural analysis on local Martian materials. The surface of Mars, which has a basaltic soil structure, is very rich in sulfur, and since the sulfur used as a binder in concrete does not require liquid water during its production, the liquid water to be used for construction can be used in other necessary areas of the Mars settlement. Even though it does not have the same compressive and tensile strength as materials brought from Earth.

In the tests carried out in a high CO2 environment, the flexural strength of regolith concrete based on 60% and 70% sulphur was measured as 5.95±0.25 MPa, the compressive strength as 3.66±0.25 MPa and the modulus of elasticity as 9.57±0.32 GPa. (Tute & Goulas, 2024) In addition, another study predicted that the compressive strength could vary between 5-50 MPa depending on the content of the material, and the tensile strength was measured to be 3.44 MPa. (Khoshnevis et al., n.d.)

The values on which we base these analyses are the resultant values from the research carried out by Tute and Goulas (2024). In order to calculate values such as shear modulus, some values are added to the research carried out by Tute and Goulas (2024) and preliminary assumptions such as setting Poisson’s ratio at 0.2 have also been made.

FEA

The FEA takes into account gravity, which is 3.721 m/s2, and internal pressure loads, which are 101.3 kPa, but not thermal, micrometeoroid, wind or seismic loads, as detailed in the previous ‘Loads’ section.

Finite element analysis is applied in two forms: before and after internal pressure loading; primitive dome-like shell (Fig.34) and Arabidopsis-like shell (Fig.35). The ultimate purpose of analysing both shapes is to compare the shape that is affected by internal pressure loads and whose resistance to compressive and tensile loads is expected to increase based on the Arabidopsis cell wall. The analyses were first applied to the primitive dome-shaped shell that emerged after gravitational loading (Fig.36,38,40) and the resulting shell that resembled the Arabidopsis cell wall after internal pressure of 101.3 kPa and gravitational loading. (Fig.37,39,41)

The analysis used the sulphur concrete described above as the main and only material in the 15 cm thick structure. The ultimate purpose of analysing both forms is to compare the form that is affected by internal pressure loads and whose resistance to compressive and tensile loads is expected to increase based on the Arabidopsis cell wall.

In the results, while negative red values given as a result of the FEA analysis indicate compressive strength, positive blue values indicate tensile strength. Although the values given in the legends of the FEA analyses are in kN/cm2, we will give the values in MPa when reporting the results here for the better comparison with the material. As can be seen, the principal stress and von Mises stress distributions to which the structures are subjected in the structural analyses vary between the primitive dome-like shell shape, which forms only under gravity loads, and the Arabidopsis-like shell, which forms under internal pressure and gravity loads.

Looking at the analysis values of the simple dome-shaped shell, in the primary principle stress analysis, the highest compressive stress value was 0.045 MPa, while the highest tensile stress value was 6.28 MPa (fig.36). In the secondary principal stress analysis, the highest compressive stress value was 0.788 MPa, while the highest tensile stress value was 3.83 MPa (fig.38). In Von Mises analyses, the highest tensile stress was measured to be 5.75 MPa (fig.40). The maximum displacement was measured to be 0.436 cm (fig.44).

Looking at the analysis values of the final inner shell, i.e. the Arabiodpsis-like shell, it can be seen that the stress distribution generally decreases across the surface of the shell, but the stresses increase more at the junctions of the regions that take on the shape of an inverted dome in accordance with the shape. In the primary principal stress analysis, the highest compressive stress value was 4.23 MPa and the highest tensile stress value was 16.59 MPa (fig.37). In the secondary principal stress analysis, the highest compressive stress value was 15.9 MPa and the highest tensile stress value was 5.27 MPa (fig.39). In Von Mises analyses, the maximum tensile stress was measured to be 15.2 MPa (fig.41). The maximum displacement was measured to be 0.807 cm (fig.45).

As a result of the structural analyses of the structure taking the form of the cell wall of Arabiopdisis applied to the structure: it was seen that the final structure distributes the stress over a large part of its surface, but the transferred stress at the joints of the inverted dome-shaped regions inwards has a higher value than the primitive dome-like shell.

At the end of this stage, the final structure obtained somewhat promising results by reducing the stress on most of the surface, but the tensile strength value of the sulphur regolith material used in the analysis was given as 5.95±0.25 MPa and the compressive strength value was given as 3.66±0.25 MPa (Tute & Goulas, 2024). According to these values, it is important to reconsider and reinforce the newly proposed form in places where the tensile stress increases, that is, in the joints of the inverted dome-shaped regions in the structure, where high stress is transferred. This will be addressed in the next chapter.

4.4 Modification of The Structure

It is a fact that the analysed structure needs to be reinforced where the tensile zones increase. While on Earth this can be done with various types of materials, on the surface of Mars it is currently almost impossible due to the complex process and high energy requirements of producing materials such as steel.

Materials such as carbon fibre or aramid

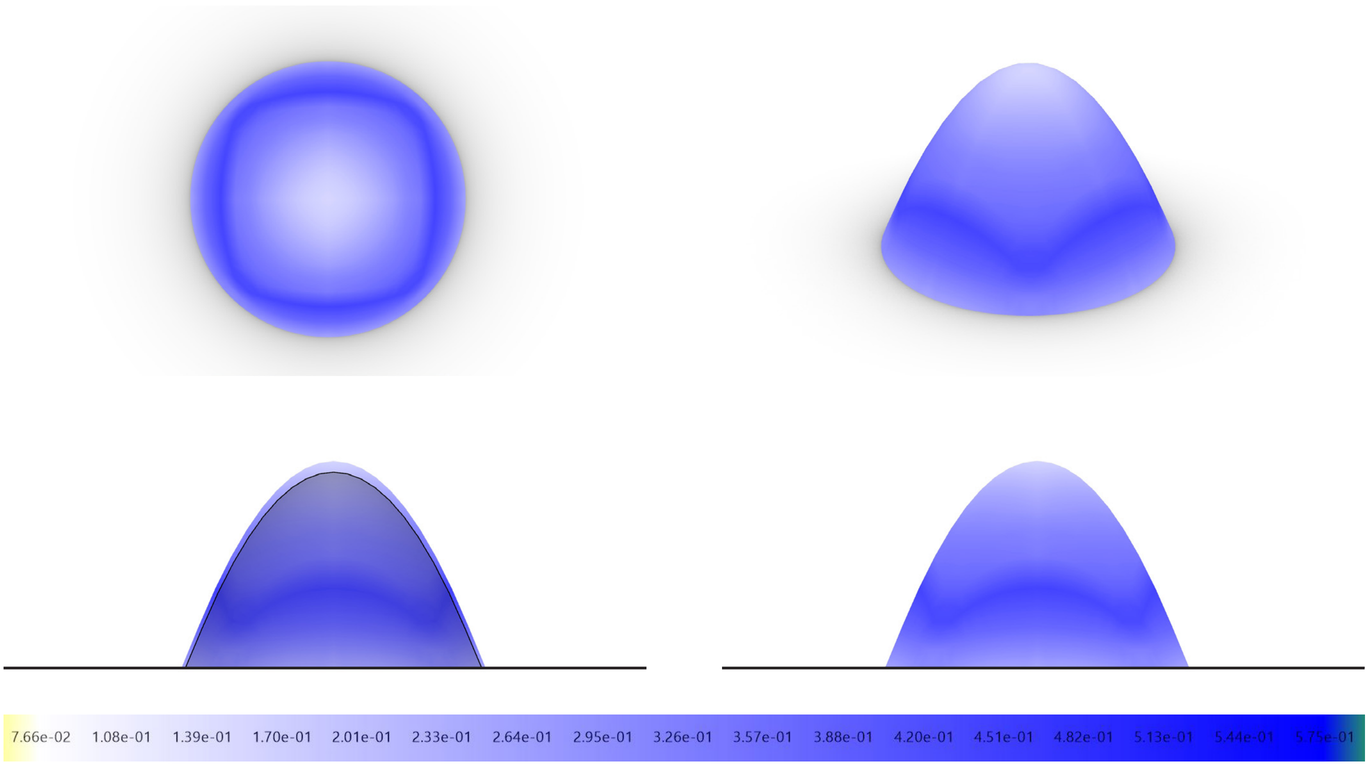


Figure 36: Simple dome principle stress

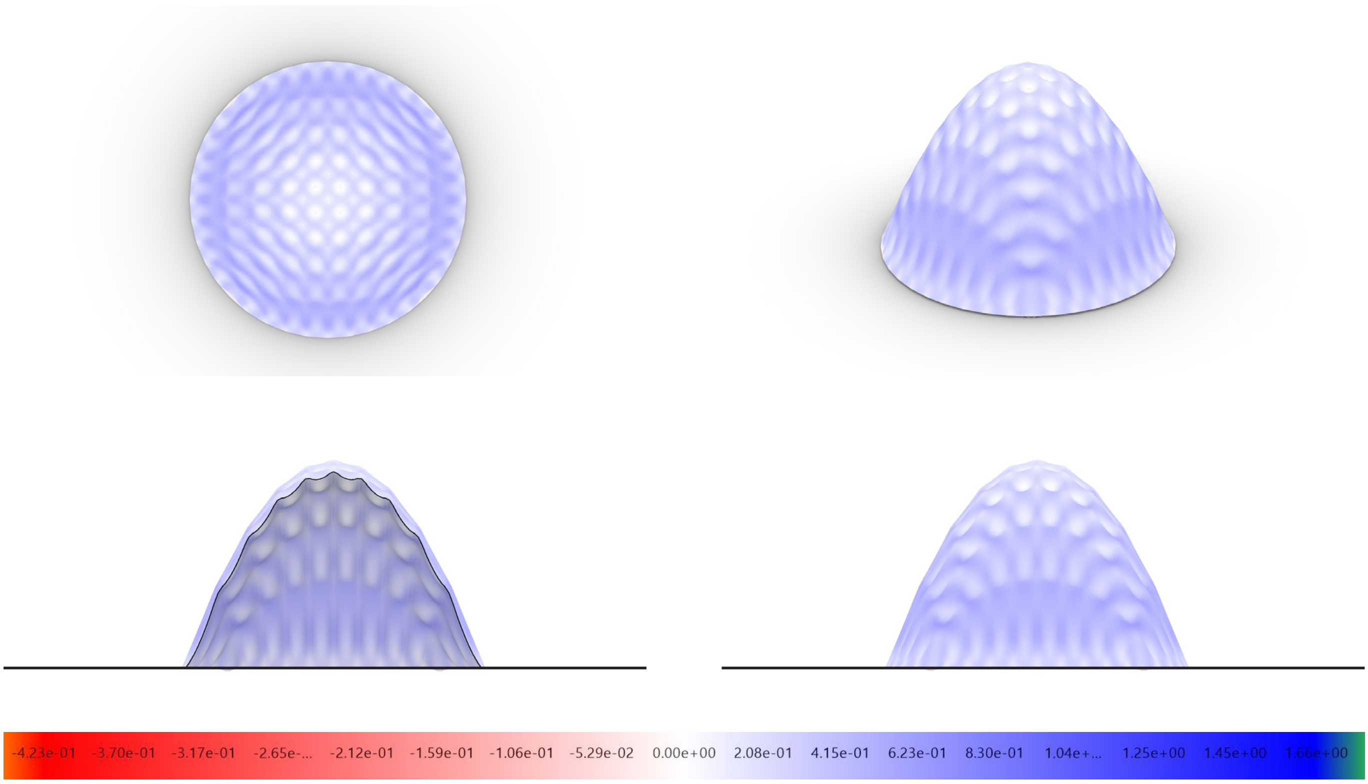


Figure 37: Inner shell principle sress

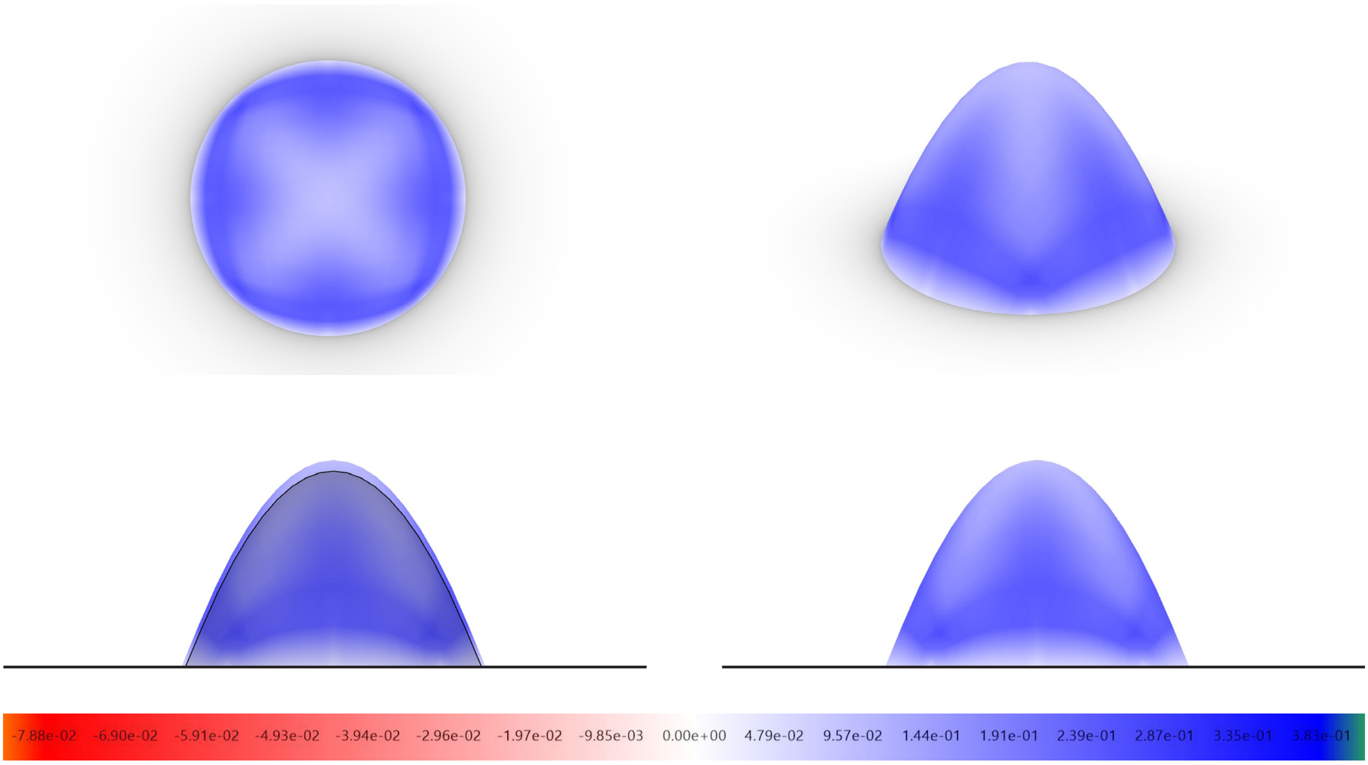


Figure 38: Simple dome secondary principle stress

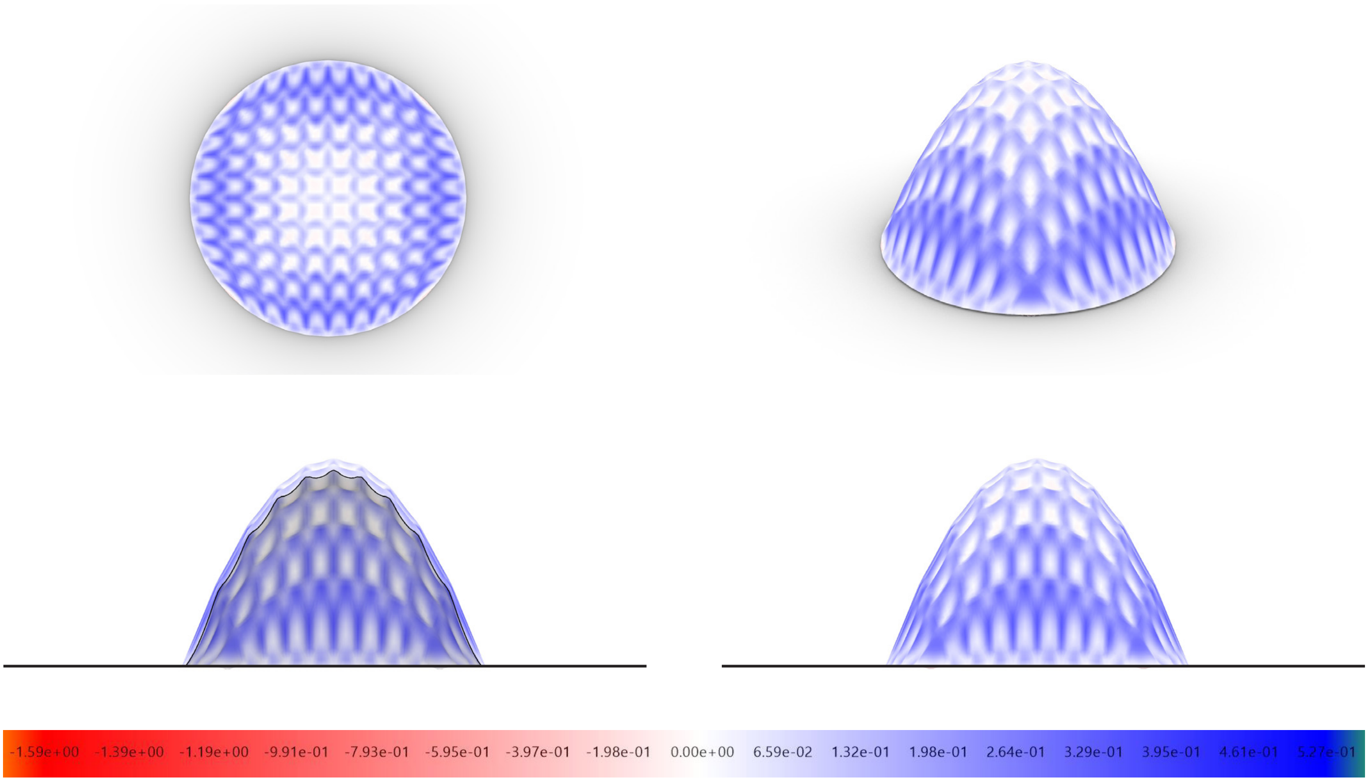


Figure 39: Inner shell secondary principle stress

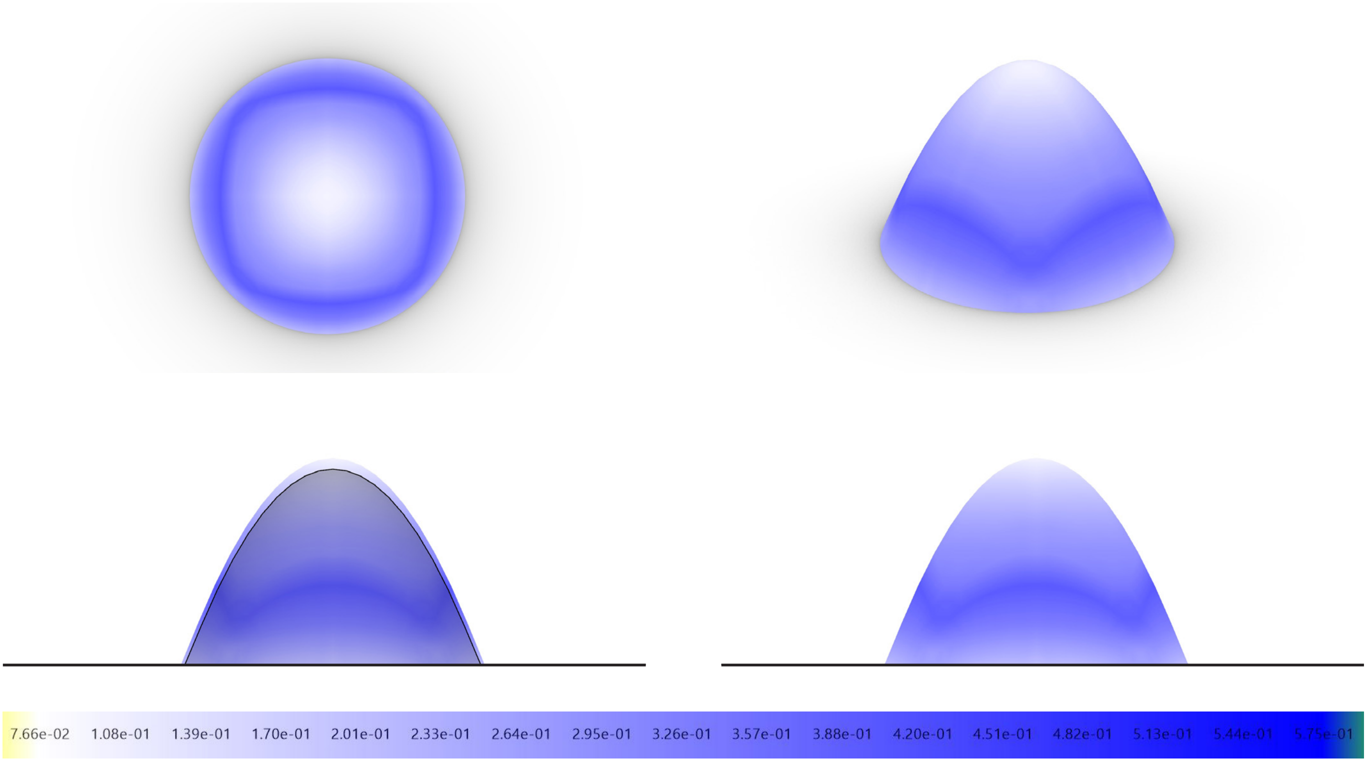


Figure 40: Single dome Von Misses stress

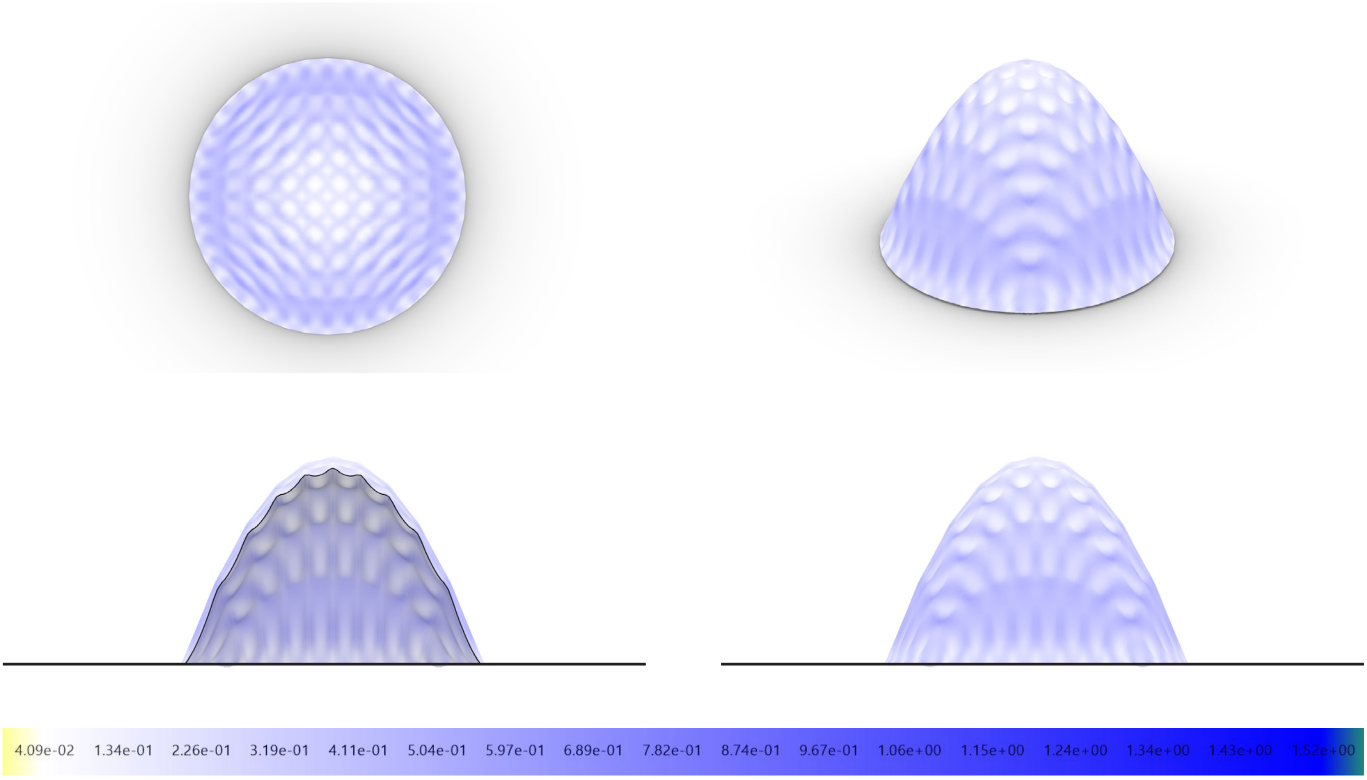


Figure 41: Inner shell Von Misses stress

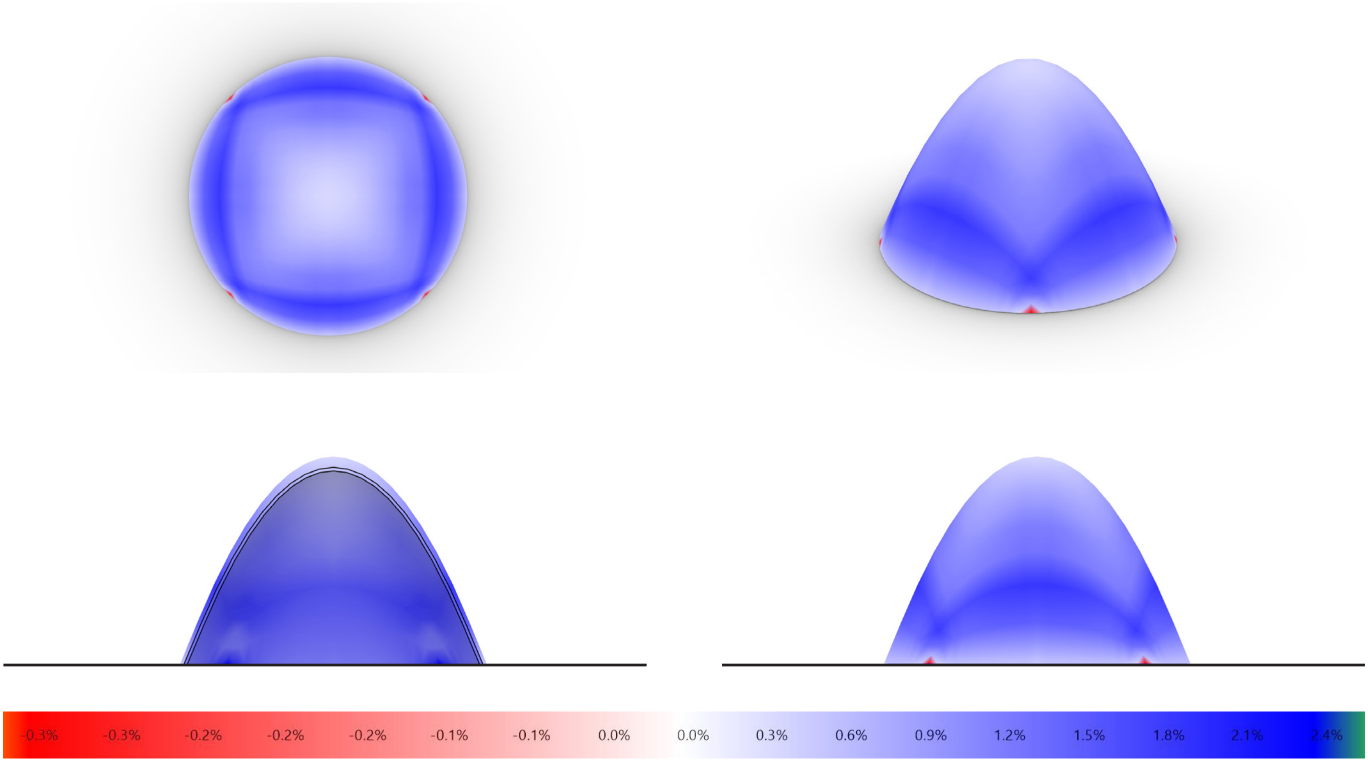


Figure 42: Single dome utilization stress

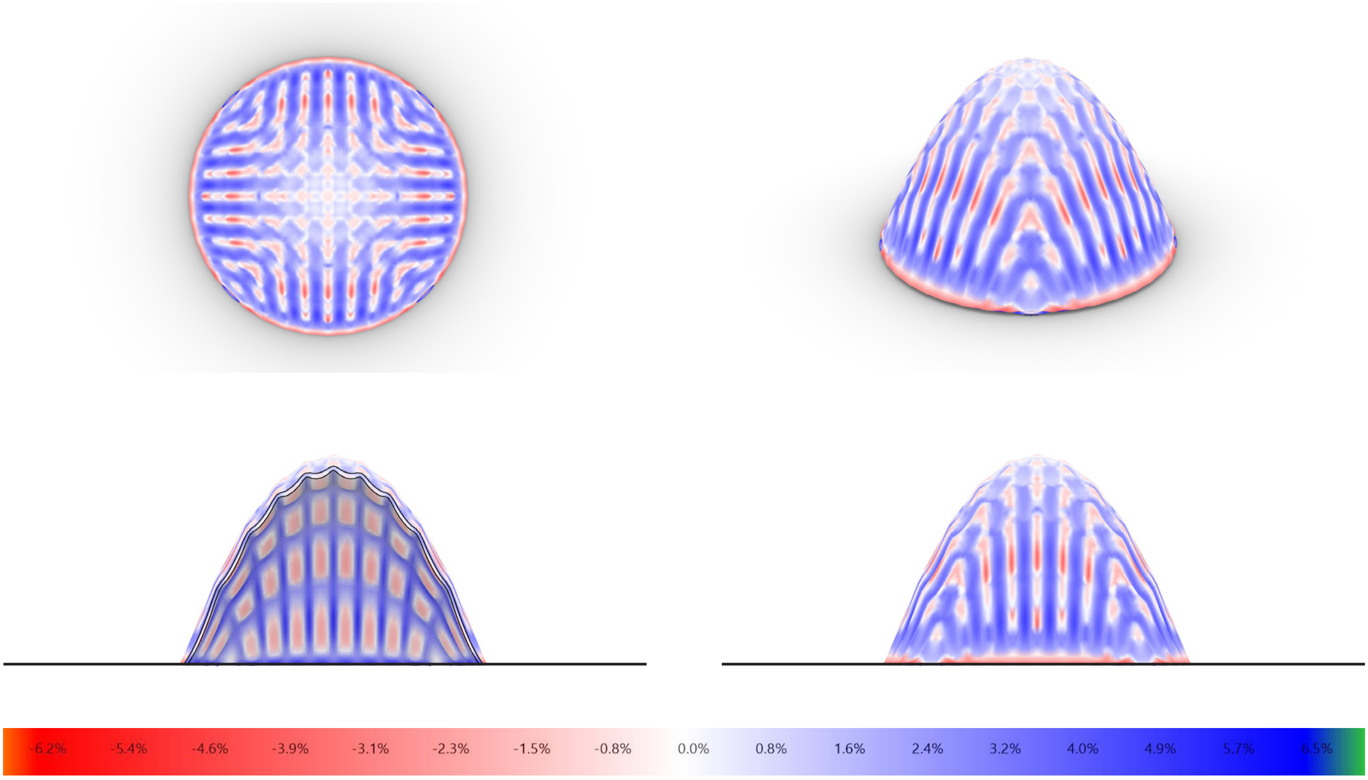


Figure 43: Inner shell utilization stress

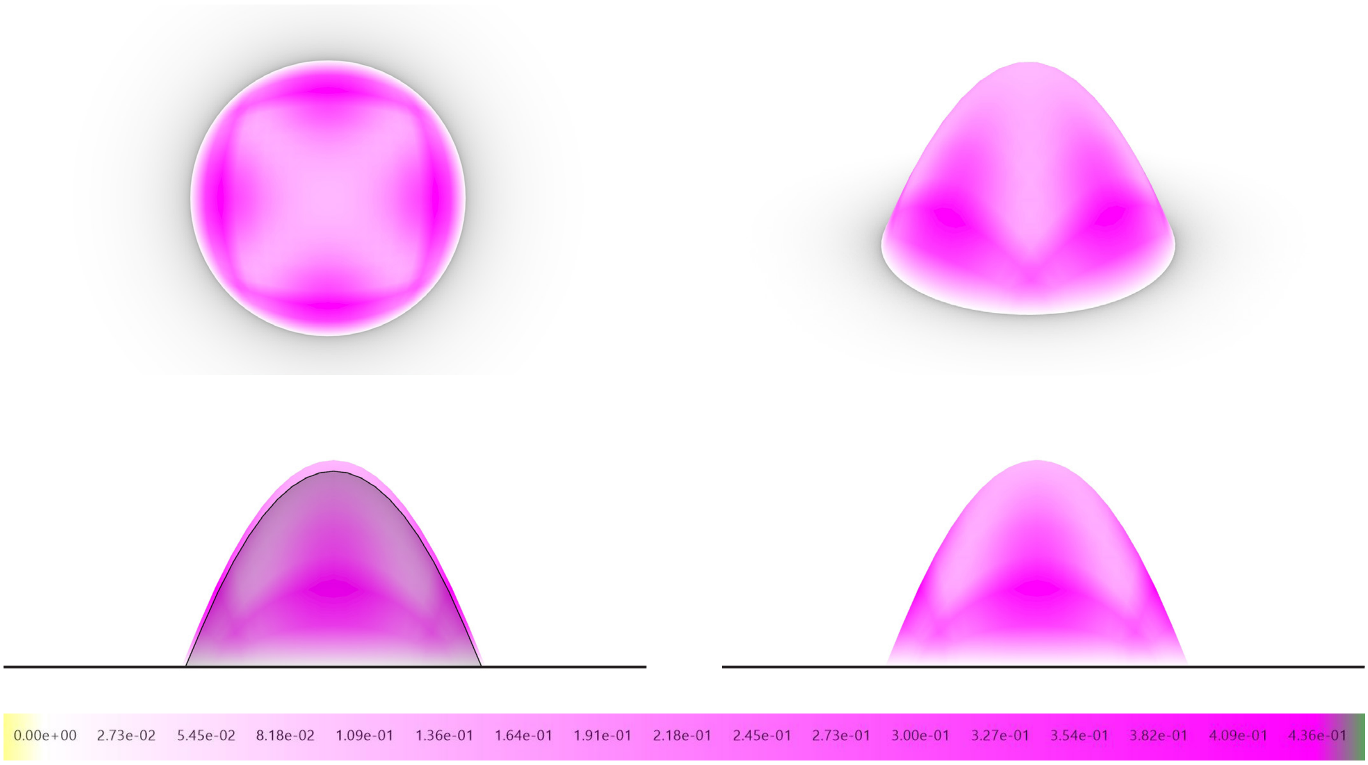


Figure 44: Single dome displacement stress

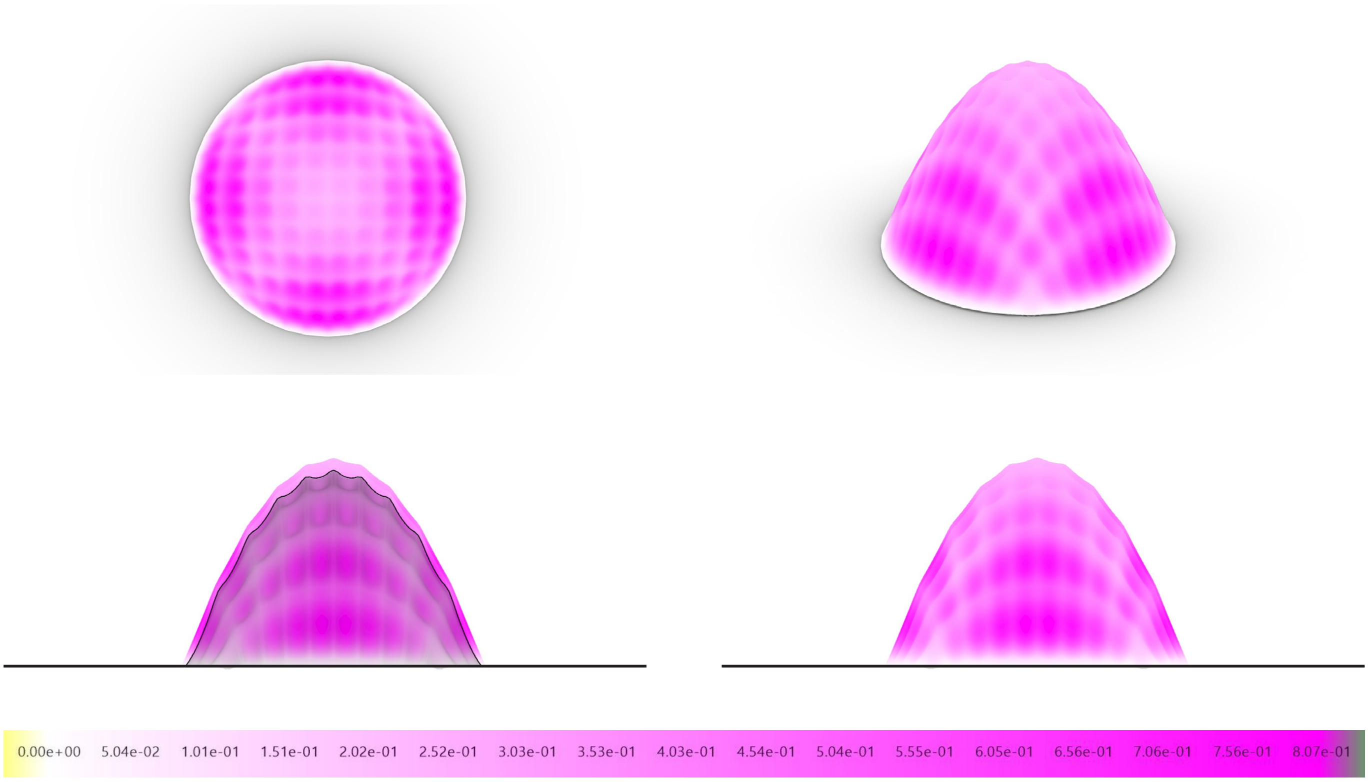


Figure 45: Inner shell displacement stress

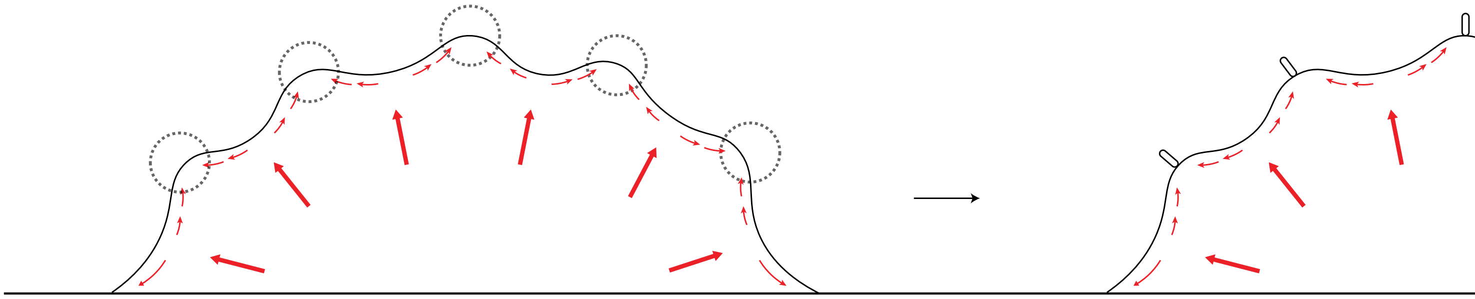


Figure 46: Structural progress

fibre (Kevlar), which are widely used for reinforcement on Earth, are the first to come to mind. The high tensile strength of carbon fibre, ranging from 3 GPa to 7 GPa (Mirdehghan, 2021), and the tensile strength of aramid fibre, ranging from 2.758 GPa to 3 GPa (Jia et al., 2023), are very satisfactory. Unfortunately, they have to be transported from the earth.

For this reason, the use of fibres derived from basalt material, which is abundant on Mars and has a volcanic soil for a sustainable Mars settlement, will reduce transport costs. In addition, the tensile strength of basalt fibres, which ranges from 2.7 GPa to 3.2 GPa (Li, 2020), is very satisfactory compared to carbon and aramid fibres, reducing transport costs.

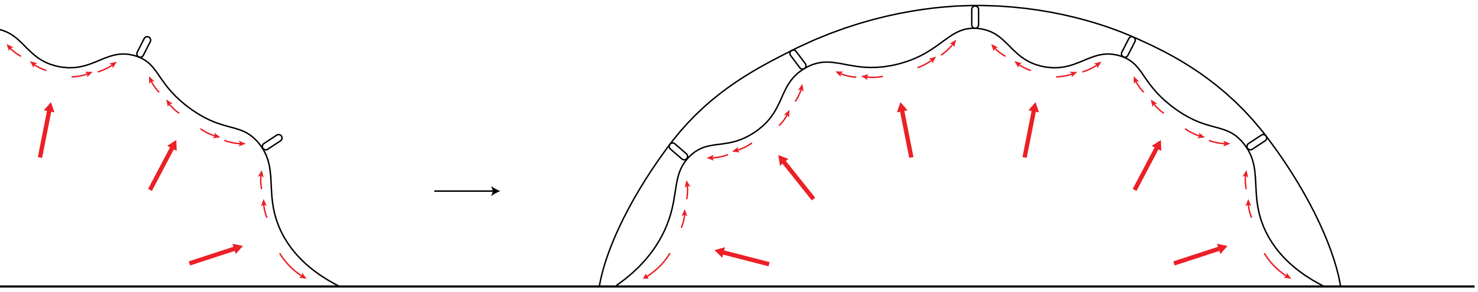
Therefore, as a first step, we decided to reinforce the areas of high tensile stress with basalt fibre (Fig.46,47). We then decided to support these areas with a rib structure based on the microfilaments in the cell wall structure of Arabidopsis (fig.46,48). For this structure, which will be slightly thinner than the main structure, we first carried out a form finding process under gravitational forces (Fig.48).

In the subsequent structural analyses of the rib structure, in the primary principal stress analysis, the highest compressive stress value was 0.002 MPa, while the highest tensile stress value was 0.01 MPa (Fig.49). In the secondary principal stress analysis, the highest compressive stress value was 0.004 MPa, while the highest tensile stress value was 0.005 MPa (Fig.50). In Von Mises analyses, the highest tensile stress was measured to be 0.014 MPa (Fig.51).

Final layer

Although the most important environmental factor to consider for a Mars structure is the pressure differential, there are other factors we must consider for the well-being of the inhabitants and equipment within the habitat.

Among the factors affecting the design of the Martian structure that we touched on in Chapter 2, it is essential to include a layer for radiation, sandstorms and temperature fluctuations.



While radiation is a much more dangerous element in a vacuum environment (e.g. deep space travel such as Mars) or on the surface of the Moon, the fact that Mars has a relatively thin atmosphere, which at least provides some filtering, is still far below the desired level. While different materials and different thicknesses are required for radiation, it is very important which type of radiation affects the surface. Whilst certain materials will act as a successful barrier to SPE radiation at various thicknesses, the radiation we call GRC is much more dangerous. An average of 1 to 2 metres of regolith will provide the required level of protection, but the thickness varies depending on the type of material.

Global dust storms, which we see as another important element, are actually caused by wind and are the process of the wind lifting dust off the ground. Although the wind loads are not very important, as mentioned above, the particles carried by the wind pose a threat to the habitat. Since Martian dust contains toxic substances, a habitat that is not sealed well enough will have many problems in the future.

Perhaps the second most important factor after radiation is temperature variation. Temperatures that can vary between -153 C and 20 C during the day will put some stress on the shielding structures of Mars habitats.
In our previous steps, we designed a rib structure, which we thought would support our inner shell, based on the microfilament-like structures also found in the cell walls of Arabidopsis, on top of our inner shell, which we designed based on the inner layer of the cell walls of Arabidopsis, which we designed to be resistant to internal pressure. Now, for reasons such as radiation, temperature fluctuations and sand storms, we add a final layer, like the last layer of the Arabidopsis cell walls, and complete our structure.

In this layer, after the gravitational form-finding (Fig.52), we carried out the structural analysis. As a result of the structural analysis, in the primary principal stress analysis, the highest tensile stress value was 0.007 MPa (Fig.53). In the secondary principal stress analysis, the highest tensile stress value was 0.002 MPa (Fig.54). In Von Mises analyses, the highest tensile stress was measured to be 0.006 MPa (Fig.55).

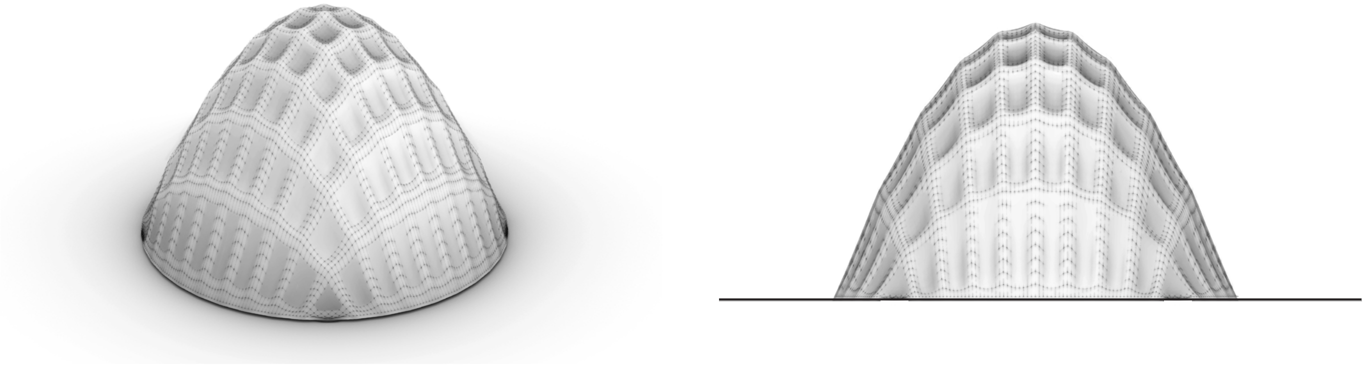


Figure 47: Microfilaments, basalt fiber structure

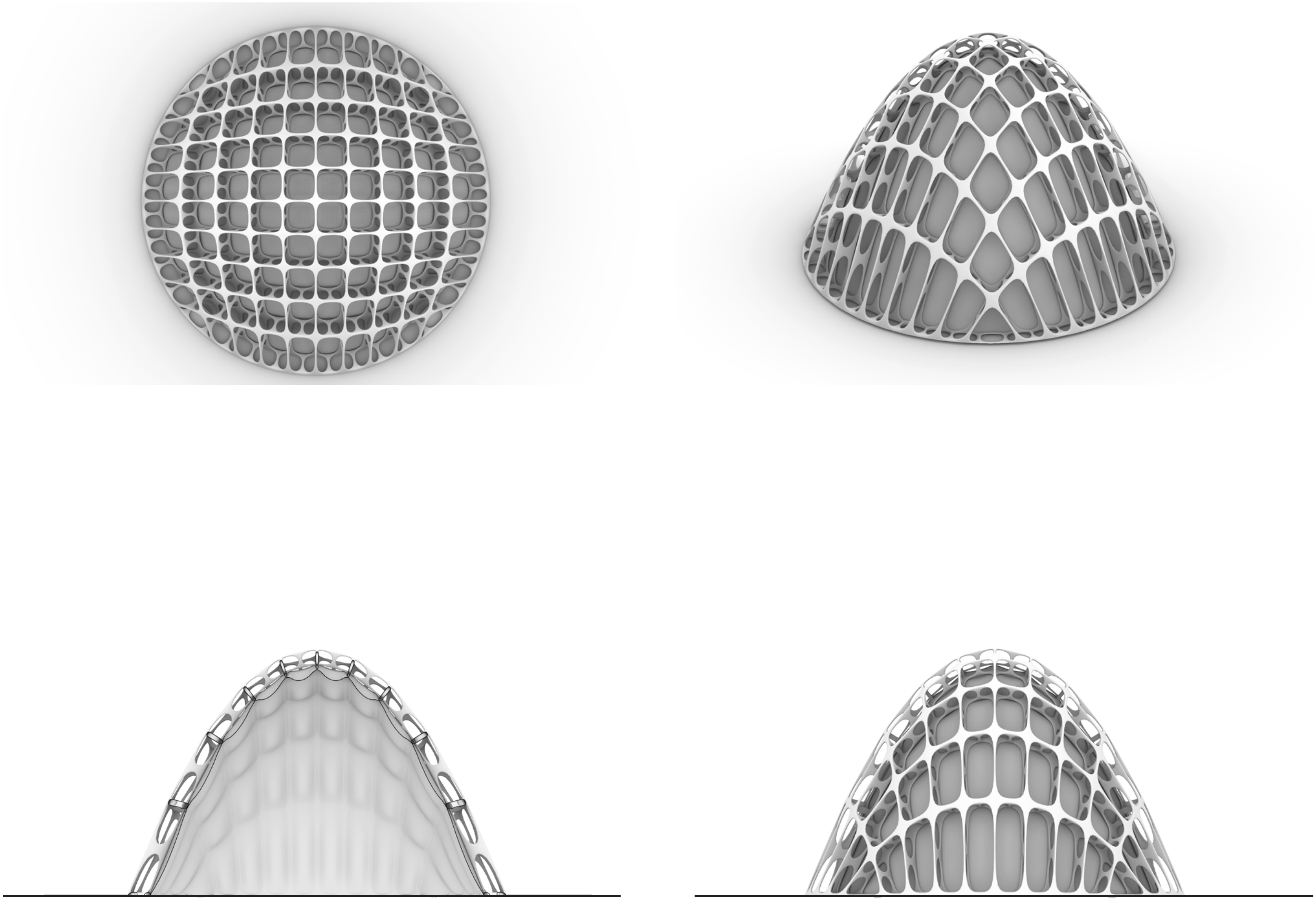


Figure 48: Rib structure form-finding

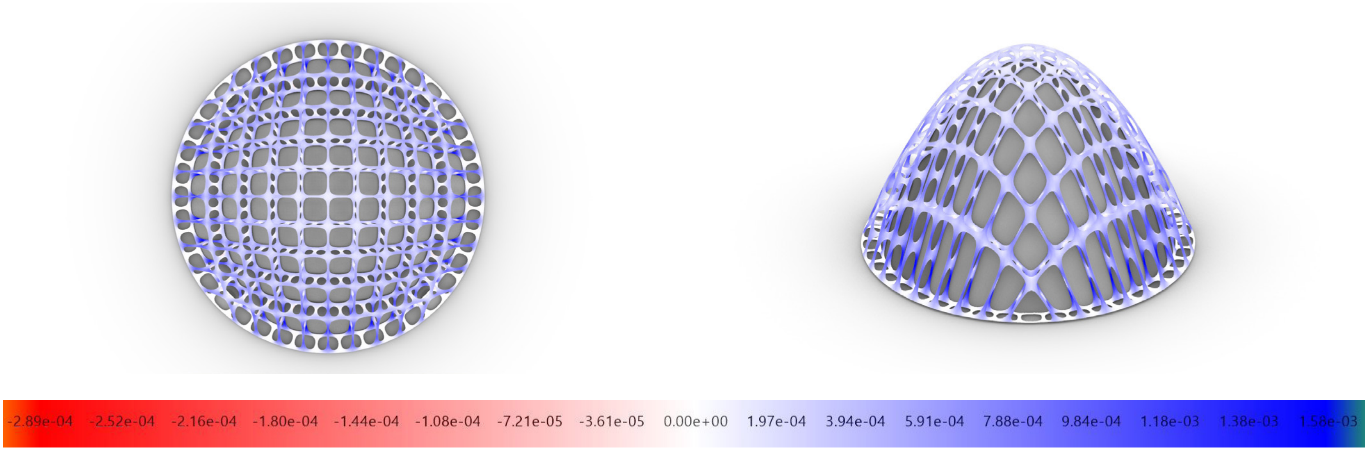


Figure 49: Rib structure principle stress

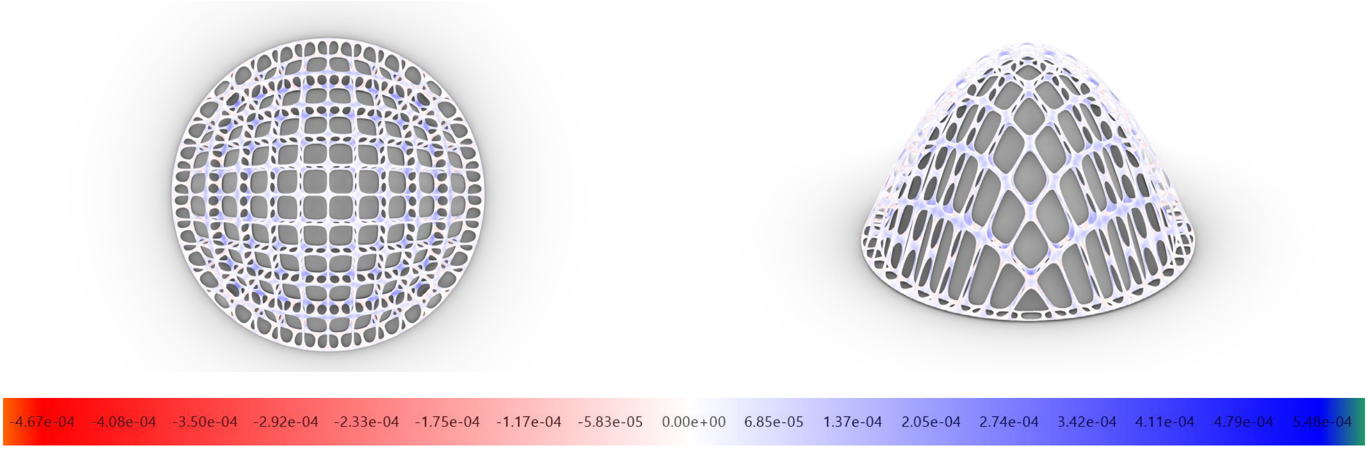


Figure 50: Rib structure secondary principle stress

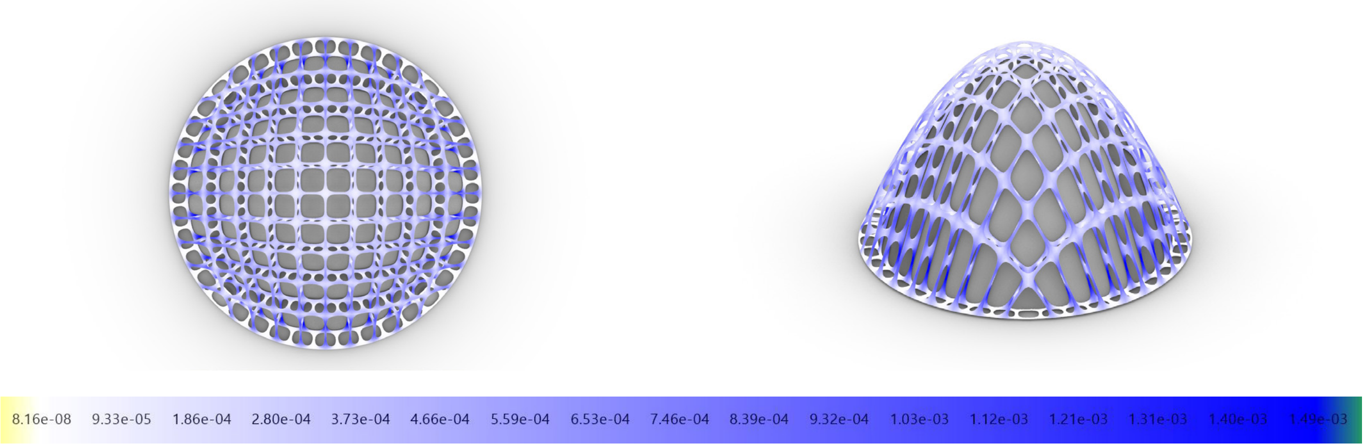


Figure 51: Rib structure Von Misses stress

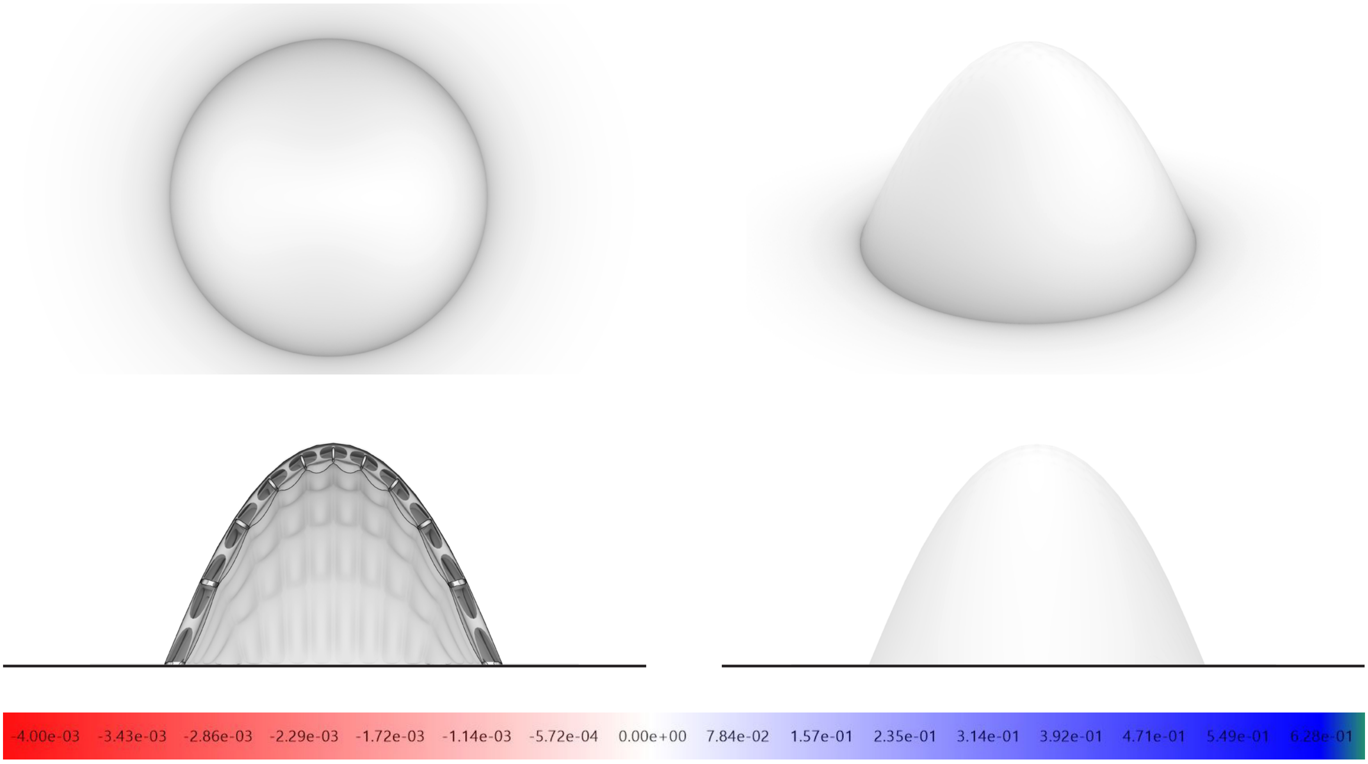


Figure 52: Outer shell form-finding

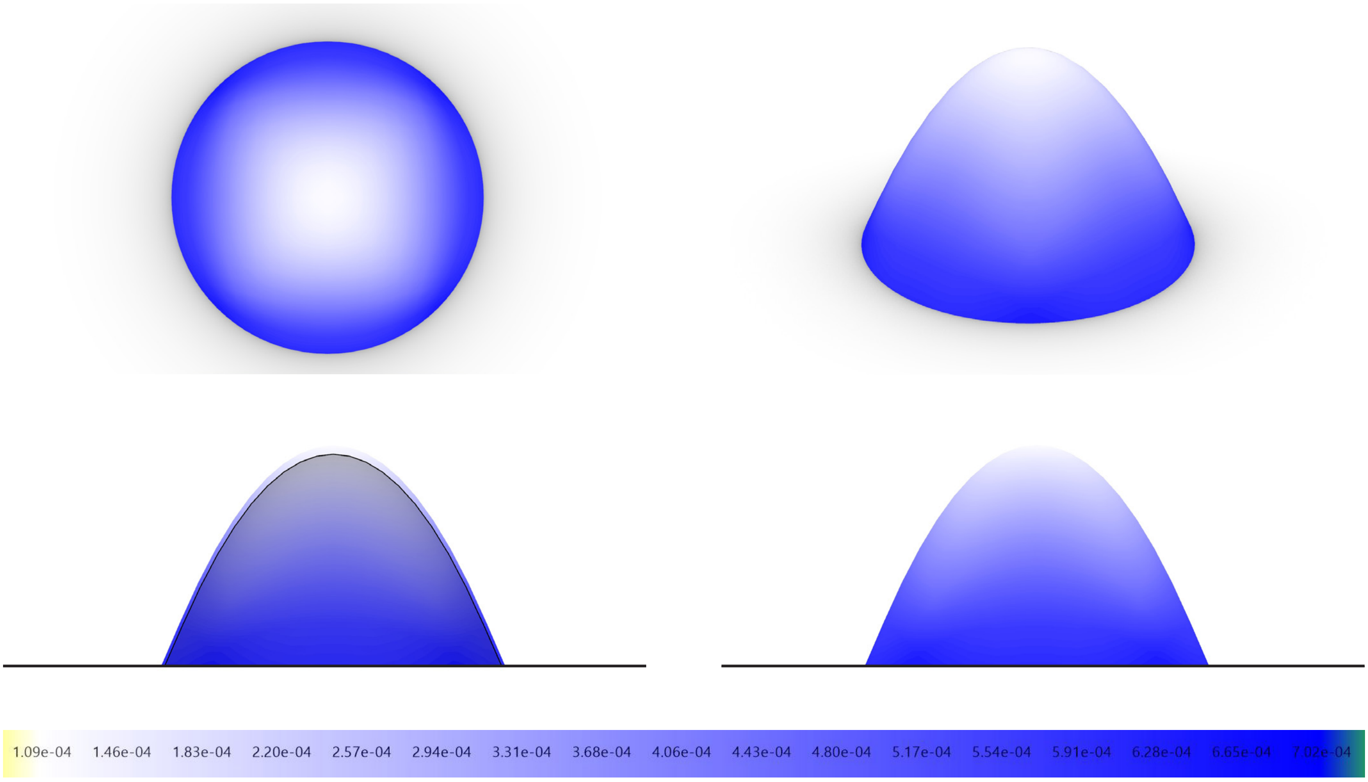


Figure 53: Outer shell principle stress

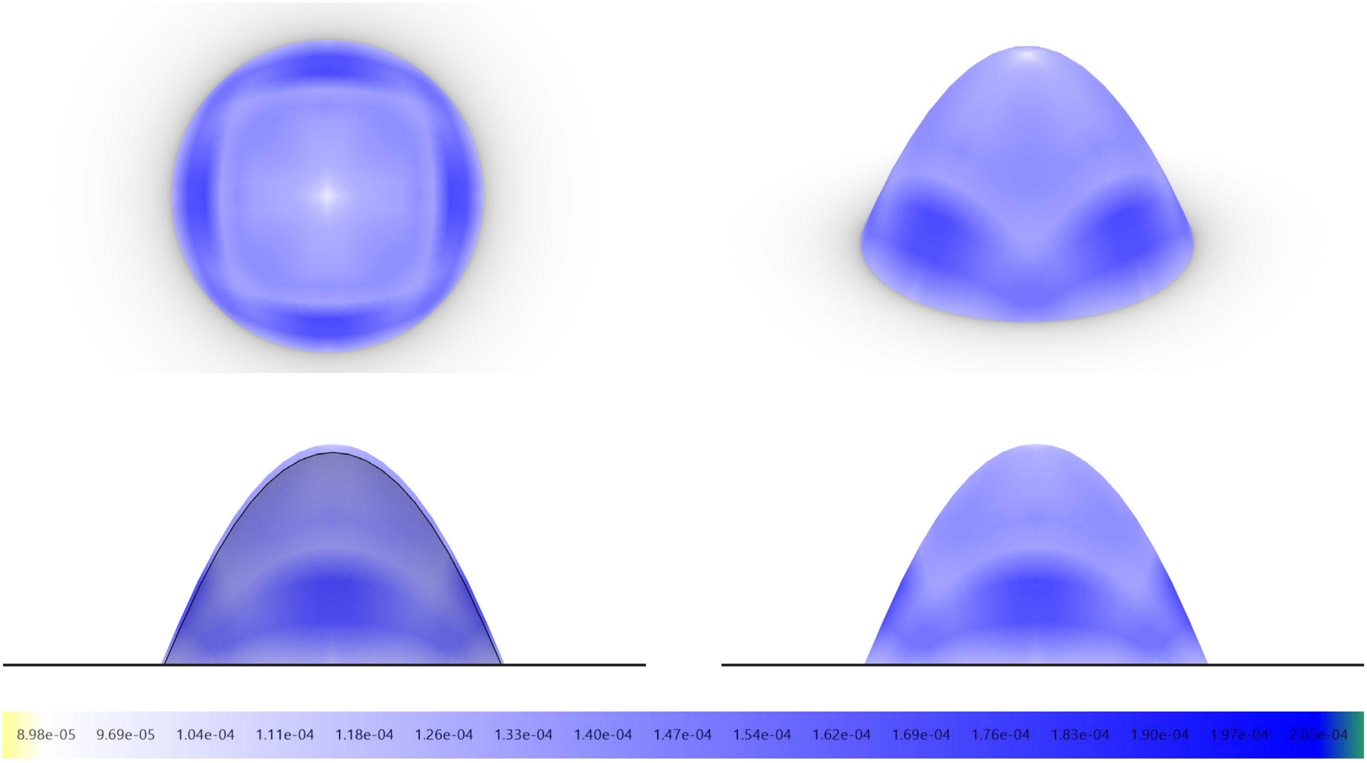


Figure 54: Outer shell secondary principle stress

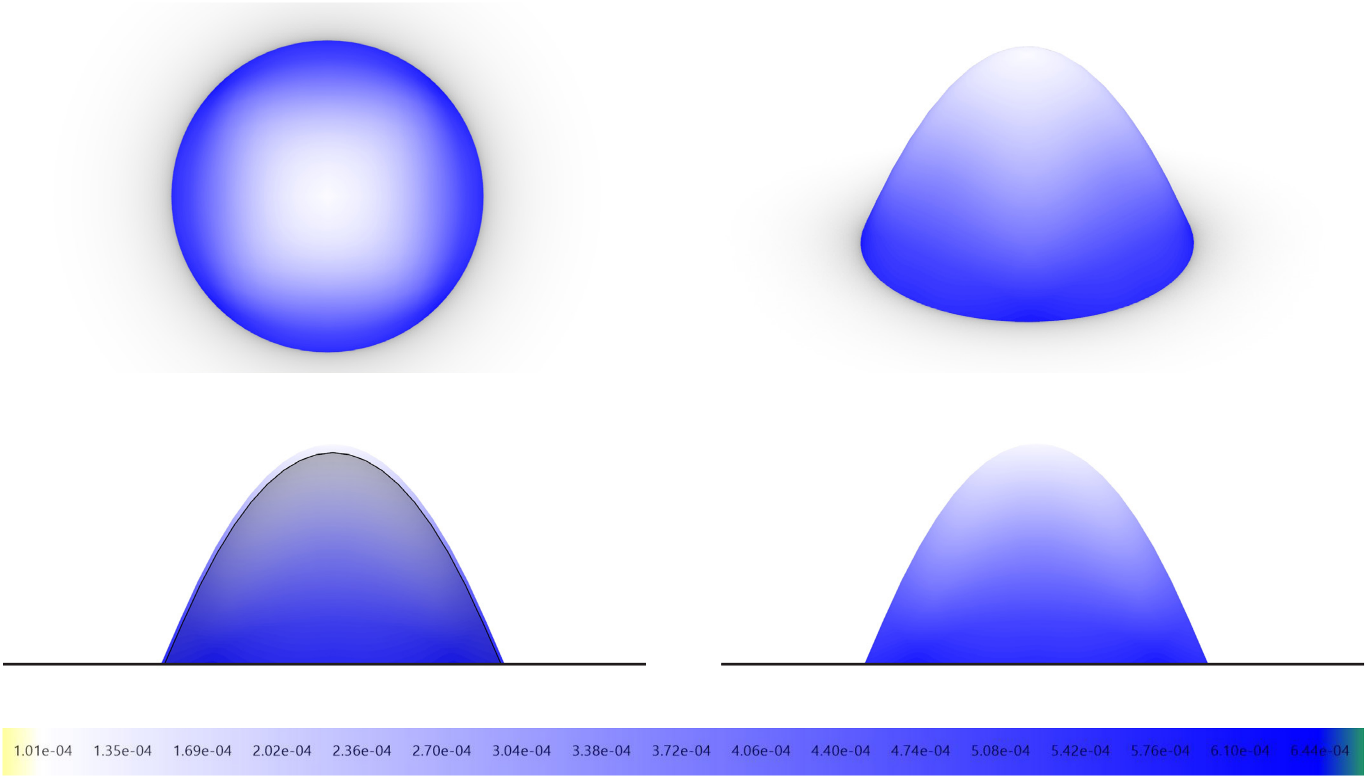
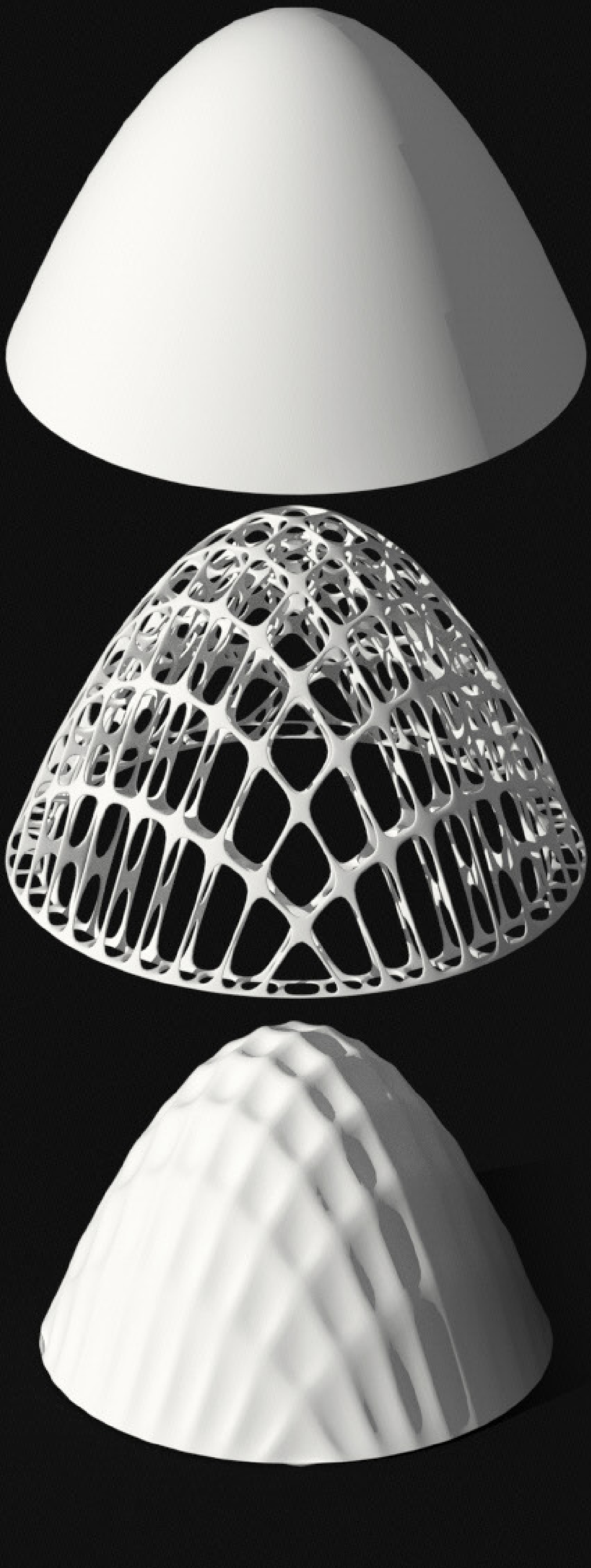


Figure 55: Outer shell Von Misses stress



Part 5
Closing Remarks

This part is a brief summary of what we obtained as a result of the proposed structure based on the research question. In the discussion section, we go back to the research question and explain the analytical evaluation of the proposed structure and the limitations we encountered in both designing and analyzing the structure. The conclusion chapter will give a general overview of the thesis, evaluate the overall findings and further research opportunities.

5.1 Discussion

A form-finding procedure was first carried out for the designed shell under gravitational loads and pressure loads caused by the internal and external pressure difference of the habitat, based on the form of the cell walls of Arabidopsis Thaliana, the main biological reference of the research, under internal turgor pressure. The structural analysis of the shell was based on the sulphur concrete material to be produced from local Martian materials.

As a result of the structural analysis, it was observed that the proposed structure distributed the stress better over the surface, but stress accumulation occurred at the joints of the inverted dome-shaped sections towards the inside of the habitat. The highest compressive stress to which the structure was subjected in these areas was measured to be 4.23 MPa, while the highest tensile stress was measured to be 16.59 MPa. Based on these results, it was understood that sulphur concrete, which has an average compressive strength of 5.95 MPa and a tensile strength of 3.66 MPa (Tute & Goulas, 2024), could not provide sufficient strength in areas where tensile stresses were concentrated.

For this reason, reinforcement was applied in two stages to the joints where tensile stress is high. In the first step, fibres with a tensile strength of 2.7 GPa to 3.2 GPa (Li, 2020), obtained from basalt material, which is abundant on the surface of Mars, were added to reinforce these parts of the structure. Then, in a second step, these regions were supported with a ribbed structure similar to microfilaments, which increase the structural strength between the two layers of the cell walls of Arabidopsis Thaliana. As these structures were not subjected to internal pressure, the maximum compressive and tensile stresses they were subjected to varied between 0.002 MPa and 0.01 MPa, as determined by structural analysis under gravitational loads.

A further shell was added on top of the rib structure to protect it from other extreme environmental factors such as radiation, global sand storms and temperature fluctuations. The shape of this shell was determined and a base was prepared for the required radiation isolation by separating it from the inner shell by 1 metre. The structural analysis of this structure showed that the maximum stress varied between 0.007 MPa and 0.002 MPa.

However, it was also found that there were some shortcomings in the analysis of the structure. The displacement experienced by the inner shell could not be entered as an input to the rib structure and therefore the rib structure analysis resulted in strength data without the deformation data of the underlying structure. A similar scenario occurred for the last layer, the outer shell, and the displacement data of the rib structure and inner shell underneath could not be entered as input.

When analysing the outer shell, which is the outer layer that protects the habitat from environmental extremes such as temperature fluctuations, sandstorms and radiation, it was only analysed under gravitational loads, and loads due to temperature changes were not included in the analysis. Since the site selection element required to include these analyses, i.e. the location on Mars where this structure would be built, is beyond the scope of this research the outer shell was placed from an architectural point of view to complete the design.

The final drawback was that the final structure could not be analyzed as a monolithic structure. The inner shell, the rib structure and the outer shell were connected but could not be defined and analyzed as a single structure.

On the other hand perhaps because the main topic of this research was to investigate a structure with high compressive strength, the 1 metre gap between the two structures was not filled for another important environmental factor such as radiation, which we would have been fine with if it had not been a showstopper. After proper research into what these materials are and what their thicknesses should be, this gap could have been filled or other layers could have been added to the structure.

5.2 Conclusion

The main objective of this research was to study the behavior of a Class III structure, i.e. a structure made entirely of Martian materials found on the surface of Mars, under pressure loads, which we consider to be the main prevailing load for structures on the surface of Mars, and to find a solution in the form of a response to Martian materials whose resistance to tensile loads is not very suitable, making biomimicry the main part of the reference.

In the beginning of the reseach, we tried to understand Mars in depth, and after looking at the reasons for the extreme environmental conditions on Mars, we discussed the basic environmental factors affecting a Martian structure. While we were trying to minimize the stress caused by the pressure differential, which is the main factor we identified on the basis of this, we tried to do this on a shape because of the inherently low tensile stress of Martian materials. So we applied the shape of the cell walls of the plant Arabidopsis Thaliana, which is the biomimetic rol model we use, to the Martian structure under internal pressure.

We obtained the structure to which we applied the pressure differential and gravity loads using the form-finding method, and then carried out structural analyses. As a result of these analyses, the structure, which was developed step by step, generally distributed the loads well, but the stress intensity was high in the areas where the loads were collected. For this reason, the rib structure was added as a second layer to the structure by reinforcing the areas of high tensile stress, and its strength was expected to increase.

The structure was completed by adding a third layer to cope with the environmental factors on Mars, such as radiation and temperature fluctuations, and to protect the rib structure and inner shell from these stresses.

The completed structure consists of three layers, each designed to withstand different environmental factors: the inner shell, which is designed to withstand loads due to pressure differentials; the rib structure, which is placed on top of the inner shell to support the inner shell where high tensile stresses are experienced; and finally the outer shell, which protects the inner structures and, of course, the habitat from the environmental factors of Mars. There were, of course, a number of shortcomings in the finished structure which were the subject of further researches.

Finally, in future research, to reduce the stress distribution concentrated in certain areas of the inner layer, considering the shape of the Arabidopsis cell wall under turgor pressure, the tissue between the cell walls is also dense, to increase the strength where stress accumulates, the regions where stress is concentrated in the inner layer of the structure can be designed according to this behavior. Also, a better connection between the rib structure and the outer shell can be made in the regions of the structure where stress is concentrated, and better results can be achieved by playing with the form, dimensions and density in the regions where stress is concentrated throughout the structure.

We hope that this research, despite its shortcomings, has been able to contribute to the literature on how to make a structure built with Martian materials resistant to the stresses caused by the pressure differential, which we consider to be the most important problem to be solved for a sustainable and permanent Mars settlement.

References

A, N. a. S., & O'Neill, G. K. (2004). Space Settlements. http://books.google.ie/books?id=sk8AAAAACAAJ&dq=Space+settlements&hl=&cd=4&source=gbs_api

Adams, C., Arenales, O., Cohen, M., Coniglio, S., Cook, J., Dominoni, A., Downard, M., Duerk, D., Durao, M. J., Eichold, A., Fairburn, S., Favata, P., Hall, T., Hauplik, S., Hertz, C., Howe, A. S., Imhof, B., Komure, Y., Konopek, A., . . . Zigon, A. (n.d.). THE MILLENNIUM CHARTER: Fundamental Principles of Space Architecture. In SPACE ARCHITECTURE MISSION STATEMENT.

Alberts, B., Johnson, A., Lewis, J., Morgan, D., Raff, M., Roberts, K., & Walter, P. (2008). Molecular Biology of the Cell. Garland Science. http://books.google.ie/books?id=_NkpygAACAAJ&dq=molecular+biology+BruceAlbert&hl=&cd=3&source=gbs_api

Aristoteles, & Babür, S. (1997). Gökyüzü üzerine. http://books.google.ie/books?id=NzcwAAAACAAJ&dq=Aristoteles+G%C3%B6ky%C3%BCz%C3%BC+%C3%9Czerine&hl=&cd=1&source=gbs_api

Aung, M., & Balaram, J. (2020, April). Mars Helicopter/Ingenuity. NASA Facts. https://mars.nasa.gov/files/mars2020/MarsHelicopterIngenuity_FactSheet.pdf

Barlow, N. (2008). Mars: An Introduction to its Interior, Surface and Atmosphere. Cambridge University Press. http://books.google.ie/books?id=o25Bojs7FMkC&dq=Mars+:+an++introduction+to+its+interior&hl=&cd=1&source=gbs_api

Barnett, J. S., & Kring, J. P. (2003). Human Performance in Extreme Environments: A Preliminary Taxonomy of Shared Factors. Proceedings of the Human Factors and Ergonomics Society Annual Meeting/ Proceedings of the Human Factors and Ergonomics Society . . . Annual Meeting, 47(8), 961–964. https://doi.org/10.1177/154193120304700802

Beck, C. B. (2010). An Introduction to Plant Structure and Development. Cambridge University Press. http://books.google.ie/books?id=zSK1BuxMh9cC&printsec=frontcover&dq=An+Introduction+to+Plant+Structure+and+Development&hl=&cd=1&source=gbs_api

Benaroya, H. (2018). Building Habitats on the Moon. Springer. http://books.google.ie/books?id=hp1GDwAAQBAJ&printsec=frontcover&dq=Building+Habitats+on+the+Moon&hl=&cd=1&source=gbs_api

Benyus, J. M. (2009). Biomimicry. Harper Collins. http://books.google.ie/books?id=mDHKVQyJ94gC&printsec=frontcover&dq=benyus&hl=&cd=1&source=gbs_api

Bhushan, B. (2016). Biomimetics. Springer. http://books.google.ie/books?id=oMWbCwAAQBAJ&printsec=frontcover&dq=Biomimetics+Bharat+Bhushan&hl=&cd=2&source=gbs_api

Birnbaum, K., Sindelar, R., Gärtner, J. R., & Wirtz, D. C. (2002). Material properties of trabecular bone structures. Surgical and Radiologic Anatomy, 23(6), 399–407. https://doi.org/10.1007/s00276-001-0399-x
Carr, M. H. (2007). The Surface of Mars. Cambridge University Press. http://books.google.ie/books?id=uLHIJ6sjohwC&printsec=frontcover&dq=The+Surface+of+Mars&hl=&cd=1&source=gbs_api

Carr, M. H., & Evans, N. (1980). Images of Mars. http://books.google.ie/books?id=i00CAAAAIAAJ&printsec=frontcover&dq=Images+of+Mars:+The+Viking+Extended+Mission&hl=&cd=1&source=gbs_api

Chambers, J. E. (2004). Planetary accretion in the inner Solar System. Earth and Planetary Science Letters, 223(3–4), 241–252. https://doi.org/10.1016/j.epsl.2004.04.031

Chapman, M. (2007). The Geology of Mars. Cambridge University Press. http://books.google.ie/books?id=96N2Ik3ABRYC&printsec=frontcover&dq=the+geology+of+mars&hl=&cd=1&source=gbs_api

Cohen, M. M. (1996). Habitat Distinctions: Planetary versus Interplanetary Architecture. In 1996 AIAA Space Programs and Technologies Conference (p. September 24-26). American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.1996-4467

Cohen, M. M. (2002). SELECTED PRECEPTS IN LUNAR ARCHITECTURE.

Coles, K. S., Tanaka, K. L., & Christensen, P. R. (2019). The Atlas of Mars. Cambridge University Press. http://books.google.ie/books?id=2R6pDwAAQBAJ&printsec=frontcover&dq=The+Atlas+of+Mars&hl=&cd=1&source=gbs_api

Coles, P. (2001). Cosmology: A Very Short Introduction. OUP Oxford. http://books.google.ie/books?id=6tkOUkpwSIAC&printsec=frontcover&dq=a+short+introduction+to+cosmology&hl=&cd=1&source=gbs_api

Connors, M. M., Harrison, A. A., & Akins, F. R. (1985). Living Aloft. http://books.google.ie/books?id=5-8zTvXxNjsC&printsec=frontcover&dq=Living+aloft:+human+requirements&hl=&cd=1&source=gbs_api

Cosgrove, D. J. (1993). Wall extensibility: its nature, measurement and relationship to plant cell growth. New Phytologist, 124(1), 1–23. https://doi.org/10.1111/j.1469-8137.1993.tb03795.x

Cosgrove, D. J. (1997). Relaxation in a high-stress environment: the molecular bases of extensible cell walls and cell enlargement. the Plant Cell, 9(7), 1031–1041. https://doi.org/10.1105/tpc.9.7.1031

Cosgrove, D. J. (2000). Expansive growth of plant cell walls. Plant Physiology and Biochemistry, 38(1–2), 109–124. https://doi.org/10.1016/s0981-9428(00)00164-9

Cosgrove, D. J. (2015). Plant cell wall extensibility: connecting plant cell growth with cell wall structure, mechanics, and the action of wall-modifying enzymes. Journal of Experimental Botany, 67(2), 463–476. https://doi.org/10.1093/jxb/erv511

Cosgrove, D. J. (2017). Diffuse Growth of Plant Cell Walls. Plant Physiology, 176(1), 16–27. https://doi.org/10.1104/pp.17.01541

Cowley, A., Imhof, B., Teeney, L., Waclavicek, R., Spina, F., Canals, A., Schleppi, J., & Soriano, P. L. (2016). An ISRU-Based Architecture for Human Habitats on Mars: the “Lava Hive” Concept. https://doi.org/10.5281/zenodo.202220

Cox, P. B., & Cohen, A. (2019). The Planets. HarperCollins UK. http://books.google.ie/books?id=WYpoDwAAQBAJ&printsec=frontcover&dq=The+Planets&hl=&cd=2&source=gbs_api

Ching, F. D. K., Onouye, B. S., & Zuberbuhler, D. (2009). Building Structures Illustrated. Wiley. http://books.google.ie/books?id=gVgzOAAACAAJ&dq=Building+Structures+Illustrated&hl=&cd=3&source=gbs_api

De Blasio, F. V. (2018). Mysteries of Mars. Springer. http://books.google.ie/books?id=wdhwDwAAQBAJ&printsec=frontcover&dq=De+Blasio,+F.+V.+(2018).+Mysteries+of+Mars.+Springer.&hl=&cd=1&source=gbs_api

Dk. (2017). The Astronomy Book. Dorling Kindersley Ltd. http://books.google.ie/books?id=LhgrDwAAQBAJ&printsec=frontcover&dq=the+astronomy+book&hl=&cd=1&source=gbs_api

Feldman, W. C., Prettyman, T. H., Maurice, S., Plaut, J. J., Bish, D. L., Vaniman, D. T., Mellon, M. T., Metzger, A. E., Squyres, S. W., Karunatillake, S., Boynton, W. V., Elphic, R. C., Funsten, H. O., Lawrence, D. J., & Tokar, R. L. (2004). Global distribution of near surface hydrogen on Mars. Journal of Geophysical Research, 109(E9). https://doi.org/10.1029/2003je002160

Fisher, J. A., Richardson, M. I., Newman, C. E., Szwast, M. A., Graf, C., Basu, S., Ewald, S. P., Toigo, A. D., & Wilson, R. J. (2005). A survey of Martian dust devil activity using Mars Global Surveyor Mars Orbiter Camera images. Journal of Geophysical Research, 110(E3). https://doi.org/10.1029/2003je002165

Garcia, M. O., Tree, J. P., Wessel, P., & Smith, J. R. (2020). Pūhāhonu: Earth's biggest and hottest shield volcano. Earth and Planetary Science Letters, 542, 116296. https://doi.org/10.1016/j.epsl.2020.116296

Greeley, R., Arvidson, R. E., Barlett, P. W., Blaney, D., Cabrol, N. A., Christensen, P. R., Fergason, R. L.,

Golombek, M. P., Landis, G. A., Lemmon, M. T., McLennan, S. M., Maki, J. N., Michaels, T., Moersch, J. E., Neakrase, L. D. V., Rafkin, S. C. R., Richter, L., Squyres, S. W., De Souza, P. A., . . . Whelley, P. L. (2006). Gusev crater: Wind related features and processes observed by the Mars Exploration Rover Spirit. Journal of Geophysical Research, 111(E2). https://doi.org/10.1029/2005je002491

Gohnert, M. (2022). Shell Structures. Springer Nature. http://books.google.ie/books?id=GMIcEAAAQBAJ&printsec=frontcover&dq=mitchell+gohnert&hl=&cd=1&source=gbs_api

Gruber, P. (2008). The signs of life in architecture. Bioinspiration & Biomimetics, 3(2), 023001. https://doi.org/10.1088/1748-3182/3/2/023001

Gruber, P. (2011). Biomimetics in Architecture. Springer. http://books.google.ie/books?id=_6VSwKITN3EC&dq=PETRA+GRUBER+B%C4%B0OM%C4%B0MET%C4%B0CS+%C4%B0N+ARCH%C4%B0TECTURE&hl=&cd=1&source=gbs_api

Gruber, P., & Benti, D. (2013). Biomimetic strategies for innovation and sustainable development. Biomimetic Strategies for Innovation and Sustainable Development. https://www.researchgate.net/publication/304625195_Biomimetic_strategies_for_innovation_and_sustainable_development

Gruber, P., Häuplik, S., Imhof, B., Özdemir, K., Waclavicek, R., & Perino, M. A. (2007). Deployable structures for a human lunar base. Acta Astronautica, 61(1–6), 484–495. https://doi.org/10.1016/j.actaastro.2007.01.055

Gutiérrez, J. L., Jones, C. G., Strayer, D. L., & Iribarne, O. O. (2003). Mollusks as ecosystem engineers: the role of shell production in aquatic habitats. Oikos, 101(1), 79–90. https://doi.org/10.1034/j.1600-0706.2003.12322.x

Haeuplik-Meusburger, S., & Ozdemir, K. (2012). Deployable Lunar Habitation Design. In Springer eBooks (pp. 469–502). https://doi.org/10.1007/978-3-642-27969-0_20

Hamant, O., Heisler, M. G., Jönsson, H., Krupinski, P., Uyttewaal, M., Bokov, P., Corson, F., Sahlin, P., Boudaoud, A., Meyerowitz, E. M., Couder, Y., & Traas, J. (2008). Developmental Patterning by Mechanical Signals in Arabidopsis. Science, 322(5908), 1650–1655. https://doi.org/10.1126/science.1165594

Hartmann, W. K., & Neukum, G. (2001). Cratering Chronology and the Evolution of Mars. In Space sciences series of ISSI (pp. 165–194). https://doi.org/10.1007/978-94-017-1035-0_6

Häuplik-Meusburger, S. (2011a). Architecture for Astronauts. Springer. http://books.google.ie/books?id=uZTBjgEACAAJ&dq=Architecture+for+Astronauts&hl=&cd=2&source=gbs_api

Häuplik-Meusburger, S., & Bannova, O. (2016). Space Architecture Education for Engineers and Architects. Springer. http://books.google.ie/books?id=_ITeCwAAQBAJ&printsec=frontcover&dq=Sandra+Hauplik-Meusberger&hl=&cd=3&source=gbs_api

Häuplik-Meusburger, S., & Bishop, S. (2021b). Space Habitats and Habitability. Springer Nature. http://books.google.ie/books?id=1wcxEAAAQBAJ&pg=PA1&dq=Space+Habitats+and+Habitability.+Springer+Nature&hl=&cd=1&source=gbs_api

Häuplik-Meusburger, S., & Griffin, B. (2021). The Interesting Challenges of Designing for Humans in Space. ResearchGate. https://doi.org/10.7480/spool.2021.2.5267

Heilbron, J. (2001, April 27). Measuring the Earth, Modernized | Geodetic Surveys, GPS & Satellite Imaging. Encyclopedia Britannica. https://www.britannica.com/topic/Measuring-the-Earth-Modernized-1673316

Hinterman, E., Moccia, A., Baber, S., Maffia, F., Sciarretta, S., Smith, T., Stamler, N., Nowak, H., Lukic, J., Sumini, V., Zhan, Z., Schneiderman, T., Lordos, G., Seaman, E., Babakhanova, S., Kusters, J., Bernelli-Zazzera, F., Maggiore, P., Mainini, L., & Hoffman, J. (2022). MarsGarden: Designing an ecosystem for a sustainable multiplanetary future. Acta Astronautica, 195, 445–455. https://doi.org/10.1016/j.actaastro.2022.03.011

Hollander, J. B. (2023). The First City on Mars: An Urban Planner's Guide to Settling the Red Planet. Springer Nature. http://books.google.ie/books?id=H3WrEAAAQBAJ&printsec=frontcover&dq=The+First+City+on+Mars&hl=&cd=2&source=gbs_api

Hoornaert, S., Lassabe, N., Finzinger, C., Penalva, M., Pechstein, A., Chirazi, J., & Mathis, F. (2020). Nature can inspire solutions for aeronautics and space sciences. Aeronautics and Aerospace Open Access Journal, 4(2), 69–79. https://doi.org/10.15406/aaoaj.2020.04.00109

Howe, A. S., & Sherwood, B. (2009). Out of this World. AIAA (American Institute of Aeronautics & Astronautics). http://books.google.ie/books?id=8OVNPgAACAAJ&dq=Out+of+this+world.+AIAA&hl=&cd=1&source=gbs_api

Ingber, D. E. (1993b). Cellular tensegrity: defining new rules of biological design that govern the cytoskeleton. J. Cell Sci. 104, 613-627.

InSight. (2015). NASA. https://www.nasa.gov

Ivakov A, Persson S (2012) Plant cell walls. In: eLS. Wiley, Chichester

Järvstråt, N., & Toklu, Y. C. (2004). Design and Construction for Self-sufficiency in a Lunar Colony. ResearchGate. https://www.researchgate.net/publication/228918710_Design_and_Construction_for_Self-sufficiency_in_a_Lunar_Colony

Jia, H., Sheng, Y., Guo, P., Underwood, S., Chen, H., Kim, Y. R., Li, Y., & Ma, Q. (2023). Effect of synthetic fibers on the mechanical performance of asphalt mixture: A review. Journal of Traffic and Transportation Engineering/Journal of Traffic and Transportation Engineering, 10(3), 331–348. https://doi.org/10.1016/j.jtte.2023.02.002

Kapsali, V. (2016). Biomimicry for Designers. National Geographic Books. http://books.google.ie/books?id=bNiNEAAAQBAJ&dq=veronika+kapsali+biomimetics+for+designers&hl=&cd=2&source=gbs_api

Keaveny, T. M., Wachtel, E. F., Guo, X., & Hayes, W. C. (1994). Mechanical behavior of damaged trabecular bone. Journal of Biomechanics, 27(11), 1309–1318. https://doi.org/10.1016/0021-9290(94)90040-x

Kennedy, K. (2002). The Vernacular of Space Architecture. https://doi.org/10.2514/6.2002-6102
Khan, A., Ceylan, S., Van Driel, M., Giardini, D., Lognonné, P., Samuel, H., Schmerr, N. C., Stähler, S. C., Duran, A. C., Huang, Q., Kim, D., Broquet, A., Charalambous, C., Clinton, J. F., Davis, P. M., Drilleau, M., Karakostas, F., Lekic, V., McLennan, S. M., . . . Banerdt, W. B. (2021). Upper mantle structure of Mars from InSight seismic data. Science, 373(6553), 434–438. https://doi.org/10.1126/science.abf2966

Khoshtinat, Shiva. (2015). Biomimetic Architecture.

Knippers, J., Nickel, K. G., & Speck, T. (2016). Biomimetic Research for Architecture and Building Construction. Springer. http://books.google.ie/books?id=XtHBDQAAQBAJ&printsec=frontcover&dq=biomimetic+research+-for+architecture&hl=&cd=1&source=gbs_api

Knippers, J., Schmid, U., & Speck, T. (2019). Biomimetics for Architecture. Birkhäuser. http://books.google.ie/books?id=lb7tDwAAQBAJ&printsec=frontcover&dq=Biomimetics+for+Architecture+Jan+Knippers&hl=&cd=1&-source=gbs_api

Kozlova, L. V., Nazipova, A. R., Gorshkov, O. V., Petrova, A. A., & Gorshkova, T. A. (2020). Elongating maize root: zone-specific combinations of polysaccharides from type I and type II primary cell walls. Scientific Reports, 10(1). https://doi.org/10.1038/s41598-020-67782-0

Kuban, D. (2010). Ottoman Architecture. Antique Collectors Club Dist. http://books.google.ie/books?id=nX-5OPgAACAAJ&dq=Do%C4%9Fan+Kuban&hl=&cd=6&source=gbs_api

Kubis, J. F. (1967). Habitability: General Principles and Applications to Space Vehicles (pp. 399–427). https://doi.org/10.1007/978-3-7091-3032-2_25

Kutschera U (2015) Comment: 150 years of an integrative plant physiology. Nat
Lasue, J., Mangold, N., Hauber, E., Clifford, S., Feldman, W., Gasnault, O., Grima, C., Maurice, S., & Mousis, O. (2012). Quantitative Assessments of the Martian Hydrosphere. Space Science Reviews, 174(1–4), 155–212. https://doi.org/10.1007/s11214-012-9946-5

Lévy, F., & Fardal, J. (2010). Indoor-Air Quality Implications of 222RN from Lunar Regolith. In Advances in engineering (pp. 277–290). https://doi.org/10.1201/9781420083330-c22

Li, D. (2020). Choice of materials for cut protective textile. In Elsevier eBooks (pp. 129–218). https://doi.org/10.1016/b978-0-12-820039-1.00005-5
Meistermann, A. (2017). Basics Loadbearing Systems. Birkhäuser. http://books.google.ie/books?id=unwk-DwAAQBAJ&printsec=frontcover&dq=Alfred+Meistermann&hl=&cd=1&source=gbs_api

Malin, M. C., Carr, M. H., & Belton, M. J. (2024, July 7). Mars | Facts, Surface, Moons, Temperature, & Atmosphere. Encyclopedia Britannica. https://www.britannica.com/place/Mars-planet/Spacecraft-exploration

Manzey, D., & Lorenz, B. (1998). Mental performance during short-term and long-term spaceflight. Brain Research Reviews, 28(1–2), 215–221. https://doi.org/10.1016/s0165-0173(98)00041-1

Mars 2020. (2019). https://www.nasa.gov

Mars Exploration Rover NASA Facts. (2004).

Mars Science Laboratory/Curiosity. (n.d.). In NASA Facts.

MARSHA — AI Spacefactory. (n.d.). AI Spacefactory. https://spacefactory.ai/marsha

Material Synthesis. (2015c). John Wiley & Sons. http://books.google.ie/books?id=jBWzCQAAQBAJ&printsec=frontcover&dq=metaerial+synthesis+achim+menges&hl=&cd=1&source=gbs_api

Melodie Yashar, "Personal Interview," 2019.

Minimum Acceptable Net Habitable Volume for Long⊗Duration Exploration Missions. (2014). In Subject Matter Expert Consensus Session Report.

Mirdehghan, S. A. (2021). Fibrous polymeric composites. In Elsevier eBooks (pp. 1–58). https://doi.org/10.1016/b978-0-12-824381-7.00012-3

Mirzaali, M. J., Schwiedrzik, J. J., Thaiwichai, S., Best, J. P., Michler, J., Zysset, P. K., & Wolfram, U. (2016). Mechanical properties of cortical bone and their relationships with age, gender, composition and microindentation properties in the elderly. Bone, 93, 196–211. https://doi.org/10.1016/j.bone.2015.11.018

Mlodinow, L., & Hawking, S. (2010). A Briefer History of Time. Random House. http://books.google.ie/books?id=NVPpTEiSQEkC&printsec=frontcover&dq=A+short+history+of+time,+stephen+hawking&hl=&cd=3&source=gbs_api

Morris, M., Ciardullo, C., Lents, K., & Yashar, M. (2016). Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O. ResearchGate. https://www.researchgate.net/publication/307965857_Mars_Ice_House_Using_the_Physics_of_Phase_Change_in_3D_Printing_a_Habitat_with_H2O

Moussavi, F. (2018). The Function of Form. Actar. http://books.google.ie/books?id=BR6dDAEACAAJ&dq=The+Function+of+Form&hl=&cd=1&source=gbs_api

Mueller, R. P., Prater, T. J., Roman, M., Edmunson, J. E., & Fiske, M. R. (2019). NASA CENTENNIAL CHALLENGE: THREE DIMENSIONAL (3D) PRINTED HABITAT, PHASE 3. 70th International Astronautical Congress (IAC), Washington, D.C., 1–13.

Myers, W. (2018). Bio Design. http://books.google.ie/books?id=FTvBswEACAAJ&dq=bio+design+william&hl=&cd=1&source=gbs_api

Niederberger, T. (2021, December 15). extremophile. Encyclopedia Britannica. https://www.britannica.com/science/extremophile

Noguchi, T., Kawano, S., Tsukaya, H., Matsunaga, S., Sakai, A., Karahara, I., & Hayashi, Y. (2014). Atlas of Plant Cell Structure. Springer. http://books.google.ie/books?id=mrpeBAAAQBAJ&printsec=frontcover&dq=atlas+of+plant+cell+structure&hl=&cd=1&source=gbs_api

Ozdemir, K. (2013). Extreme catalogue for space: Building a registry for extreme environment architecture. https://doi.org/10.1109/rast.2013.6581323

Ozdemir, K. (2020). Mars'ta ev yapmak. TMMOB Mimarlar Odası Ankara Şubesi.

Pavese, M., Manuello Bertetto, A. D. B., & Corrêa Caracas, A. C. (2023b). EARTH, MOON, AND MARS: THE INFLUENCE OF THE ENVIRONMENT ON STRUCTURAL DESIGN AND CHOICE OF CONSTRUCTION MATERIALS. In Corso Di Laurea Magistrale in Ingegneria Civile.

Pawlyn, M. (2019). Biomimicry in Architecture. Routledge. http://books.google.ie/books?id=xbKoDwAAQBAJ&printsec=frontcover&dq=michael+pawlyn&hl=&cd=1&source=gbs_api

Pawlyn, M. (2019b). Biomimicry in Architecture. Routledge. http://books.google.ie/books?id=xbKoDwAAQBAJ&printsec=frontcover&dq=michael+pawlyn&hl=&cd=1&source=gbs_api
Petranek, S. (2015). How We'll Live on Mars. Simon and Schuster. http://books.google.ie/books?id=Ld-9jAwAAQBAJ&printsec=frontcover&dq=How+we+will+live+on+Mars&hl=&cd=1&source=gbs_api Plants 1:1–3

Plaut, J. J., Picardi, G., Safaeinili, A., Ivanov, A. B., Milkovich, S. M., Cicchetti, A., Kofman, W., Mouginot, J., Farrell, W. M., Phillips, R. J., Clifford, S. M., Frigeri, A., Orosei, R., Federico, C., Williams, I.

P., Gurnett, D. A., Nielsen, E., Hagfors, T., Heggy, E., . . . Edenhofer, P. (2007). Subsurface Radar Sounding of the South Polar Layered Deposits of Mars. Science, 316(5821), 92–95. https://doi.org/10.1126/science.1139672

Pohl, G., & Nachtigall, W. (2015). Biomimetics for Architecture & Design. Springer. http://books.google.ie/books?id=Kb3YCgAAQBAJ&printsec=frontcover&dq=biomimetics+for+architecture+%26+design&hl=&cd=1&source=gbs_api

Pohl, G., & Nachtigall, W. (2015b). Biomimetics for Architecture & Design. Springer. http://books.google.ie/books?id=Kb3YCgAAQBAJ&pg=PR19&dq=g%C3%B6ran+pohl&hl=&cd=1&source=gbs_api

Radiation Exposure Comparisons with Mars Trip Calculation. (n.d.). NASA Jet Propulsion Laboratory (JPL). https://www.jpl.nasa.gov/images/pia17601-radiation-exposure-comparisons-with-mars-trip-calculation

Rapp, D. (2023). Human Missions to Mars. Springer Nature. http://books.google.ie/books?id=S-fOkEAAAQBAJ&printsec=frontcover&dq=human+missons+to+mars&hl=&cd=1&source=gbs_api

Rocard, F. (2020). Dernières nouvelles de Mars. Flammarion. http://books.google.ie/books?id=khz-jDwAAQBAJ&printsec=frontcover&dq=Francis+Rocard&hl=&cd=1&source=gbs_api

Rose, J. K. C. (2009b). Annual Plant Reviews, The Plant Cell Wall. John Wiley & Sons. http://books.google.ie/books?id=R9LU3uiNFnYC&printsec=frontcover&dq=the+plant+cell+wall+rose&hl=&cd=1&source=gbs_api

Rothery, D. A. (2010). Planets: A Very Short Introduction. OUP Oxford. http://books.google.ie/books?id=03t-poDkVTb8C&printsec=frontcover&dq=david+a+rothery&hl=&cd=2&source=gbs_api
Rovelli, C. (2014). Miletli Anaksimandros ya da bilimsel düşüncenin doğuşu. http://books.google.ie/books?id=-n1ijwEACAAJ&dq=Miletli+Anaksimandros&hl=&cd=1&source=gbs_api

Sahi, V. P., & Baluška, F. (2019). The Cytoskeleton. Springer Nature. http://books.google.ie/books?id=Qx-jBDwAAQBAJ&printsec=frontcover&dq=The+Cytoskeleton+Diverse+Roles+in+a+Plant%E2%80%99s+Life&hl=&cd=1&source=gbs_api

Sassi M, Ali O, Boudon F, Cloarec G, Abad U, Cellier C, Chen X, Gilles B, Milani P, Friml J (2014) An auxin-mediated shift toward growth isotropy promotes organ formation at the shoot meri- stem in Arabidopsis. Curr Biol 24:2335–2342

Sleep, N. H. (1994b). Martian plate tectonics. Journal of Geophysical Research, 99(E3), 5639–5655. https://doi.org/10.1029/94je00216

Smith, D. E., Zuber, M. T., & Neumann, G. A. (2001). Seasonal Variations of Snow Depth on Mars.

Science, 294(5549), 2141–2146. https://doi.org/10.1126/science.1066556

Smith, D. E., Zuber, M. T., Solomon, S. C., Phillips, R. J., Head, J. W., Garvin, J. B., Banerdt, W. B., Muhleman, D. O., Pettengill, G. H., Neumann, G. A., Lemoine, F. G., Abshire, J. B., Aharonson, O., David, C., Brown, N., Hauck, S. A., Ivanov, A. B., McGovern, P. J., Zwally, H. J., & Duxbury, T. C. (1999). The Global Topography of Mars and Implications for Surface Evolution. Science, 284(5419), 1495–1503. https://doi.org/10.1126/science.284.5419.1495

Stuster, J. W. (2011). Bold Endeavors. Naval Institute Press. http://books.google.ie/books?id=u0EibcxPJCUC&printsec=frontcover&dq=Jack+Stuster&hl=&cd=1&source=gbs_api

Szymanski DB, Cosgrove DJ (2009) Dynamic coordination of cytoskeletal and cell wall systems during plant cell morphogenesis. Curr Biol 19:R800–R811

Tavşan, C., Çelenk, A., & Tavşan, F. (2021b). Doğa ve Teknoloji Kesişiminde Neri Oxman'ın Tasarım Yaklaşımı. International Journal of Eastern Anatolia Science Engineering and Design, 3(2), 405–424. https://doi.org/10.47898/ijeased.944635

Taylor, S. R., & McLennan, S. (2009). Planetary Crusts. Cambridge University Press. http://books.google.ie/books?id=4WAxH-nYGy8C&printsec=frontcover&dq=Planetary+Crusts&hl=&cd=1&source=gbs_api

Temperature, & Atmosphere. Encyclopedia Britannica. https://www.britannica.com/place/Mars-planet/Spacecraft-exploration

Thales, M., & Anaksimandros. (2019). Fragmanlar. http://books.google.ie/books?id=oI9gzwEACAAJ&dq=fragmanlar+thales+anaksimandros&hl=&cd=1&source=gbs_api

Timoshenko, S. (1983). History of Strength of Materials. Courier Corporation. http://books.google.ie/books?id=tkScQmyhsb8C&printsec=frontcover&dq=HISTORY+OF+STRENGTH+OF+MATERIALS&hl=&cd=1&source=gbs_api

Topal, S. (2020). Kaostan Kozmosa Evrenin Hikayesi. http://books.google.ie/books?id=f7jAzQEACAAJ&dq=sel%C3%A7uk+topa+kaostan+kozmosa&hl=&cd=1&source=gbs_api

Villanueva, G. L., Mumma, M. J., Novak, R. E., Käufl, H. U., Hartogh, P., Encrenaz, T., Tokunaga, A., Khayat, A., & Smith, M. D. (2015). Strong water isotopic anomalies in the martian atmosphere: Probing current and ancient reservoirs. Science, 348(6231), 218–221. https://doi.org/10.1126/science.aaa3630

Vogel, S. (1988). Life's Devices. Princeton University Press. http://books.google.ie/books?id=i7R5DyPQ13sC&printsec=frontcover&dq=steven+vogel&hl=&cd=1&source=gbs_api

Vogel, S. (2000). Cats' Paws and Catapults: Mechanical Worlds of Nature and People. W. W. Norton & Company. http://books.google.ie/books?id=82_dCgAAQBAJ&printsec=frontcover&dq=cats+and+paws&hl=&cd=2&source=gbs_api

Wang, L., Xu, P., Yin, H., Yue, Y., Kang, W., Liu, J., & Fan, Y. (2023). Fracture Resistance Biomechanisms of Walnut Shell with High Strength and Toughening. Advanced Science, 10(27). https://doi.org/10.1002/advs.202303238

Ward, W. R. (1973). Large-Scale Variations in the Obliquity of Mars. Science, 181(4096), 260–262. https://doi.org/10.1126/science.181.4096.260

Watters, T. R., & Schultz, R. A. (2010). Planetary Tectonics. Cambridge University Press. http://books.google.ie/books?id=9PD5hxPb6fkC&printsec=frontcover&dq=planetary+tectonics&hl=&cd=1&source=gbs_api

Weintraub, D. A. (2020). Life on Mars. Princeton University Press. http://books.google.ie/books?id=vRHiD-wAAQBAJ&printsec=frontcover&dq=David+A.+Weintraub&hl=&cd=1&source=gbs_api

Whelley, P. L., & Greeley, R. (2006). Latitudinal dependency in dust devil activity on Mars. Journal of Geophysical Research, 111(E10). https://doi.org/10.1029/2006je002677
White, S., & Ree, J. (1963). HABITABILITY IN SPACE STATIONS. https://doi.org/10.2514/6.1963-138

Wilson, S. A., Howard, A. D., Moore, J. M., & Grant, J. A. (2016). A cold wet middle latitude environment on Mars during the Hesperian Amazonian transition: Evidence from northern Arabia valleys and paleolakes. Journal of Geophysical Research. Planets, 121(9), 1667–1694. https://doi.org/10.1002/2016je005052

Wilson, Z. (2000b). Arabidopsis. OUP Oxford. http://books.google.ie/books?id=C8FQJxoncKUC&printsec=frontcover&dq=arabidopsis+zoe&hl=&cd=1&source=gbs_api

Wise, J. (1985). The quantitative modelling of human spatial habitability.

Xiao, N., Felhofer, M., Antreich, S. J., Huss, J. C., Mayer, K., Singh, A., Bock, P., & Gierlinger, N. (2021). Twist and lock: nutshell structures for high strength and energy absorption. Royal Society Open Science, 8(8), 210399. https://doi.org/10.1098/rsos.210399

Yashar, M., Ciardullo, C., Morris, M., & Case, D. (2019). Mars X-House: Design Principles for an Autonomously 3D- Printed ISRU Surface Habitat. ResearchGate. https://www.researchgate.net/publication/335703520_Mars_X-House_Design_Principles_for_an_Autonomously_3D-_Printed_ISRU_Surface_Habitat

Zalasiewicz, J. (2018). Geology: A Very Short Introduction. Oxford University Press. http://books.google.ie/books?id=I45lDwAAQBAJ&printsec=frontcover&dq=geology+a+brief+intro&hl=&cd=3&source=gbs_api

Zhang, J., Li, H., Zhou, Y., Chen, S., & Rong, Q. (2023). An Analysis of Trabecular Bone Structure Based on Principal Stress Trajectory. Bioengineering, 10(10), 1224. https://doi.org/10.3390/bioengineering10101224

Zhu, D., Adebisi, W. A., Ahmad, F., Sethupathy, S., Danso, B., & Sun, J. (2020). Recent Development of Extremophilic Bacteria and Their Application in Biorefinery. Frontiers in Bioengineering and Biotechnology, 8. https://doi.org/10.3389/fbioe.2020.00483

Zuber, M. T., Smith, D. E., Solomon, S. C., Abshire, J. B., Afzal, R. S., Aharonson, O., Fishbaugh, K., Ford, P. G., Frey, H. V., Garvin, J. B., Head, J. W., Ivanov, A. B., Johnson, C. L., Muhleman, D. O., Neumann, G. A., Pettengill, G. H., Phillips, R. J., Sun, X., Zwally, H. J., . . . Duxbury, T. C. (1998). Observations of the North Polar Region of Mars from the Mars Orbiter Laser Altimeter. Science, 282(5396), 2053–2060. https://doi.org/10.1126/science.282.5396.2053

Zurek, R. W., & Martin, L. J. (1993). Interannual variability of planet encircling dust storms on Mars. Journal of Geophysical Research, 98(E2), 3247–3259. https://doi.org/10.1029/92je02936

Figures

Figure 1: by author

Figure 2: by author

Figure 3: Society, P. (2020, April 15). Interior structures of Earth, Mars and the Moon, to scale. The Planetary Society. https://www.planetary.org/space-images/interior-structures-of-earth-mars-moon

Figure 4: Mars - NASA Science. (n.d.). https://science.nasa.gov/mars/

Figure 5-10: by authors

Figure 11: Claudiagarage. (2023, January 12). Leonardo's flying machines, Zoroaster da Peretola, the test flight. The Florence Insider. https://theflorenceinsider.com/leonardo-flying-machine/

Figure 12: Familia, S. (2018, February 5). The Sagrada Família, a repository of other Gaudí projects - Blog Sagrada Família. Blog Sagrada Família. https://blog.sagradafamilia.org/en/divulgation/the-sagrada-familia-repository-of-other-gaudi-projects/

Figure 13: Admin. (2023, May 11). Frei Otto – pioneer and founder of lightweight membrane roofs - Texstyleroofs.com. Texstyleroofs.com. https://texstyleroofs.com/frei-otto-pioneer-and-founder-of-lightweight-membrane-roofs/

Figure 14 : Zurich, M. B. P. D. a. E. (n.d.). Isler the model as a working method | Structural Design. https://schwartz.arch.ethz.ch/Forschung/islerthemodelasaworkingmethod.php

Figure 15: ICD/ITKE Research Pavilion 2016-17 | Institute for Computational Design and Construction | University of Stuttgart. (n.d.). Universität Stuttgart. https://www.icd.uni-stuttgart.de/projects/icditke-research-pavilion-2016-17/

Figure 16: Elytra Filament Pavilion, Vitra Campus | Institute for Computational Design and Construction | University of Stuttgart. (n.d.). Universität Stuttgart. https://www.icd.uni-stuttgart.de/projects/elytra-filament-pavilion-vitra/

Figure 17: Aguahoja. (n.d.). Aguahoja. https://oxman.com/projects/aguahoja

Figure 18: Gloeocapsa blue-green alga - Stock Image B307/0155. (2023, March 10). Science Pho- to Library. https://www.sciencephoto.com/media/16263/view/gloeocapsa-blue-green-alga

Figure 19: Amy.Dobos. (2017, November 7). She sells sea shells. . .. Curious. https://www.science.org.au/curious/earth-environment/sea-shells

Figure 20: Amy.Dobos. (2017, November 7). She sells sea shells. . .. Curious. https://www.science.org.au/curious/earth-environment/sea-shells

Figure 21: Sea urchin shell, SEM - Stock Image C036/9543. (2023, June 22). Science Photo Library. https://www.sciencephoto.com/media/873150/view/sea-urchin-shell-sem

Figure 22: https://www.dreamstime.com/stock-illustration-diatoms-d-model-diatom-simulating-electron-microscope-observation-cleaner-than-most-real-observations-remains-image71833153

Figure 23: File:91 ANM Glass sponge 1.jpg - Wikimedia Commons. (2008b, March 5). https://commons.wikimedia.org/wiki/File:91_ANM_Glass_sponge_1.jpg

Figure 24: Kytyr, Dan & Petranova, Veronika & Jiroušek, Ondřej. (2012). Assessment of micromechanical properties of trabecular bone using quantitative backscattered electron microscopy. 119-122.

Figure 25: Limited, A. (n.d.). Plant cell micrograph hi-res stock photography and images - Alamy. Alamy. https://www.alamy.com/stock-photo/plant-cell-micrograph.html?sortBy=relevant

Figure 26: Popper, Z. A. (2020b). The Plant Cell Wall. Humana. http://books.google.ie/books?id=Da5KzQEACAAJ&dq=the+plant+cell+wall+zoe&hl=&cd=2&source=gbs_api

Figure 27: Popper, Z. A. (2020b). The Plant Cell Wall. Humana. http://books.google.ie/books?id=Da5KzQEACAAJ&dq=the+plant+cell+wall+zoe&hl=&cd=2&source=gbs_api

Figure 28: author

Figure 29: author

Figure 30: Galleries | Rat Kangaroo Cell Intermediate Filaments. (n.d.). Nikon's MicroscopyU. https://www.microscopyu.com/gallery-images/rat-kangaroo-cell-intermediate-filaments-2

Figure 31: Rogers, K. (2024, June 8). Mitochondrion | Definition, Function, Structure, & Facts. Encyclopedia Britannica. https://www.britannica.com/science/mitochondrion

Figure 32: Moussavi, F. (2021). The Function of Style. Actar D, Inc. http://books.google.ie/books?id=eTopEAAAQBAJ&printsec=frontcover&dq=farshid+moussavi&hl=&cd=1&source=gbs_api

Figure 33: by author

Figure 34-55: author

Tables

Table 1: Missions to Mars. (n.d.). https://www.esa.int/ESA_Multimedia/Images/2019/05/Missions_to_Mars

Table 2 : Coles, K. S., Tanaka, K. L., & Christensen, P. R. (2019). The Atlas of Mars. Cambridge University Press. http://books.google.ie/books?id=2R6pDwAAQBAJ&printsec=frontcover&dq=the+atlas+of+mars&hl=&cd=1&source=gbs_api

Table 3 : Barlow, N. (2008). Mars: An Introduction to its Interior, Surface and Atmosphere. Cambridge University Press. http://books.google.ie/books?id=o25Bojs7FMkC&dq=Mars+and+intro+to+its+-surface&hl=&cd=2&source=gbs_api

Table 4 : Radiation Exposure Comparisons with Mars Trip Calculation - NASA Science. (n.d.). https://science.nasa.gov/resource/radiation-exposure-comparisons-with-mars-trip-calculation/

Table 5 : Mars - NASA Science. (n.d.). https://science.nasa.gov/mars/

Table 6: NASA/JPL, edited by authıors – https://science.nasa.gov/resource/pressure-cycles-on-mars/ Edited by the authors.

Table7 : https://toolbox.biomimicry.org/methods/process/. Redrawn by author

Table 9,10:authors

Images

Image from page 6: Mars - NASA Science. (n.d.). https://science.nasa.gov/mars/

Image from page 10: Mars - NASA Science. (n.d.). https://science.nasa.gov/mars/. Redrawn by authors.

Image from page 12: https://science.nasa.gov/mission/hubble/science/universe-uncovered/hubble-galaxies/

Image from page 42: 17: Microscopic cross section cut of a Arabidopsis plant stem under the microscope. Dream- stime. https://www.dreamstime.com/microscopic-cross-section-cut-plant-stem-under-micro- scope-view-cells-botanic-education-root-image127055348

Image from page 64: By authors.

Image from page 84: By authors.

Softwares

Grasshopper. (n.d.). Algorithmic Modeling for Rhino. https://www.grasshopper3d.com/

Karamba3D. (2023, May 25). Karamba3D. https://karamba3d.com/

Kangaroo Physics. (2022, May 17). Food4Rhino. https://www.food4rhino.com/en/app/kangaroo-physics

Rhinoceros 3D. (n.d.). www.rhino3d.com. https://www.rhino3d.com/

Biomimetic Structures for Martian Habitats :

In the Light of Form-Finding