Building on Mars

Construction of a radiation shielding Martian habitat with in-situ materials via suitable construction methodologies.

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PREFACE

Human brain is designed to think. The reason of constant thinking in our brain is due to the desire of creating the "appreciable" and the "beneficial". However, the real challenge is turning thoughts into reality through the process of creating. In the field of architecture, thoughts are expressed with projects designed on computers and the sketches made on a piece of paper.

The way to reach those realities truly passes through engineering capabilities where individuals are often limited by their intellect. Those limitations can be surpassed by "big question marks" that trigger our brain to think clearly, process faster, and innovate solutions.

My very personal "big question mark" has always been related to what I see when I raised my head up to a dark night with a clear sky. Hereby, I would like to cordially thank Ulrich Knaack and Michela Turrin for the supervision and support they have provided, which enabled me to take my very first step towards answering this question mark.

Very special thanks to my dear friend Carlijn van der Werf, with whom I had delightfully collaborated throughout this study, Building on Mars.

For her never ending support, critical thinking and her constructive comments, I would like to thank Alessandra Menicucci. Her great contribution in the field of space engineering has inspired and motivated me to improve this project profoundly.

In addition, I would like to thank Kevin Cowan and Angelo Vermeulen for answering many questions related to space and introducing new discussions that enabled me to approach challenges from different perspectives. Very special thanks to Olga Bannova for the time she spared and verified numerous findings that my peer and I utilized to create a credible project. Also, I would like to thank Paulo Cruz for his inputs that helped designing construction with ice that is very core to this project.

I would like to wish lots of luck and success to Layla van Ellen for the thesis she is currently working on, who is also trying to find solutions to building on Mars. I firmly believe Layla's, Carlijn's and my project will be assets to the MSc. Building Technology Track, inspiring new Bouwkunde students to build on the foundation we have created.

I would like to offer my deepest gratitude for my dear family, for being my anchor through the years. Their presence has been excellent, cheering and easing. Last but not the least, I would like to thank my marvelous friends who have been always been there for me no matter what. I will always appreciate their support.

Finally, my mother's strength in overcoming problems, her dedication to the best she can ever achieve and her caring personality have inspired me to become a fine person and encouraged me to take on challenges in the search for answers to my "big question marks". Therefore, I wish to dedicate this thesis to my endearing mother, Semra Mutafoglu

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ABSTRACT

Throughout the time humans have always looked up to starry skies and wondered about travelling to the stars. With the current developments in the aerospace field, travelling to neighboring planets have never been more possible. On the top of the agendas of numerous organizations today is the exploration of the Red Planet. However, there are many factors that complicate travelling to and building habitats on Mars. First and foremost constraint is the fragile human health that can not withstand the biological effects of ionizing space radiation. Following is the costliness and difficulty of carrying materials to Mars in hopes for building habitations. Last but not the least, the 22 minutes transmission delay between Earth and Mars, which makes it impossible to run and control operations on Mars surface in real time, and arises the necessity that majority of the operations has to run autonomously. All these limitations brings about one question that this thesis tries to answer; how to autonomously construct a radiation shielding habitat on Mars.

In order to come up with a methodology, it was necessary to take a step back and start the project from selecting a mission among those defined in DRA 5.0 by NASA, as the mission characteristics limit the construction tools and methods for building on Mars. After mission details are set and landing site is chosen, the study started defining the construction methodology by choosing the appropriate material for radiation shielding. This material, water, is the core to the construction of the habitation and due to transportation limitations, in-situ materials on the Martian surface were evaluated. The regolith, in other words the Martian soil, and water were two potential candidates due to their presence on the surface. Water was chosen as a better shield for space radiation due to its highly hydrogenated structure. The water on Mars is encapsulated in four types of reserves; regolith, glacier ice, poly-hydrated sulfate minerals, and phyllosilicate minerals. Without rover missions and on-site data collection, it is not possible to confirm the presence of the remaining three reserves except from regolith at the landing site. Therefore, regolith was selected as the main reserve for water extraction, which brought about the question of energy requirements for such a process. Two possible energy generation systems including solar and fission power were then analysed, and a simultaneous use of both was deemed to be the most beneficial approach. Although fission power systems work with high efficiency, this type of generators can not be the sole source of energy due to their biological effects on human health and must be positioned at least a kilometer away from the habitat. In order to protect the crew, the solar energy systems that provide clean energy is selected to support the habitation while the fission powered systems are firstly tasked with generating energy for the return vehicles, then to the habitat from a far distance. After all these details on material selection, extraction and energy generation are determined, the project moved on to the construction steps.

The construction process starts when one inflatable habitat module, which is pre-manufactured on Earth, is sent to the surface of Mars. The envelope around the module consists of water/ice bags that will then be filled with the water, extracted from the regolith, via a robotic arm. The water has been ISRU derived by processing the regolith with microwave technologies, which was deemed as the most efficient way of extracting water from regolith. In order to transport regolith to the ISRU plants 4 rassors will employed. These rassors will also play a vital role in the previous construction steps.

At the end of this autonomous construction, the habitat is planned to accommodate a crew of six, for 539 days on the surface of the Mars. The habitat was designed with an aim of keeping the crew members' total equivalent dose of radiation exposure within 0.40-0.50 Sievert range inside the habitat.

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Construction of a radiation shielding Martian habitat with in-situ materials via suitable construction methodologies.

INTRODUCTION TO BUILDING ON MARS

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INTRODUCTION

1.1

The dream of exploration has been pushing humankind to seek new solutions and technologies, and ultimately it brought betterment to the world by the means of knowledge. Humans have learned a lot from arctic explorations that the world is undergoing a tremendous climate change and that appropriate precautions should be taken, such as, the contribution in the built environment, sustainable buildings. In 1971, America's manned mission to Moon, to beyond of low earth orbit (LEO), showed human that utilizing the near space may successfully meet the needs of contemporary man, such as satellites for international communication and worldwide weather forecasting. On the other hand, landing on moon has also pushed human to seek the new destination for habitation in the near space environment, and the answer lies in our practically next door neighbour in the solar system, Mars (Seedhouse, 2009) .With its Earth-like features among the other planets the red planet is the most desirable land that human desires to explore (L. Vogt, 2008) In order to do so, advancing the new technologies invented by scientist to build on a planet without human force may have tremendous contribution to built environment here on Earth, such as autonomous construction sides without human presence or providing technical performances that can withstand the most challenging conditions on Earth.

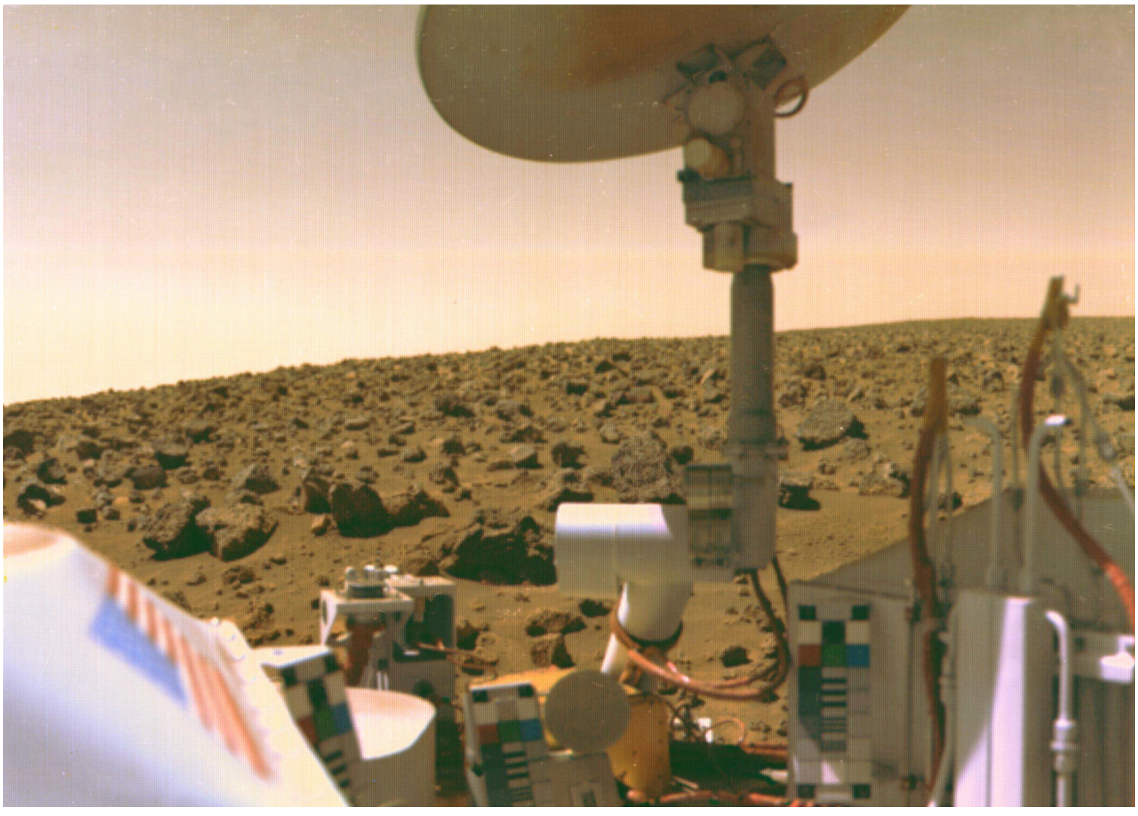


Figure 1.1: Image from Mars taken by the Viking 2 lander. Credit: NASA

PROBLEM STATEMENT

1.1.1

Building on Mars is a hot topic to many space agencies. Especially NASA, due to its manned mission experiences, has been the leading agency among European Space Agency and the collaborative agency by Russia and China and others, as claimed by Kevin Cowan in the interview in December 2016 (Space.com, 2017). Although there has been many architectural concepts developed by different architectural firms around the globe resulting from NASA's 3D Printed Mars Habitat Challenge, the technical performances such as structural capabilities of proposed in-situ materials, radiation shielding properties, and construction techniques are yet missing scientific verifications.

Main Human Health and Performance Risks for Exploration	Not mission limiting GO [green]	Not mission limiting, but increased risk GO [yellow]	Mission limiting NO GO [red]	Mission			
				ISS (6 mo)	Lunar (6 mo)	Deep Space (1 yr)	Mars (3 yr)
Musculoskeletal: Long-term health risk of early onset osteoporosis Mission risk of reduced muscle strength and aerobic capacity				[green]	[green]	[yellow]	[red]
Sensorimotor: Mission risk of sensory changes/dysfunctions				[green]	[yellow]	[green]	[yellow]
Ocular Syndrome: Mission and long-term health risk of microgravity-induced visual impairment and/or elevated intracranial pressure				[yellow]	[yellow]	[red]	[red]
Nutrition: Mission risk of behavioral and nutritional health due to inability to provide appropriate quantity, quality and variety of food				[green]	[green]	[yellow]	[red]
Autonomous Medical Care: Mission and long-term health risk due to inability to provide adequate medical care throughout the mission (Includes onboard training, diagnosis, treatment, and presence/absence of onboard physician)				[green]	[yellow]	[red]	[red]
Behavioral Health and Performance: Mission and long-term behavioral health risk				[green]	[yellow]	[red]	[red]
Radiation: Long-term risk of carcinogenesis and degenerative tissue disease due to radiation exposure–Largely addressed with ground-based research				[green]	[yellow]	[red]	[red]
Toxicity: Mission risk of exposure to a toxic environment without adequate monitoring, warning systems or under-standing of potential toxicity (dust, chemicals, infectious agents)				[yellow]	[yellow]	[red]	[red]
Autonomous Emergency Response: Medical risks due to life support system failure and other emergencies (fire, depressurization, toxic atmosphere, etc.), crew rescue scenarios				[yellow]	[yellow]	[red]	[red]
Hypogravity: Long-term risk associated with adaptation during intravehicular activity and extravehicular activity on the Moon, asteroids, Mars (vestibular and performance dysfunctions) and postflight rehabilitation				[green]	[green]	[yellow]	[red]

Table 1.1: Risks concerning a human mission to Space (GER, 2013)

MAIN RESEARCH QUESTION

1.1.1.1

-How to autonomously construct a radiation shielding habitat for a crew of 6 on Mars?

SUB-RESEARCH QUESTIONS

1.1.1.2

-What are the most suitable digital manufacturing techniques for the Martian habitat?
-What are the construction tools that can utilize in-situ resources in order to build in the Martian habitat?
-What are the effects of the space radiation on human anatomy?
-What are materials that can mitigate the exposure to space radiation whilst the crew is present in the Martian Habitat?
-How to generate energy that is needed to sustain the construction on Mars?

OBJECTIVE

1.1.2

Designing manned missions and aircrafts are mostly elaborated by aerospace engineers and other engineering disciplines that are highly educated in relevant topics, on the other hand, designing an outer space habitat may require the contribution of an architectural engineer who possesses the knowledge of human involvement and able to assess the technical requirements that can ensure their well being and comfort. Furthermore, the acquired knowledge in construction methods may well contribute to building such habitats in the future. Thus, the objective of this research is bridging different disciplines to build a secure indoor environment where the crew is not exposed to certain hazards such as space radiation.

QUALITATIVE RESEARCH

1.1.3.1

Qualitative research provides understanding of a phenomenon or an event originating from exploring the totality of the situation. Researchers who are have limited or no previous understanding of a phenomenon may begin with the research by using qualitative research methods. In the case of "Building on Mars", Carlijn van der Werf and I started performing case study research and literature reviews. Furthermore, in order to underpin our research findings we arranged interviews with experts who are specialized in certain topics that are closely related to our thesis; Angelo Vermeulen for space missions and isolation, Kevin Cowan for mission architecture, Alessandra Menicucci for planetary science and space radiation, and Fred Veer for materialization.

To have a general insight on the probable manufacturing and construction methods, one should take a closer look to the precedent projects that are already completed or to be completed in extreme environments. Mars Ice House, Shee Module (Fıgure 1.2), International Space Station (ISS) at LEO, Halley IV in Antarctica, Mars Habitat by Foster and Partners are some of the precedent projects that can be analysed. Then, one could assess the techniques that are used and prioritize the ones deemed to be the most suitable by the means of energy demand of the proposed technique, compatibility of techniques and tools with the environmental conditions, number of tools involved in the construction, and aimed structural capabilities which are offered by certain techniques and materials.

Apart from technical details, human involvement in such mission and their life within the Martian habitat is another important issue to be analyzed, where the architectural design background of the researcher may play a problem solving role. Since the mission to Mars by NASA may land the crew approximately 500 days to the surface of the red planet, the architectural layout should underpin the psychological well being in order to mitigate an miscarriage in the mission. Apprehending the knowledge in importance of crew's wellbeing, interviews were made with an expert who has been on an isolation

Figure 1.2: Self-deployable Habitat for Extreme Environments (SHEE) Module

QUANTITATIVE RESEARCH

1.1.3.2

"In natural sciences, quantitative research is the systematic empirical investigation of observable phenomena via statistical, mathematical or computational techniques." (Given, 2008). The investigation should be made on certain topics such as the radiation shielding feature of the habitat.Thus, quantitative research plays a key role in verifying the truthfulness of certain topics. For doing so, computational techniques, softwares, that can analyze the geometrical features (shape, size, thickness) and material properties for radiation shielding may be employed. Potential softwares are Geant4, Trisco and Spenvis, which have been often used by many scientists.

Mechanical strength of a material may be analysed through physical tests if assessment has not been fully done yet. For instance, in the case of "Building on Mars" the construction may be done with composite materials, mixing martian regolith and water. Therefore, a martian regolith substitute should be found, which may be offered by D-shape, a UK based company. This analogues may be mixed in different concentrations with water. By utilizing a freezing chamber different compositions can be frozen and undergone a compression test. The results can then be interpreted with certain softwares in regards to martian gravitational force and the a selection can be made according to those findings, providing a sound analysis.

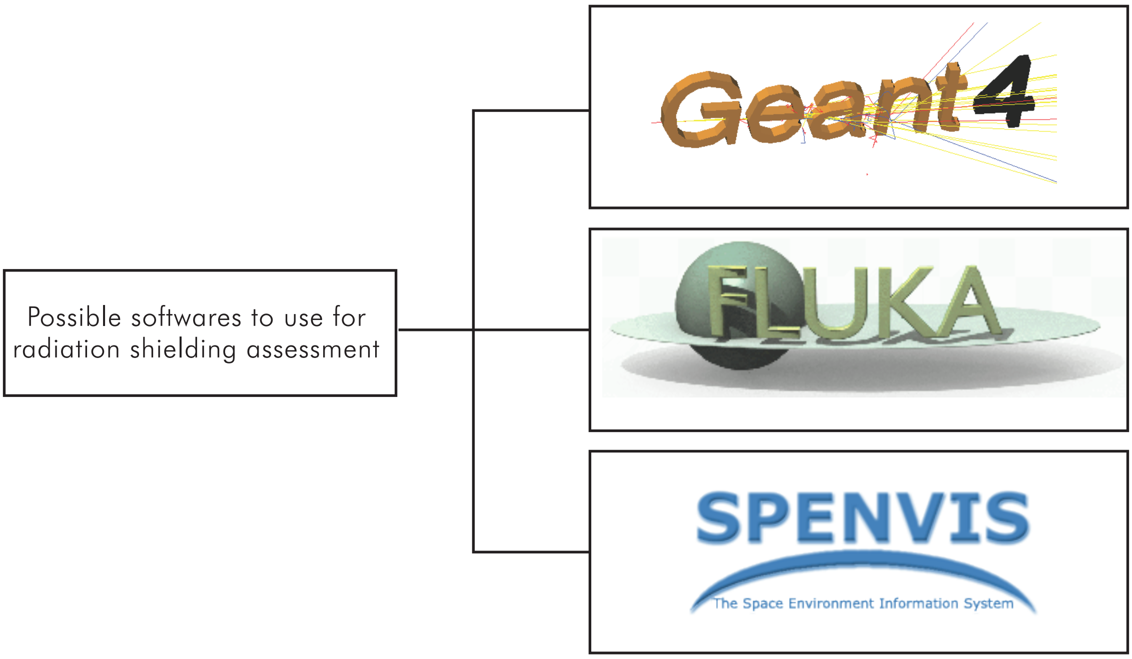


Figure 1.3: Radiation Assessment Softwares

Research on Mars Environment: The Red Planet Mars

- 1.2 -

*What are the facts that are suppose to be taken into consideration during the decision making process of construction.
The facts that are directly connected to design of the habitation are taking place in this chapter. These are the design drivers/*

MARS IN THE SOLAR SYSTEM

1.2.1

In order to give an insight in the placement of Mars, one should describe the location from a broader perspective. Our solar system takes place in the galaxy called Milky Way, which is one of the 200 billion galaxies that can be seen within the observable universe. While the exact number of galaxies in the ultra deep space remains uncertain, scientists' interest towards exploring remains vital. According to studies, solar system is located in an outer spiral arm of milky way with a distance of 27.000 light years from the galactic center, where, a supermassive black hole is located as reported by NASA scientists who found strong evidences (Gregersen, 2010)

Once the scale lowers down to the level of our solar system, similarly to the rest of the galaxies; planets, satellites, asteroids, comets and meteorites are detected. The solar system is mainly composed of one star, Sun, and eight planets orbit around it as a gravitationally bound system, where Mars orbits as the fourth closest planet to Sun in between Earth and Jupiter with an average distance of 1.52 AU (1 AU = 149.597.871 km, 1.52 AU = 227.900.000 km). (Williams and Williams, 2017)

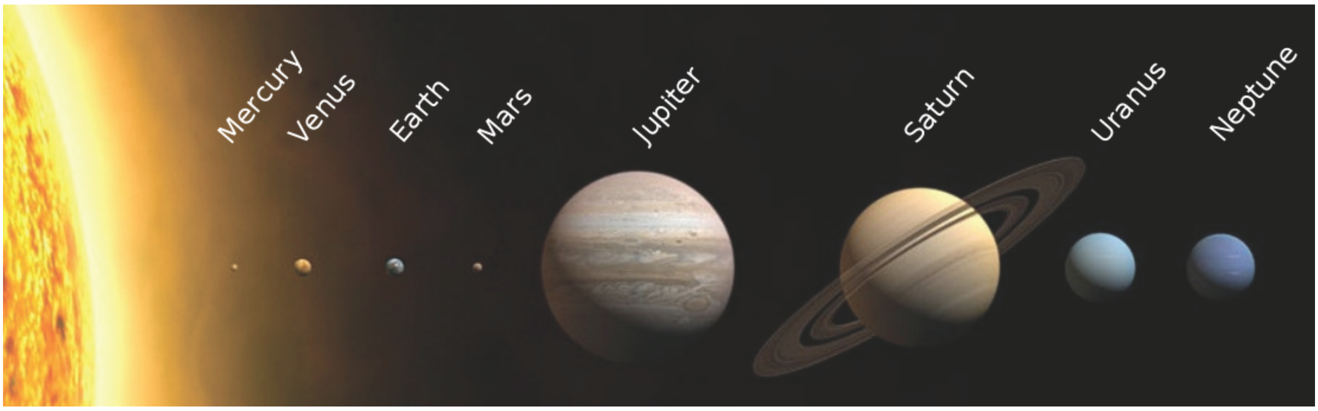


Figure 1.4: Solar System

The placement of Mars in the solar system is important because it helps in determining the circumstellar habitable zone (CHZ), meaning that the planet may have a favorable environment to life (Rycroft, 2002). The determination of the CHZ has to do with, whether the planet surface can support the presence of liquid water and have a sufficient atmospheric pressure. According to the findings of NASA's Mars Reconnaissance Orbiter (MRO) launched on August 2015, there are strong evidences of flowing water on the Mars surface, especially on the recurring slope lineas, during the warm seasons (above -23 C) (NASA, 2017) While the presence of flowing water remains promising and needs more elaboration, the atmospherics pressure on Mars is fairly unfavorable for sustaining human life. It's less than 1 kPa which is almost 1% of the atmospheric pressure on Earth, thus, it's below the Armstrong Limit (Misachi, 2017). Remaining below the limit indicates that the atmospheric pressure is too low, in which the water will boil at the normal temperature of human body (37 C) (Misachi, 2017). Therefore on Mars, human presence can only be sustained if the pressure suit is worn outside the pressured rooms.

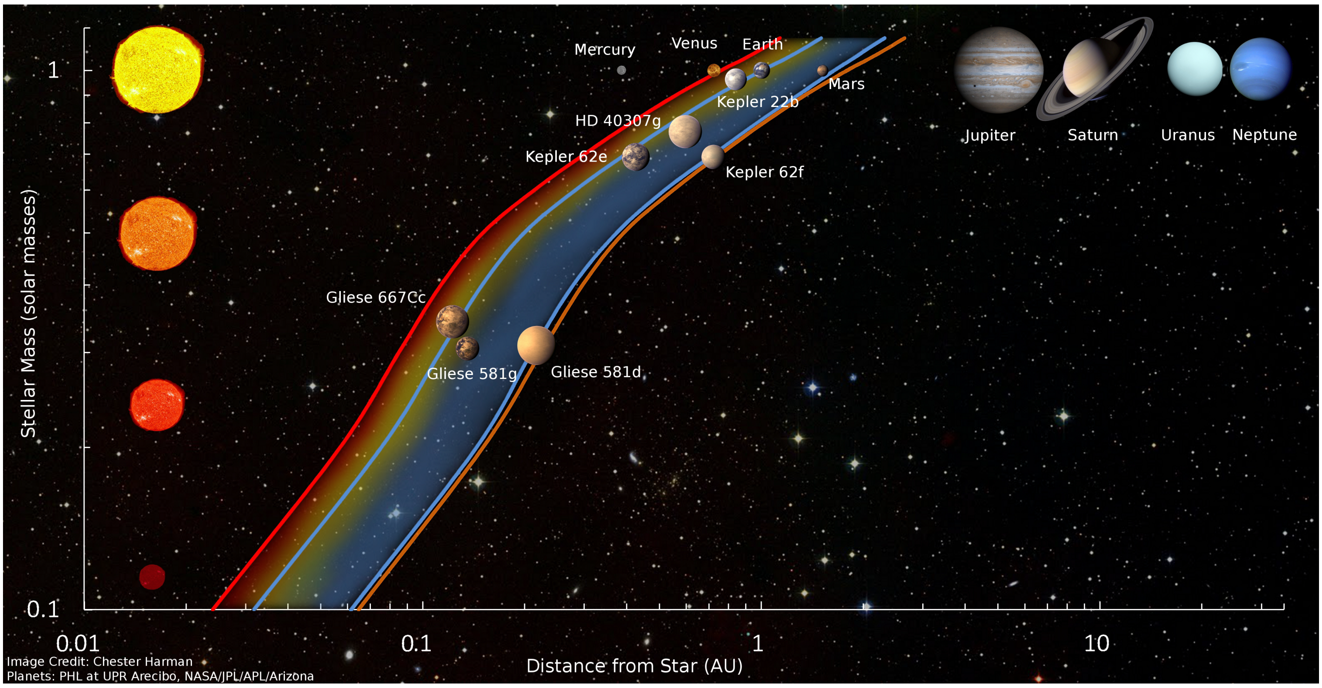


Figure 1.6: Circumstellar Habitable Zone

ORBIT CONFLICTS BETWEEN MARS AND EARTH

1.2.2

Mars and Earth orbit around the Sun due to the Sun's gravitational pull. These planets have their own orbital characteristics that are influenced by the mass of the planet, the distance from the sun and so on. The orbit of a planet mostly plays an indisputable role because of its effect on the planetary climate. Having a highly elliptical orbit changes the seasonal temperatures drastically and is closely related to the selection procedure of manufacturing methods, architectural form, construction sequence and materials. From the building technology perspective, climatic conditions are of utmost importance and can lead designers to determine critical requirements.
Other crucial aspects that should be taken into consideration about orbits of Mars and Earth are the travel time, launching windows, and planetary positions. Launching a vehicle to Mars has to be calculated well in order to make the optimal transfer (low energy). Therefore, one should pay close attention to conflicts between orbital speed of Mars and Earth. Mars orbits around the sun with of the speed of Earth (Nssdc.gsfc.nasa.gov, 2017) . Thus, there is a certain planetary position which Mars and Earth should take, so that the travel time can be optimized. Mars should be 44 degrees ahead comparing to Earth on its circular orbit for a low energy transfer. Even the shortest trip takes 6 months with a window period of 26 months (Aldrin and David, 2003). These facts may lead one to consider the in-situ resource utilization on Mars.

In order to complete the full orbit around the sun, Mars takes 687 days (if the missions takes almost 500 days, a martian year wouldn't be completed), nearly the double of the Earth's orbit around the sun. Therefore, seasons are extended comparing to their length on Earth. The completion occurs in a travel of 9.55 AU orbit travel is completed with an average orbital speed of 24 km/s (Nssdc.gsfc.nasa.gov, 2017)

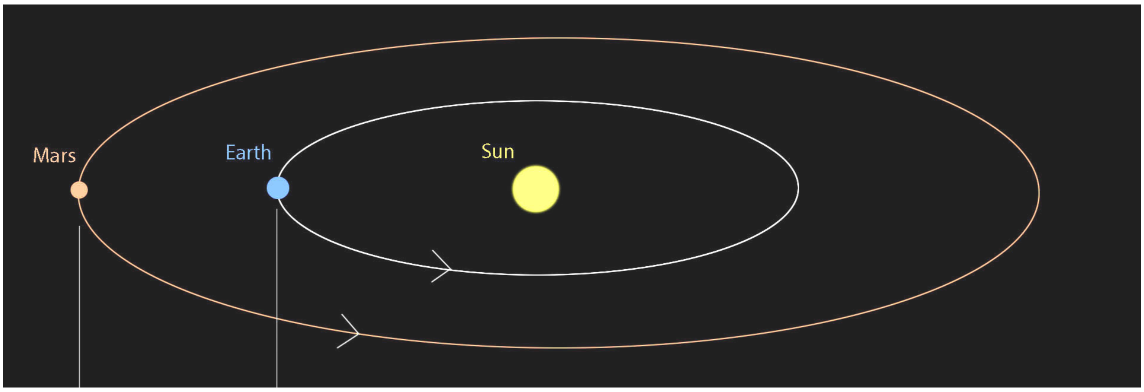


Figure 1.6: Orbit of Mars and Earth

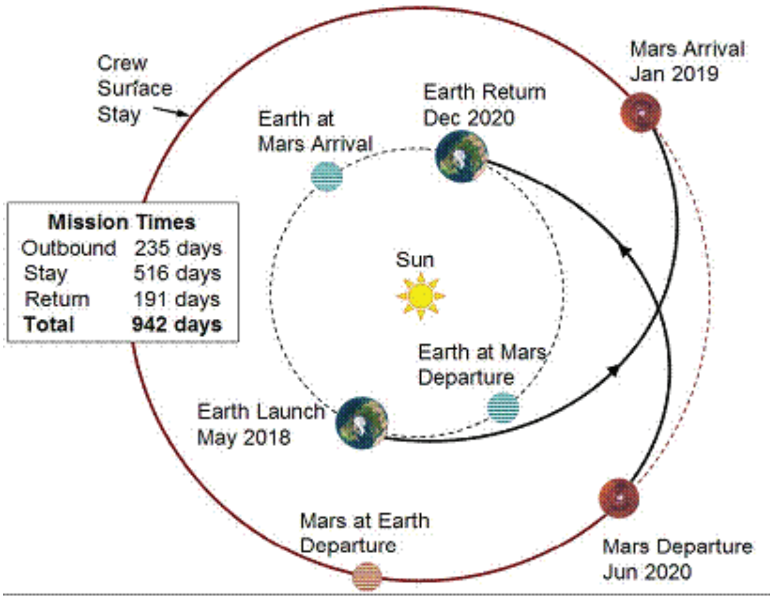


Figure 1.6: The Figure above shows a traditional conjunction-class mission profile to Mars—the trajectory path to Mars spans approximately 180 degrees. Both the inbound and the outbound trajectories are near-Hohmann tranfers. Given the Earth-Sun distance and the Mars-Sun distance, the equation below gives a transfer mission time, t trans, of approximately 250 days.

A DAY ON MARS: SOL

1.2.3

Rotational period is the amount of time that a planet takes to complete one turn around its own axis, in simple words; a day. Similar to Earth, a day on Mars is completed in every 24 hours 37 minutes, approximately 40 minutes longer than on Earth, and is called a Sol. This is the consequence of the angular speed of Mars' rotation on its axis that is relatively slower than Earth's, thus, a day is longer on Mars. In comparison to other planets such as Venus, which takes 166 days, and Jupiter, which completes a day in 9 hours 55 minutes, compatibility of Mars and Earth is quite well balanced (Williams, 2017). Once the astronauts starts with the mission on Mars, their daily cycle including sleeping patterns, will not be affected by the length of the day.

On the other hand, the temperature on Mars, near the equator is varies drastically within the same day. The temperature difference between day and night can go up to 110 C degrees .On a summer day near the equator of Mars, the temperature can raise up to 20 C, whilst during the night it may drop down to -90 C. This may have an astounding impact on the design of a habitat. Materialization, architectural form and technical performances should well be taken into consideration in regards to night and day temperature difference. For instance, 110 C degrees of difference in less than 24 hours may lead to an heightened internal stress on the structure where crack propagation can be observed. Another example can be given for the material selection; Mars Ice House consists of an ice structure as the outer shell and above 0 C condition may lead to structural imperfections.

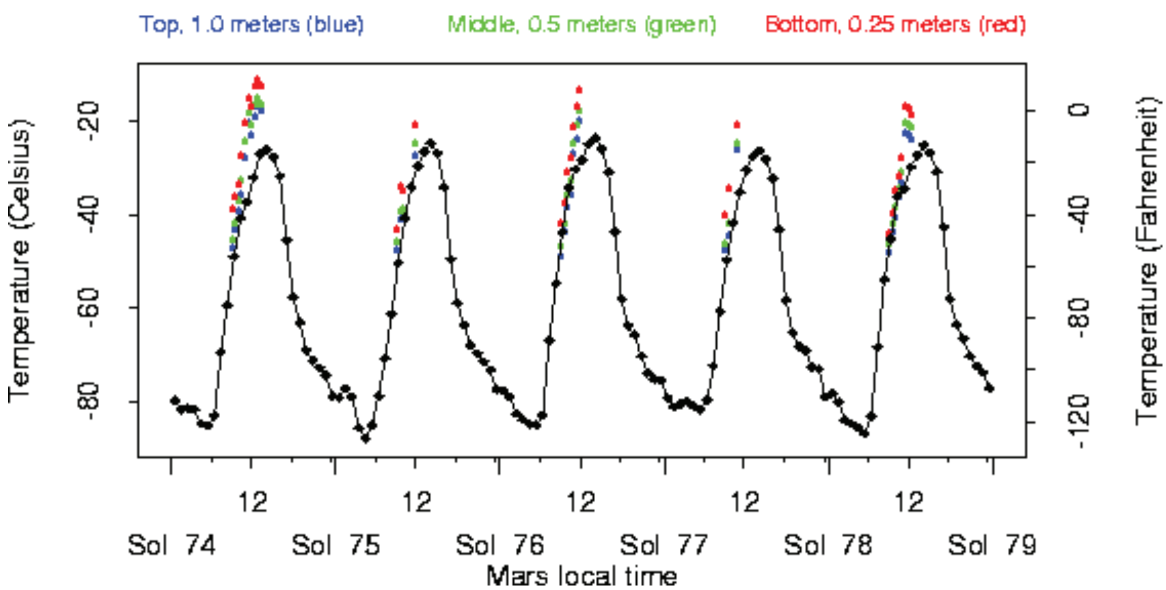


Figure 1.7: Chart of temperatures from Mars Pathfinder. A Sol is a Martian day.

Can Earthlings Adjust to a Longer Day on Mars?

1.2.3.1

A sol takes 24 hours 39 minutes and 35 seconds. It doesn’t seem much at a first glance. However the experiences of The operating group of the pathfinder mission’s rover in 1997, who were required to live indefinitely on Mars time, was a remote declaration of what may human experience on Mars with the extra 40 minutes. The operating group was living on Mars time due to the necessity of taking advantage of hours between the data transmission at the end of the rover’s day and the upload of the new commands the following Martian morning.

"They didn't really have a plan for dealing with the Martian day before they went up, and the rover lasted a lot longer than it was supposed to, so they actually had a mutiny and wanted to shut the thing off because they were so exhausted," according to what Harvard University sleep scientist Charles Czeisler says.

On the other hand, adjusting to sols are not very difficult (Barger, 2013) according to experiment led with volunteers from Phoenix lander operation crew. They were provided with education about circadian rhythms, specific sleep-wake and caffeine schedules and countermeasures such as blue-light boxes to place on their desks and 19 volunteers were monitored with medical test. The progress they made was tracked and 87% of the participants were seemed to adapt to the sol.

MARTIAN SOIL: REGOLITH

1.2.4

Figure 1.8: Curiosity's view of Martian soil and boulders after crossing the "Dingo Gap" sand dune (February 9, 2014), NASA

Mars Soil, scientifically known as regolith, consists of fine dust and indurated sand as well as rock fragments atop (Revolvy, 2017). One of the important characteristics of the Martian regolith is the fact that it is the only accessible planetary soil that has been subjected to hydrolytic, atmospheric and possibly even biologic weathering, besides Earth's (McSween, Keil, 1999). These informations are collected through the research of three landers, Viking 1, Viking 2 and Mars Pathfinder that landed on three different locations on Mars. Although it's nearly impossible to assess the soil composition of the entire planet by only investigating in three locations separated by immense distances, the soil at all of these sites have broadly similar characteristics in their composition (Clark et al.,1982; Rieder et al., 1997).

Mars, similar to Earth, is a geologically diverse planet. The traditional way of considering Martian regolith with uniformed compositional features, covering all over the planet is now outdated. Evidences from recent discoveries of varied mineralogies at regional and even local scales are present. (JPL, 2012)

-The Omega Hyperspectral imager detected:
high levels of kieserite, gypsum and polyhydrated sulfates in Vales Marineris, Margaritifer Sinus and Terra Meridiani (Gendrin 2005)

-Spirit Rover found six different soil types in Gusev Crater and in the Columbia Hills (Morris, 2006).

-Strong evidences of gypsum rich sand dunes have been detected around Oxia Planum (Langevin 2005).

-And Basaltic sands in Chryse Planitia have been found.

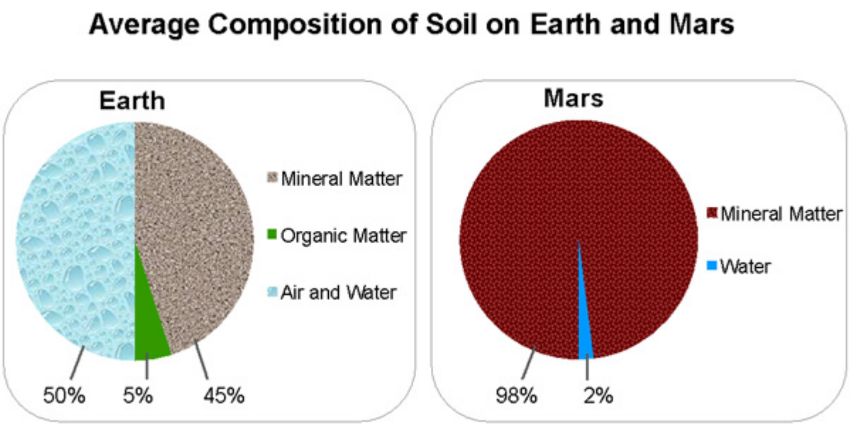


Figure 1.9: The average composition of soil on Earth and Mars. Martian soil is almost entirely mineral matter, with a small amount of water. It has none of the organic matter found in soil on Earth.

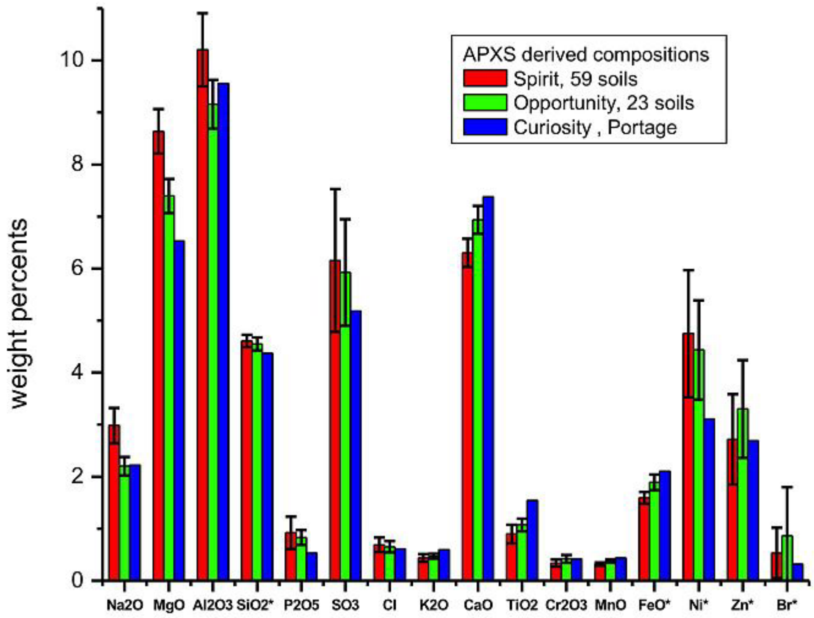


Figure 1.10: Comparison of Soils on Mars - Samples by Curiosity rover, Opportunity rover, Spirit rover (December 3, 2012)

Before NASA lands humans on Mars, they must confirm Mars is habitable for humans. This is the main motivation behind sending numerous rovers for exploration missions, one of which is the Curiosity Rover. The Curiosity Rover touched down on the martian surface in August 2012 and have investigated the surface features of Mars. The findings of the rover on the landscape suggested that once Mars have been covered by liquid water (NASA, 2014).

Three layers of rocks lie beneath the surface covered with martian soil. The bottom rock layer is the oldest which is the ancient lakebed consisting of compressed clay and minerals. The upper one is the salty layer. When the water evaporated, it left the salts behind. And the uppermost layer is the cold, icy surface covered in soil and rocks which smoothened by the high-speed winds (NASA, 2014).

Winds have been carrying and smoothening a large amount of soil that turns into a very fine dust that is rich in iron oxide (Genta, 2017). The particles are even finer than lunar dust which is 1.5μm in diameter.

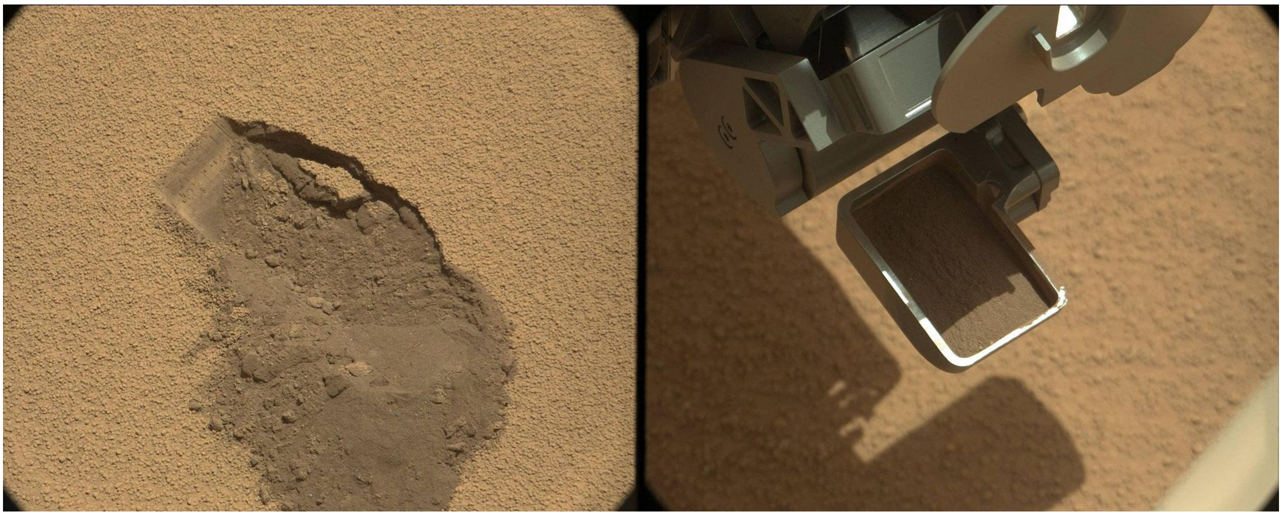


Figure 1.11: First use of the Curiosity rover scooper as it sifts a load of sand at "Rocknest" (October 7, 2012), NASA

ATMOSPHERE OF MARS

1.2.5

One of the similarities to Earth and promising facts about Mars is the presence of an atmosphere. The martian atmosphere is very thin and the atmospheric composition is fairly different from on Earth as it is comprised of 95.32% carbon dioxide(Sharp, 2017). Oxygen can be found in the martian atmosphere, however, it makes up only 0.13% of all the atmosphere (Sharp, 2017). Due to the atmospheric composition and the greater distance from the sun, the average temperature is much lower than the Earth. It's almost -60 C degreesSharp, 2017). Even though it's very thin, the martian atmosphere can still support weather, clouds and winds.Clouds of water ice were photographed by the Opportunity rover in 2004.

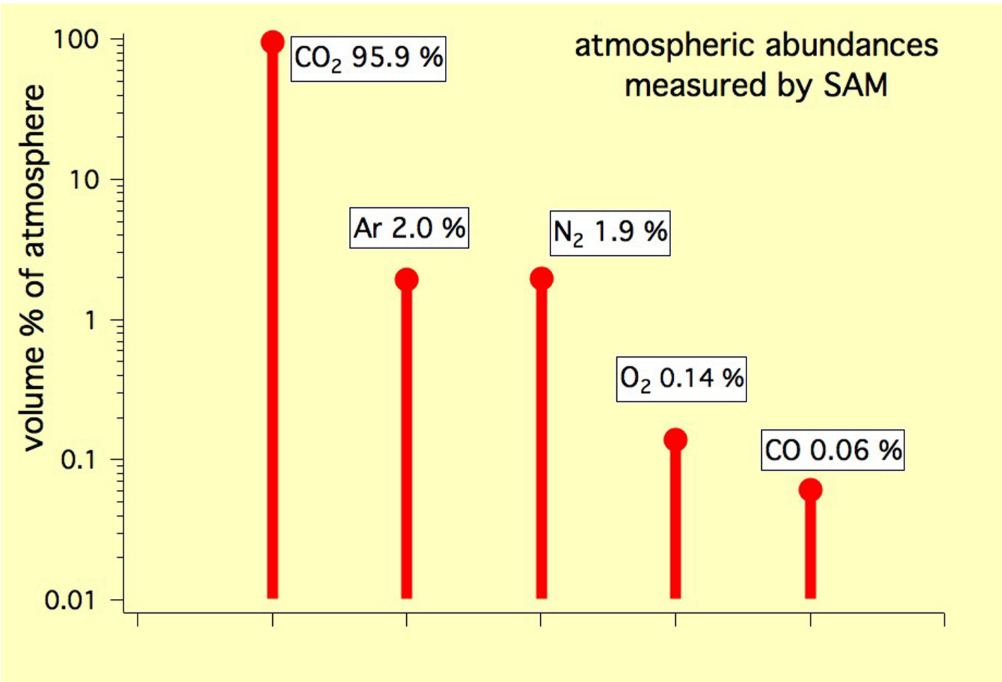


Figure 1.12: This graph shows the percentage abundance of five gases in the atmosphere of Mars, as measured by the Quadrupole Mass Spectrometer instrument of the Sample Analysis at Mars instrument suite on NASA's Mars rover in October 2012. The season was early spring in Mars' southern hemisphere, and the location was inside Mars' Gale Crater, at 4.49 degrees south latitude, 137.42 degrees east longitude

One of the inconveniences on Mars is the atmospheric pressure. On the surface, the pressure can reach only less than 1 percent of that sea level on Earth. This is much lower than the Armstrong Limit that is a physics term which depicts the lowest atmospheric pressure introduced by the altitude in which water begins to boil in the human body (Dovey, 2015). Mars' atmospheric pressure varies with altitude and latitude. The minimum pressure is found at the Olympus Mons with 0.3 millibar. In the depths of Hellas Planitia, the pressure goes over 11.6 millibars (Genta 2017). These values are very much affected by the seasons.

The density of the atmosphere is dependent upon the seasons. The average density of the atmosphere on the surface is about 0.020 kg/m3 that is considerably lower than Earth's atmospheric density. This creates quite a challenge to land on Mars because aerobraking performs better with a higher atmospheric density once the cargo mass is increased. The low martian atmospheric density constrains the EDL of the probes that are suppose to land on Mars.

Two viking landers have detected wind on Mars in 1976. The wind speed was reported as 2-7 m/s in the summer and 5-10 m/s in winter (Genta 2017). During the dust storms wind may speed up to 17-30 m/s accumulating regolith results in big sand dunes. Although the winds speeds can be considerably high, due to the very low atmospheric density the aerodynamic forces are weak.

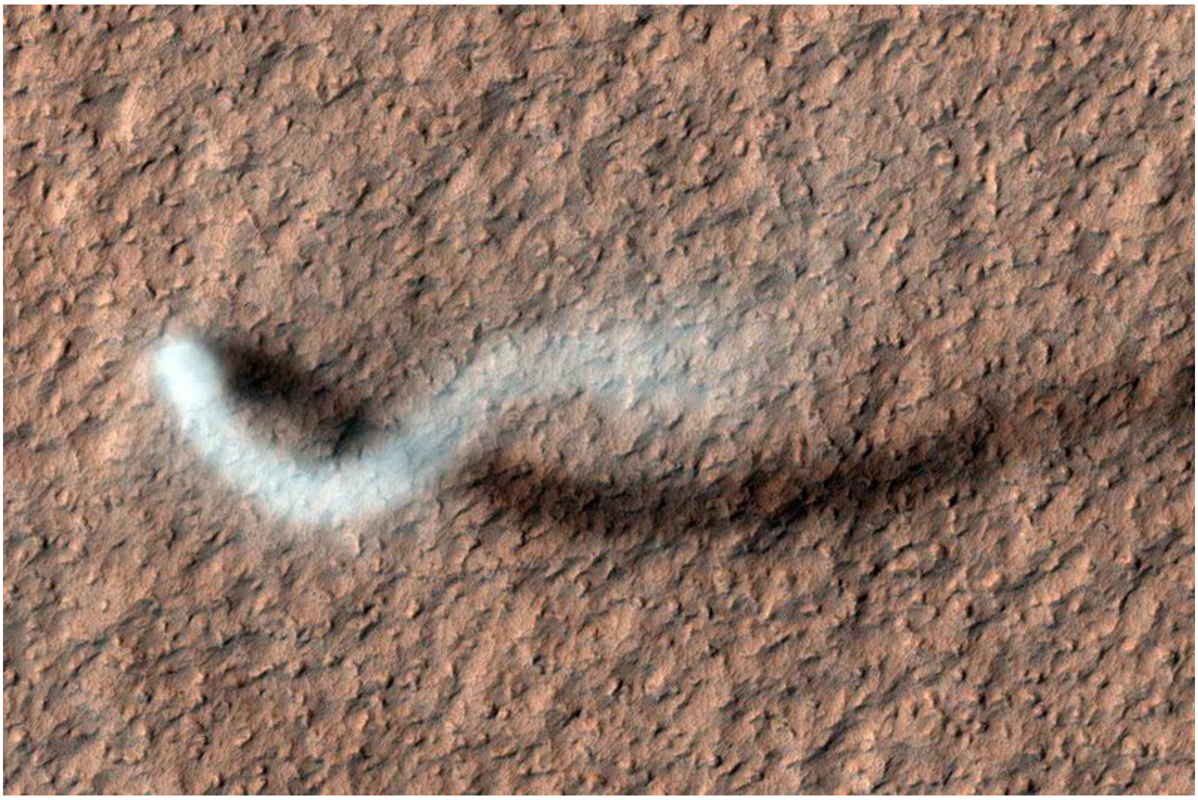


Figure 1.13: Serpent Dust Devil of Mars (MRO)

How did Mars lose its atmosphere?

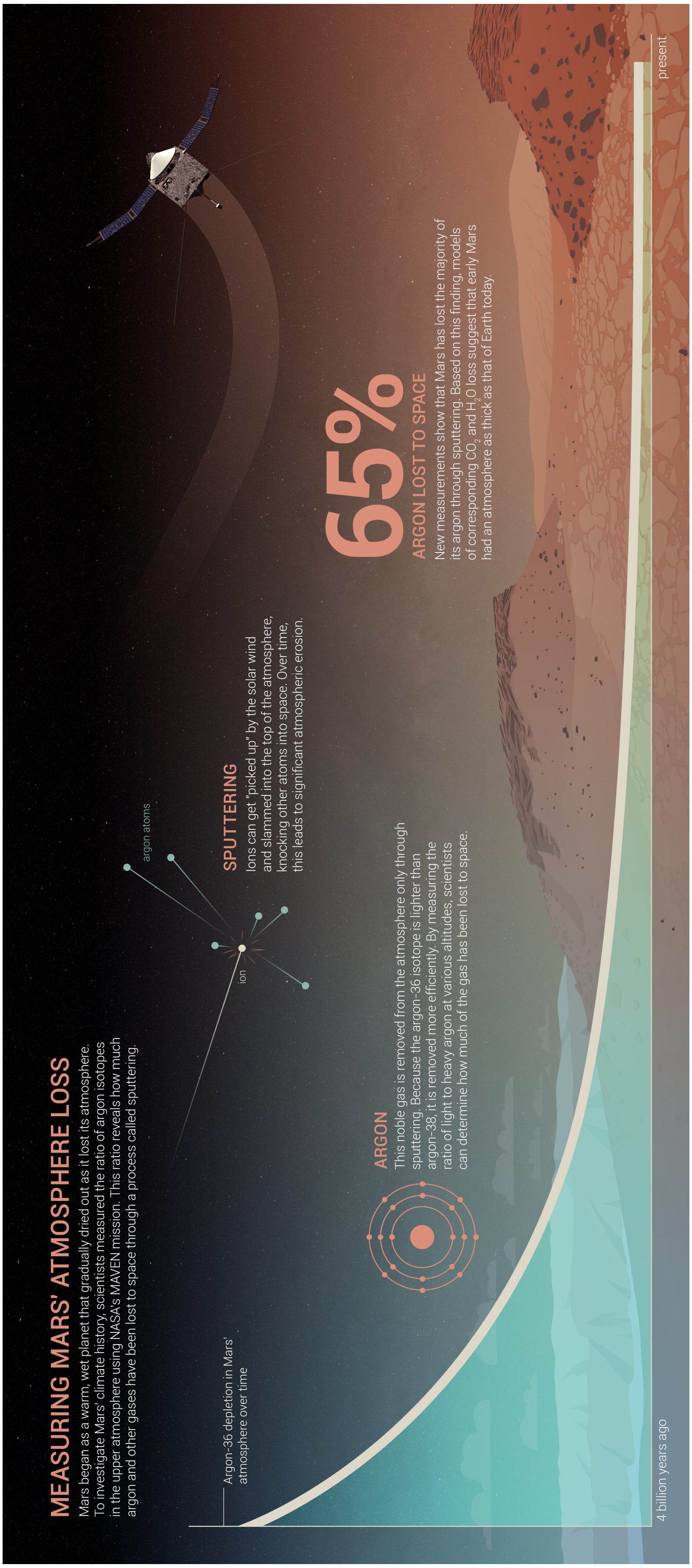
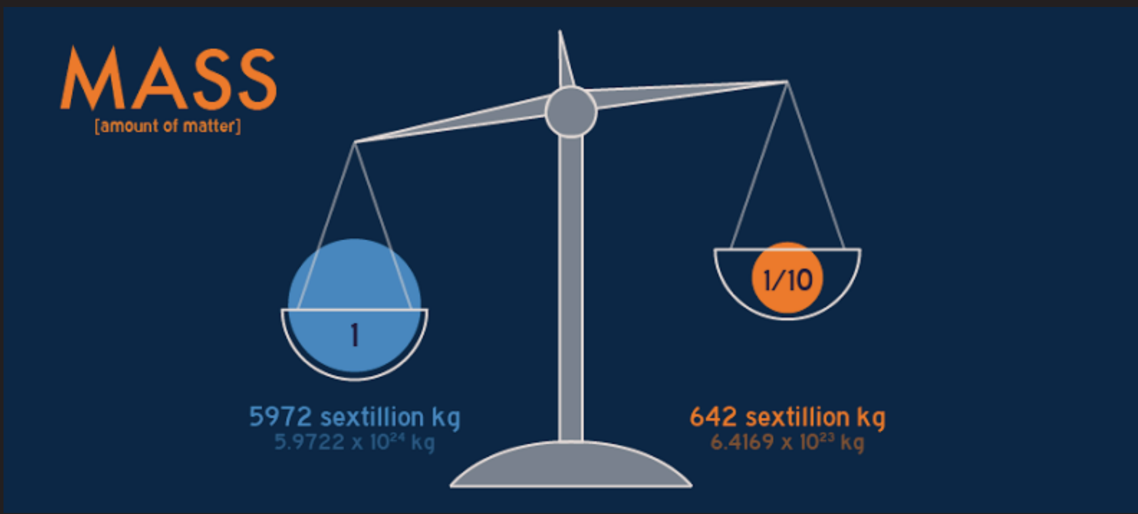


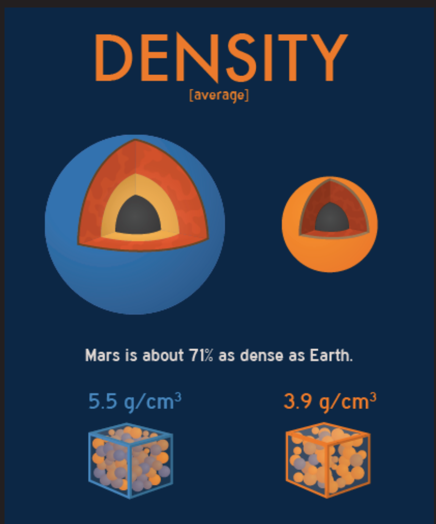
Figure 1.14: NASA's MAVEN spacecraft discovered that Mars lost its atmosphere due to solar wind and radiaton, JPL

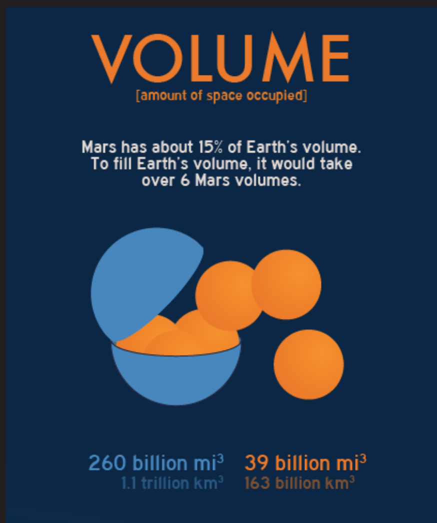
IN COMPARISON TO EARTH

Mars facts at a quick glance
Mass, density, volume, size and speed
(Mars.nasa.gov, 2017)

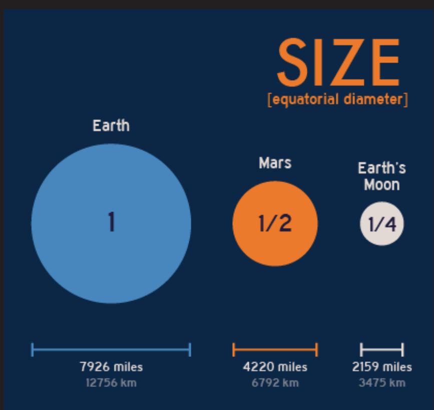


What is mass of Mars in comparison to Earth?





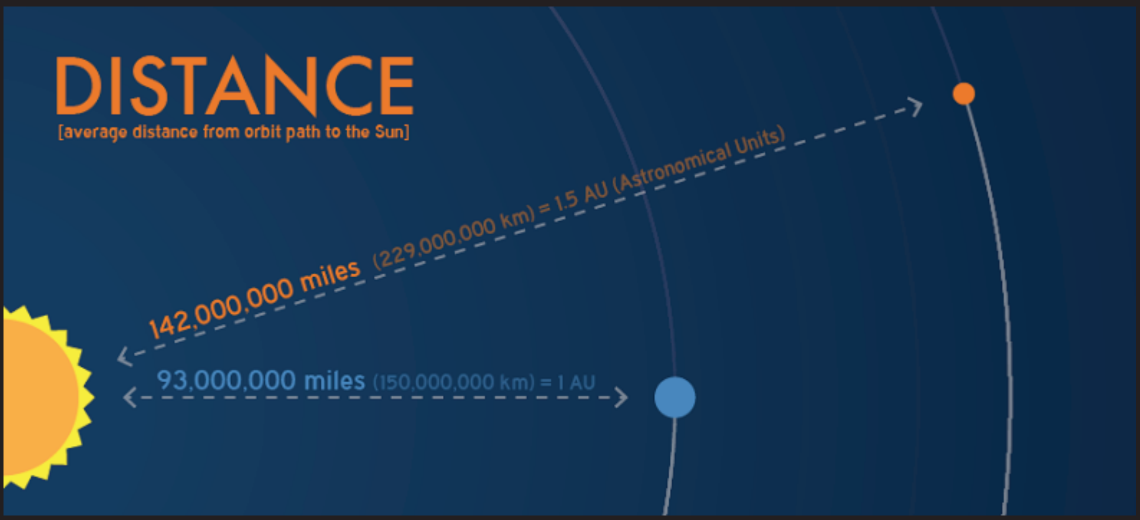
On right: what is the density of Mars in comparison to Earth?
On left: the volume of Earth and Mars



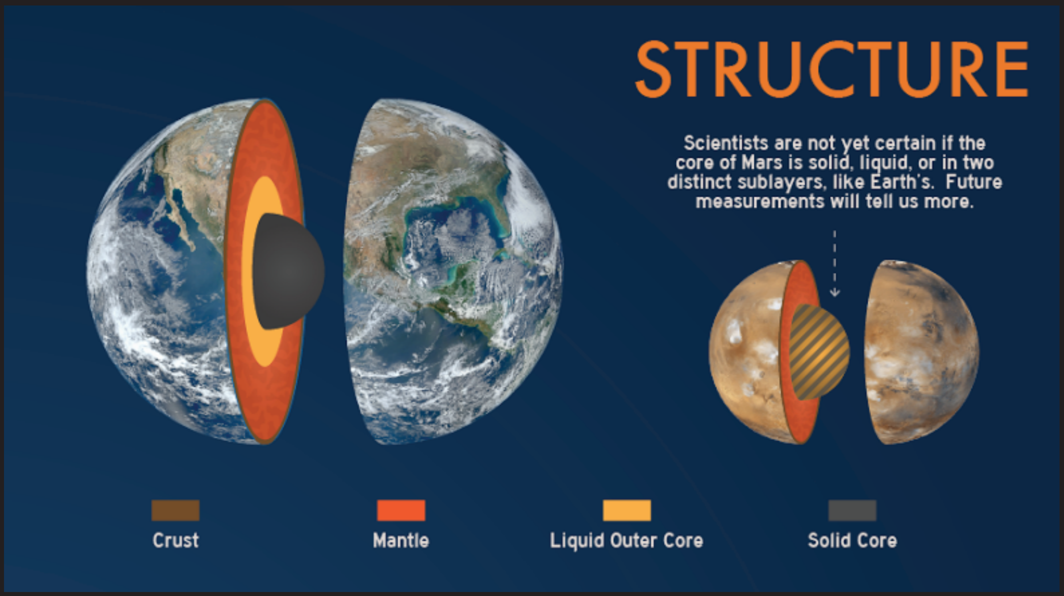
On right: Size of Earth, Mars and the Moon
On left: Speed of Mars and Earth

IN COMPARISON TO EARTH

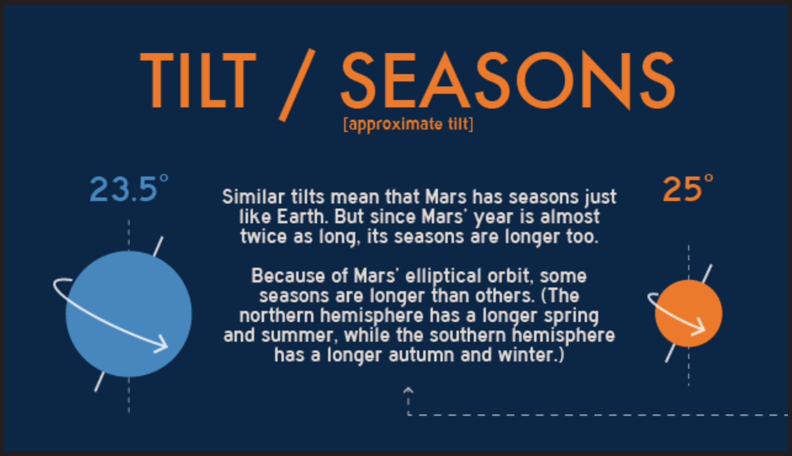
Mars facts at a quick glance
Distance, structure, tilt and seasons
(Mars.nasa.gov, 2017)



Distance between the Sun and Mars



Mars's and Earth's structural comparison



Tilt differences of Mars and Earth

PRELIMINARY CONSIDERATIONS PRIOR TO BUILDING ON MARS

Chapter
- 2 -

CHOOSING THE HABITATION ZONE

2.2.1.

Evolvable Mars Campaign (EMC) assumes that NASA's approach is to define a single exploration zone (EZ), which will accommodate durable infrastructures that will be used by future crews as well as the first crew (EMC, Crusan, 2015). Choosing the location is such a time consuming and arduous procedure that will possibly take years before providing a definite site. Region of interests (ROIs) are consisting of EZs that are approximately located within 100 km of a centralized landing site (Hou.usra.edu, 2015). The process of identifying landing sites requires an extensive work on EZs and evaluation of surface and operational systems that will perform the best for the chosen location. NASA has recently completed the "First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars", at which 47 candidate EZs were presented and discussed. (Toups, Hoffman and Watts, 2016)

After certain discussions Human Exploration of Mars Science Analysis Group of NASA shortlisted the EZ options to four, that included Mangala Valles, Jezero Crater, Arsia Mons, Centuari Montes for the manned missions. (Toups, Hoffman and Watts, 2016)

For these four locations, NASA proposed a field station site plan to further evaluate these sites:

(a) Habitation and associated logistics of the storage systems,
(b) A centralized power plant capable of supplying power to a geographically distributed (but within the central habitation zone) set of systems,
(c) Mobility systems that can be used to off load and move payloads to specific locations at the central field station site. These systems could also be used to traverse long distances to reach some of the more remote region of interests (ROIs) within the EZs,
(d) Robotic systems that can support various activities, such as system setup and maintenance, at the field station that could also be used to explore scientific ROIs and used to support site-specific ISRU production activities.

Landing Site	Lat (degN)	Long (degE)	Approx Elevation (km)	Approx Buffered Ellipse Axes (km)
Colombia Hills	-14.5478	175.6255	-1.93	9.6 x 8.7
Eberswalde	-23.7749	-33.5147	-1.49	8.6 x 7.7
Holden	-26.6130	-34.8167	-2.18	9.5 x 8.1
Jezero	18.4386	77.5031	-2.64	10.7 x 8.3
Mawrth	23.9685	-19.0609	-2.24	11.9 x 9.8
NE Syrtis	17.8899	77.1599	-2.04	11.1 x 8.2
Nili Fossae	21.0297	74.3494	-0.65	9.7 x 7.7
SW Melas	-9.8132	-76.4679	-1.92	9.7 x 8.7

Figure 2.1: Additional information on the science of the eight candidate sites, including prior science presentations related to these and other candidate 2020 landing sites.

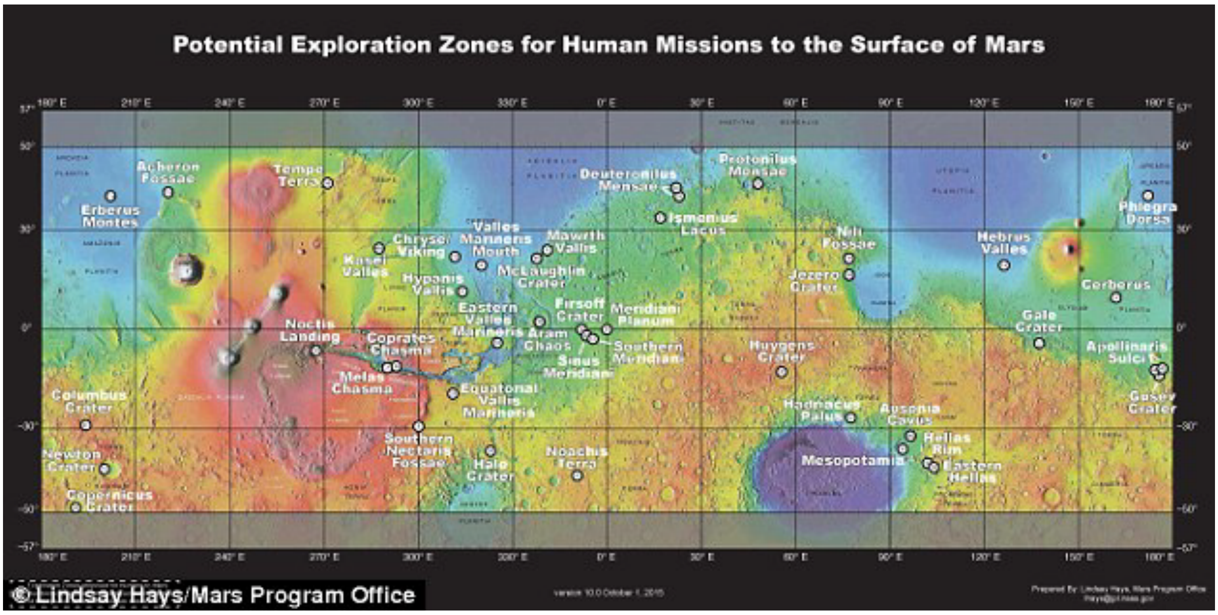


Figure 2.2: Nasa's first workshop to discuss possible landing sites for a manned mission to Mars

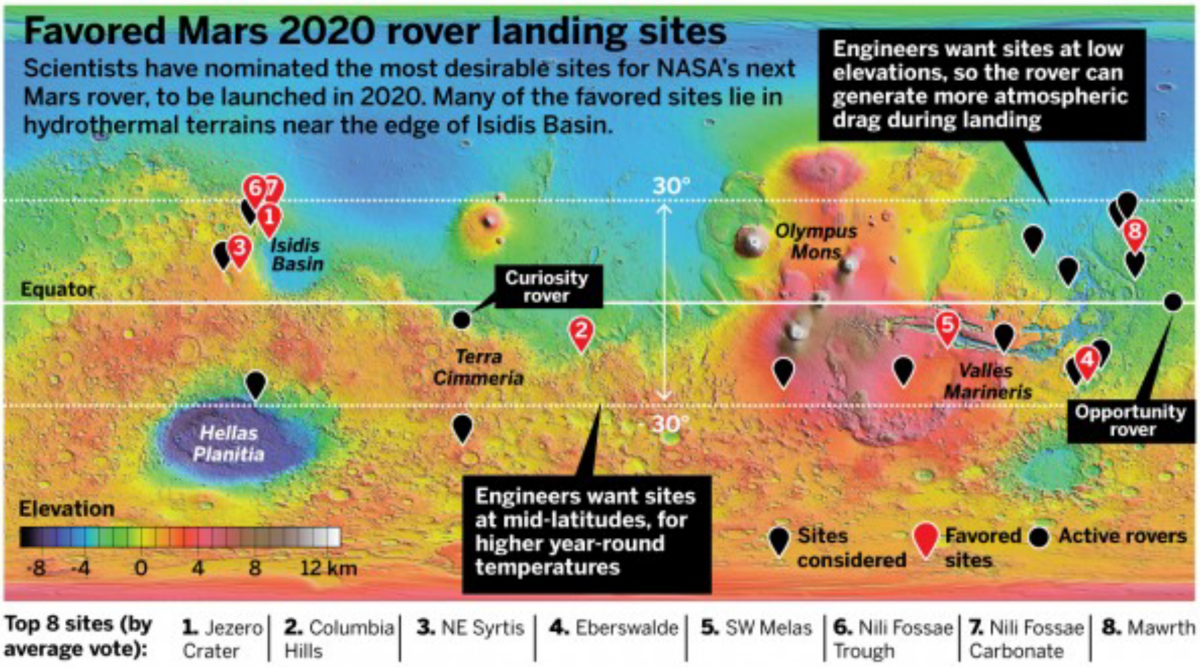


Figure 2.3: NASA's next Mars rover is due to launch in July or August 2020, and the number of potential landing sites has now been narrowed down by scientists to eight locations. Out of an initial list of 21 targets, eight sites have been chosen as candidate landing sites for the Mars 2020 Rover. Due to land on Mars in February 2021, the rover will search for rocks which could hold possible evidence of past life on the planet.

On the other hand, NASA's Jet Propulsion Laboratory (JPL) sent a letter to Mars Exploration Program NASA, on February 13th 2017, that the Jezero Crater and NE Syrtis are the top candidates and the following candidate is Columbia Hills which needs further evaluation. The purpose of the letter was to inform NASA about the landing sites that JPL was considering for landing a rover in 2020 without astronauts.

"Mars 2020 has a distinct and diverse set of goals that requires the mission to select a site that optimizes across a variety of factors: in situ investigations, preparation of a scientifically worthy sample cache for possible Earth return, seeking the signs of ancient life, and investigating non-biological aspects of Mars geology, climate, and planetary history. " (JPL, 2017)

JEZERO CRATER AS THE HABITATION ZONE

2.2.2.

Jezero crater was chosen as the habitation zone for "Building on Mars". As mentioned earlier, in the shortlist for manned mission conducted by Human Exploration of Mars Science Analysis Group, Jezero Crater was selected as one of the best options. Moreover, it was suggested as a potential landing site for NASA 2020 Rover by JPL, which will collect extensive information regarding the geographical fitness of the location for habitation. Under the light of these findings Jezero Crater was found to be the most suitable habitation zone for this project.

Jezero crater is an impact crater with a diameter of approximately 45 km.(Toups, Hoffman and Watts, 2016). This site offers great potential to answer questions on ancient Martian climate and volcanic history.

Its habitability is rated as one of the bests among the other landing sites due to its potential water production capability. After extensive research on different mineralogies on Mars, conclusion is that Jazero Creator is a rich exploration zone. The mineralogical features are not only important for research purposes but also for sustaining life on mars through ISRU production.

Furthermore, NASA's work on the site plan of Jezero Crater helps this research to have a more realistic and feasible foundation. In the site plan, the location of the habitation zone, landing sites and the power zone are determined and clearly shown.

One of the reasons why Jezero crater seemed more appealing is that the presence of a fairly flat zone that can accommodate habitation (Toups, Hoffman and Watts, 2016). Within Jezero Crater, there must be at least two landing zones, one serving to the crew's arrival, where at least to Mars Ascent Vehicles are on standby for the crew, and the other which is only used for cargo landers. These details will be further elaborated later in the construction methodology.

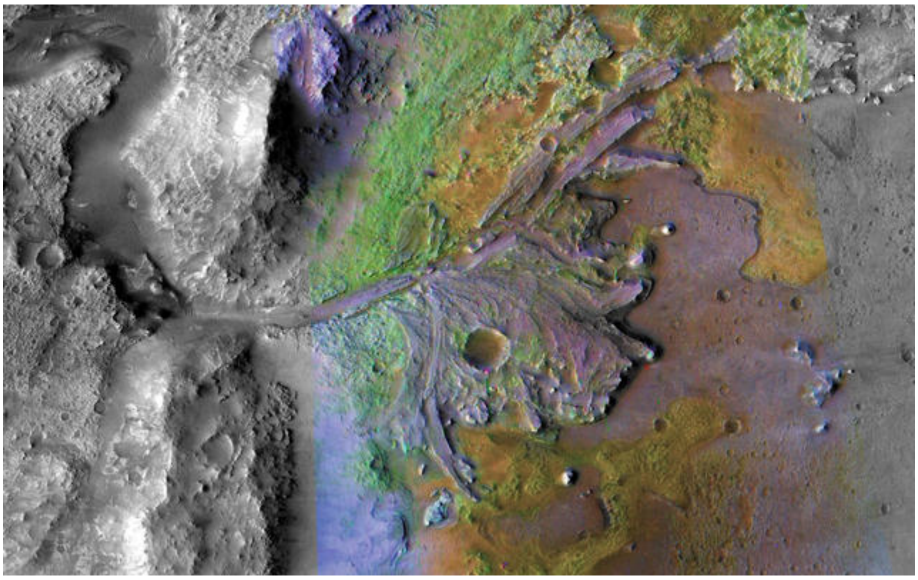


Figure 2.3: Jezero Crater, NASA

SPACE QUALIFIED MATERIALS & OTHERS

2.2.3

Space qualified materials are the materials used by the space industry in order to build durable space crafts and stations, EDL systems, and rovers. Selection of these materials is crucial for this project by the means of designing a habitat that can protect the crew from hazardous and provide a long operational life.

NEXTEL

Nextel is a woven ceramic fiber material that has the capability of turning micrometeoroids into small and less threatening debrisses. It's flexible and can be used as a multilayer cloth (Lobascio, Bricarello, Destefanis, Faraud, Gialanella, Grossi et al.)

KEVLAR

Kevlar is another fibrous material that performs exceptionally resistant under hypervelocity impacts, thus it's used for bulletproofing and such. Compositionally, it is 77.6% carbon, 4.59% hydrogen and 14.68% oxygen (Chemistry Bris,2017).

POLYETHYLENE

Nearly all of the plastic objects are made out of polyethylene that is commonly produced in semi-rigid form. It is mostly used for packaging, plastic bags, and bottling with an annual production of almost 80 million tonnes. It is highly hydrogenated with a fairly good capability of space radiation shielding. (Lobascio, Bricarello, Destefanis, Faraud, Gialanella, Grossi et al.) It is approximately 300% more effective than Nextel and 200% more effective in reducing heavy ion doses than Kevlar with the same amount of mass (Lobascio, Bricarello, Destefanis, Faraud, Gialanella, Grossi et al.)

LIQUID HYDROGEN

Liquid hydrogen consists of 99.79% parahydrogen, and 0.21% orthohydrogen. It is the liquid state of the hydrogen that normally is gaseous. It is the best performing material when it comes to shielding from radiation (O'Neill, 2006). However the handling requirements of liquid hydrogen are very burdensome.

ALUMINUM

It's the most common space material that has been used in many of the space crafts. It's ductile and very light comparing to other metallic materials

CASE STUDY: 3D PRINTING

2.2.4

Deep space mass transfer is one of the challenges for the manned mission to Mars. This is the reason why the mass of the cargo should be minimized as much as possible, meaning space agencies such as NASA, ESA and private parties should find ways to minimize the mass of the habitat or even plan for constructing it on site. arguments around minimizing mass has accelerated discussions on 3D printing on Mars, and autonomously constructing the habitat by using in-situ sources.

This mission concept of 3D printing or autonomously constructing on Mars requires technical advancement in many areas. There are certain questions remaining, which has to be answered due to their cruciality, such as: permeability of the habitat, ability to maintain pressurized environment for the crew, and radiation shielding properties (Kading, Straub, July 2014).

As mentioned earlier, the cargo phase mission would be the unmanned preparation phase, in which the habitat is constructed to support human life. Once the infrastructure and the habitat is deployed and validated, the crew mission phase would start. For this the second part of the mission involving multiple astronauts, their essential needs such as power and water must be taken care of in the previous part of the mission.

Three dimensional printing technique involves printing involves two dimensional patterns. Once the patterns are stacked layer by layer in a planer way the 3D form is given to the object. The chosen material thus needs a special treatment to be printed.

Basalt is commonly found on Mars due to the extrusions during lava flows (VHP Photo Glossary, March 2014). It is considered as an appropriate building material for radiation shielding, with a very high specific heat and very low permeability constant (Kading, Straub, July 2014). Although, the basalt is mentioned as an exemplary material here, the main concern is to better understand 3D printing possibilities on Mars regardless of the material choice in this specific part of the research.

In the case of basalt this may mean melting the material with 1100 degrees celsius (VHP Photo Glossary, March 2014). A common method used for melting Basalt us Fused Deposition Modelling (FMD). The FMD employs computer numerical control systems, which precisely leads the nozzle to extrude the molten material on the right spot. Once the previous layer freezes or solidifies the upper layer is extruded and fused together with the layer below. It is known that larger scale objects have been constructed utilizing this technology on Earth (Kading, Straub, July 2014). However, the certainty of the 3D printing on another planet with this method under different environmental conditions are yet questionable.

When it comes to 3D printing with basalt on Mars, there are two main considerations; heat and die pressure (Kading, Straub, July 2014). There is a chance that the machines may not withstand the heat the substance requires. The die also needs to be able to sustain the heat and the pressure of the substance that is molted and being extruded (Dieter, McGraw-Hill).

Pressurizing 3D printed structures:

Rigid structures are one of the key elements for pressurable indoor environments. Utilizing 3D strategies to build rigid structures may come very handy in this manner due to its suitability from utilization, protection and safety perspective (Kading, Straub, July 2014). For a habitat on Mars the internal and external pressures are considerably different, therefore the use of rigid structures can be an asset to their construction. However, the rigid structures are not the only solution for pressurable indoor environments. Expandable, pressurized structures such as the ones produced by Bigelow should also be kept in mind.

Permeability of 3D printed structures:

Maintaining the pressurized indoor environment is one of the critical concerns with 3D printed habitats. The habitat must ensure a nearly non-permeable envelope to keep the pressure stable. Although permeability of basalt has been previously studied (Saar, Manga, 1999), these studies have neither considered the basaltic compositions on Mars nor its use under the Martian atmospheric pressure. There are two possible scenarios to occur after 3D printing with basalt. First, the 3D printed structure may prevent the breathable air loss by creating an impermeable rigid structure, or secondly, the air gaps formed during the printing may lead to substantial breathable air and pressure loss.

Construction Methodology of Mars Habitat by Team GAMMA

Construction Methodology of Mars Habitat by Team GAMMA is a case study analysis where 3D printing was employed. It looks into the 3D printing technologies with swarm robotics, which was introduced by Team GAMMA, Foster and Partners (Wilkinson, Musil, Dierckx, Gallou, Kestelier et al., 2016) This case study was particularly useful for this thesis as it allowed for better analysis of 3D printing possibilities and whether they could satisfy the needs of construction on mars.

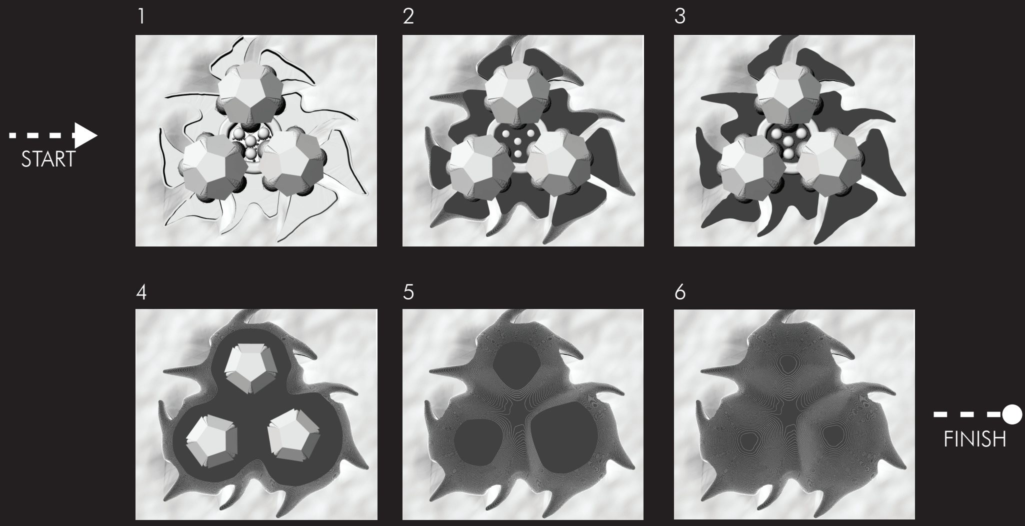
One of the leading companies in the field of architecture, Foster and Partners, have joined NASA's 3D Habitat Challenge. Team GAMMA, which is a group of architects and researchers from Foster and Partners has received the 2nd prize after designing an autonomously 3D printed habitat on Mars.

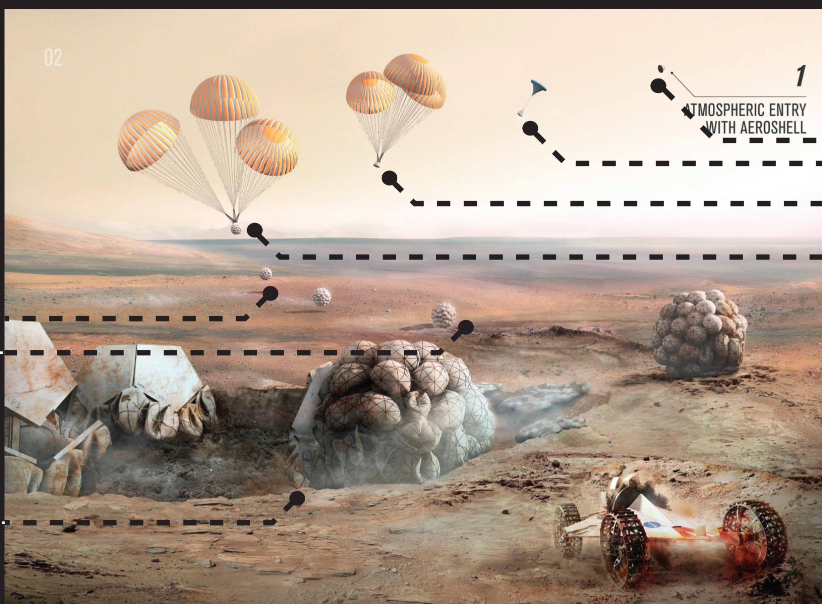
The mission design starts very similar to every other project concerning on building on Mars.
Two cargo ships containing deployable habitat units and robots that are assigned to construct the habitat are shipped within this phase.

Multi Robot Additive Regolith Construction:

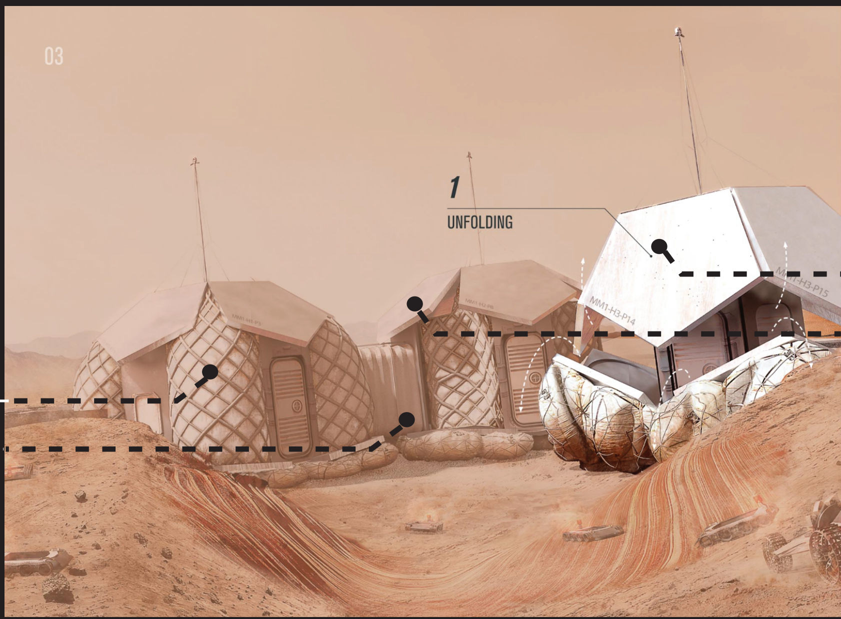
The multi-robot construction system used in the case study consists of three different robots. The first one is RAC-D, one large size digger robot. The second robot is RAC-T, there will be five medium size robots. The third kind consists of 15 small melter robots, named RAC-M. The very first task of the RAC-D is to dig 1.5 meter deep platform to accommodate the habitat modules. It will dig the loose regolith from the Martian surface (Wilkinson, Musil, Dierckx, Gallou, de Kestelier et al., 2016). Removal of the loose regolith will be carried by the RAC-T robots. The amount of removal should be the same with the amount that needs to be printed around the habitat.

MARS HABITAT
Gamma Team (+Foster)





ENTRY - DESCENT - LANDING



deployment of
supersonic
parachute
1

deployment of
supersonic
parachute
3

deployment of
supersonic
parachute
2

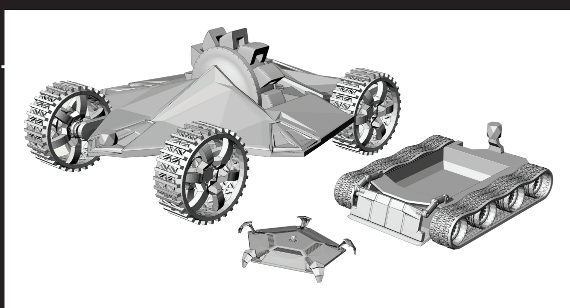
deployment of
supersonic
parachute
4

DEPLOYMENT - INFLATION

SWARM ROBOTICS

RAC-T
Carries regolith to
print zone

RAC-D
Regolith excavator
-collector



RAC-M
fuses regolith with
microwave

Once the site is ready, three modules will gather together and the inflatables around the habitat modules will deflate. After some subsequent steps the expandable airlock will extend to connect one another. Once the airlocks are connected to each other, the habitat is ready to be buried underneath the regolith shield.

In order to construct the regolith shield around the habitat modules, three different kinds of robots will be used, as mentioned. The reason behind this is to lower the risk of failure of a singular multi-functional robot which may imply drastic disruptions in the construction phase. Distributing risk across different robots that have different functions may lower the risks to an individual malfunction without causing disruption of the whole construction. These highly autonomous robots are able to make decisions and follow certain rules (Wilkinson, Musil, Dierckx, Gallou, de Kestelier et al., 2016). They are highly intelligent and they will be the assigned tasks of exploring, gathering materials and constructing habitats. However, Team GAMMA do not consider the uncertainty that the mechanical characteristics of the regolith's overburden creates (Hoffman, Andrews, Watts, 2016).

The downfall of this construction methodology is the fact that the study involves a large number of robots that are limited in their technological maturity. They are not operating inside a controlled environment, as opposed to working inside an inflatable module. Also, the robots' capabilities in performing the expected work is uncertain, since Martian environment is known to have harsh conditions. This is why, construction that is mostly led by less number of robots operating in a confined space would be favorable.

Figure 2.4: Mars Habitat, Team GAMMA, Foster and Partners

TRL: TECHNOLOGY READINESS LEVEL

2.2.5

The TRL methodology was introduced by NASA in the 1970s (Werries, 2017). This methodology helps to better apprehend the new technologies, thus, helps in decision making regarding the use of certain technologies in missions. TRL method consists of a scale that shows different levels of advancement of the technologies. This scale has proven to be very useful for "Building on Mars" in term of selecting the technologies that can be integrated in the project according to their current maturity and how promising the technology can be in the future.

TRL and Assessment Principles:

TRL is not a method to develop technologies but to assess their maturity at a given time. The measure provided by TRL is concerned with a specific element, at a specific point in time, and in a defined environment.(Werries, 2017). If one of these mentioned variables is different, the assessment becomes invalid.

Within a project framework, TRL is used during the preliminary phases (ESA-ESTEC, March 2017). It is a tool that supports the decision of whether or not to integrate a specific technology in that space mission. This decision is also related to the risk assessment regarding the maturity of that technology or object.

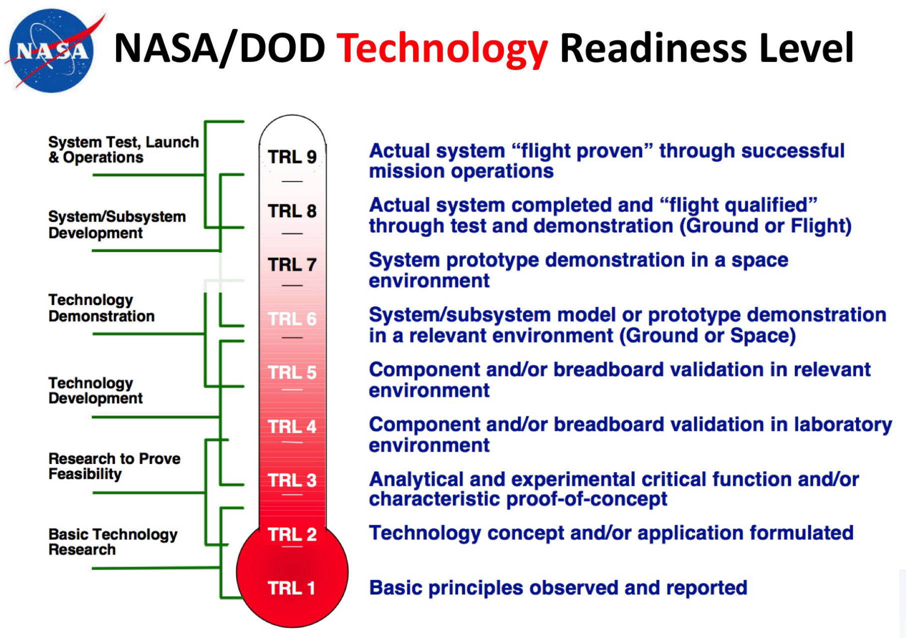


Figure 2.5: Technology Readiness Level Chart, NASA

DESIGNING FOR SPACE RADIATION ON MARS

Chapter

- 3 -

SPACE RADIATION

3.1

Radiation in space poses a significant threat to human body. There has been numerous studies researching allowable doses for sustaining health, level of radiation doses in space and effects of shielding on preventing radiation exposure. One of the greatest challenges of accommodating astronauts on Mars for a 500-day mission is to protect them from space radiation as much as possible. Although ESAS (Exploration Systems Architecture Study) has estimated radiation effects for some specific mission scenarios that provide foundations in designing missions, the effectiveness of radiation shielding remains uncertain. The shielding concept becomes extremely important when the planned missions involve humans, as protecting human body from radiation is still a field that needs further research. The effects of radiation on the human body varies from person to person, and it may take years for a person to experience the full effect of exposure.

NASA and other space associations/organizations, which design the manned missions to space, are the bodies that are suppose to define the allowable exposure. The fact that multiple organizations are working on allowable exposure levels creates an environment without universal standards and adds subjectivity into planning to build in space

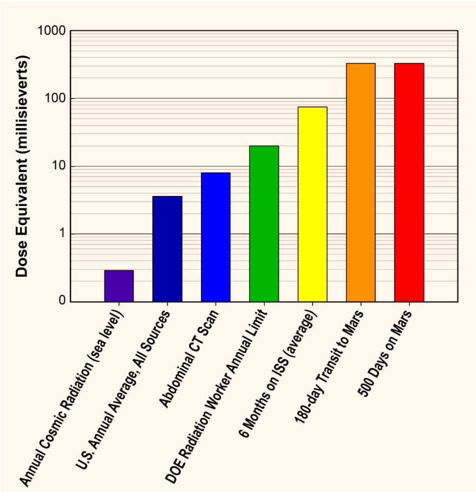


Figure 3.1: Chart compares the radiation dose equivalent for a 500-day stay on Mars.

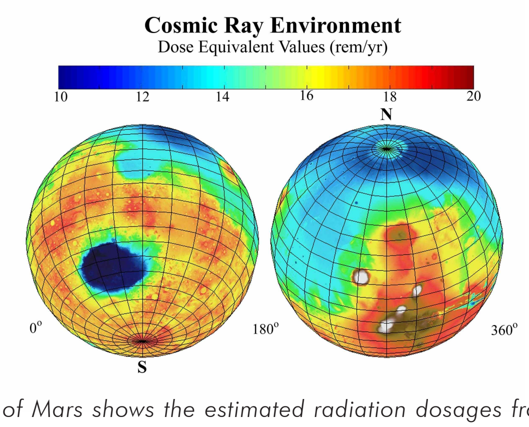


Figure 3.2: This global map of Mars shows the estimated radiation dosages from cosmic rays reaching the surface (JPL, NASA)

GALACTIC COSMIC RAYS (GCRs)

3.1.1

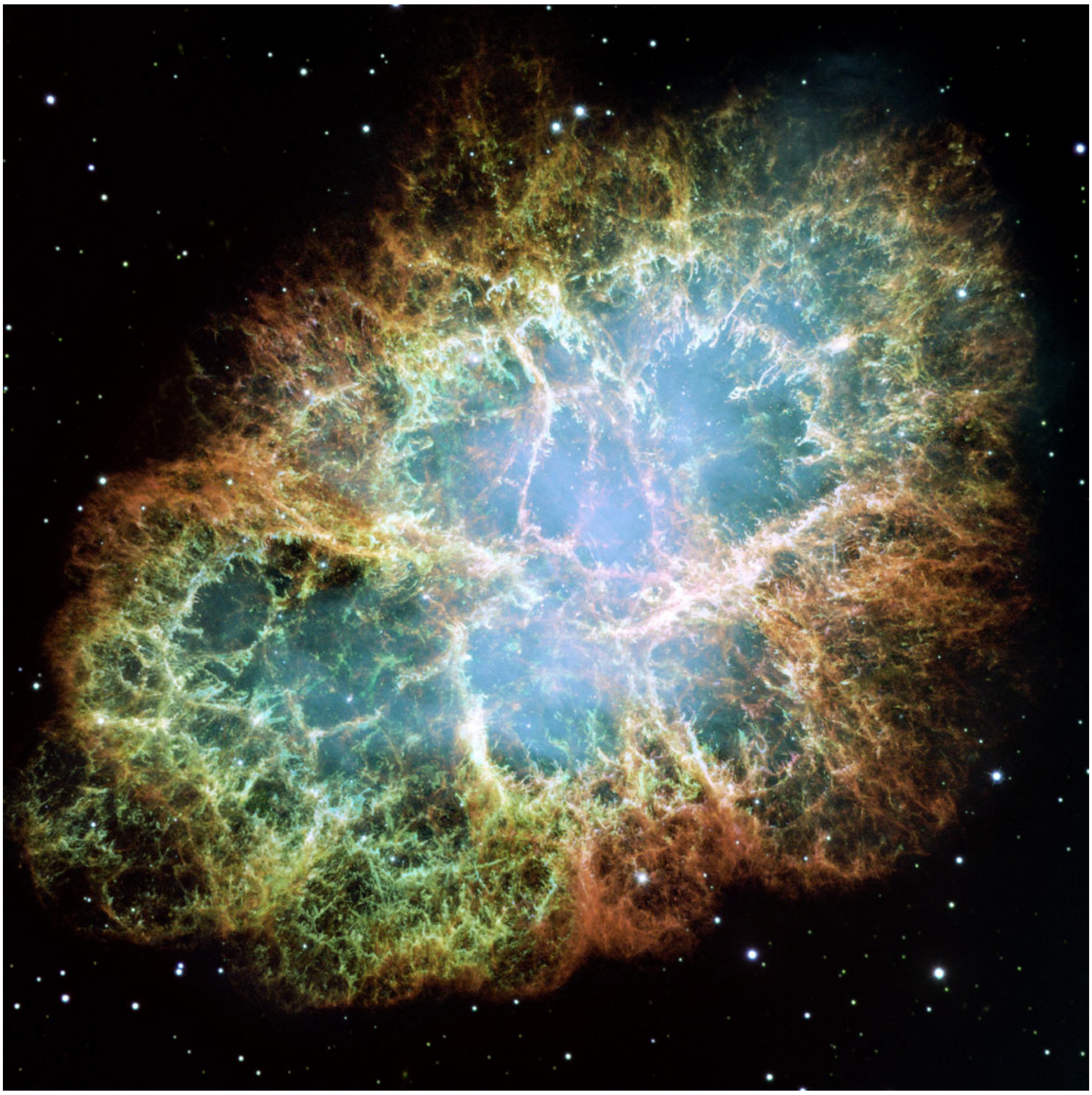


Figure 3.2: Published in a Science article[3] led by Subo Dong at the Kavli Institute of Astronomy and Astrophysics (Peking University, China) on January 15, 2016. ASASSN-15lh is the most luminous supernova ever detected; at its brightest it was approximately 50 times more luminous than the whole Milky Way galaxy.

GCRs are originated outside the solar system and they are heavy ions that are accelerated to extremely high energies due to supernova activities. GCRs are comprised of 91% protons, 8% alpha particles and 1% high energy particles (HZE) (Rapp,2006)The radiation caused by GCRs are constant and may pose a high risk to human health.

At solar maximum conditions, where a coronal mass ejection (CME) significantly releases plasma and magnetic field from the solar corona, GCR fluxes are reduced, producing almost half of that produced by the solar minimum GCR flux(Durante, 2011).

SOLAR ENERGETIC PARTICLES

3.1.2

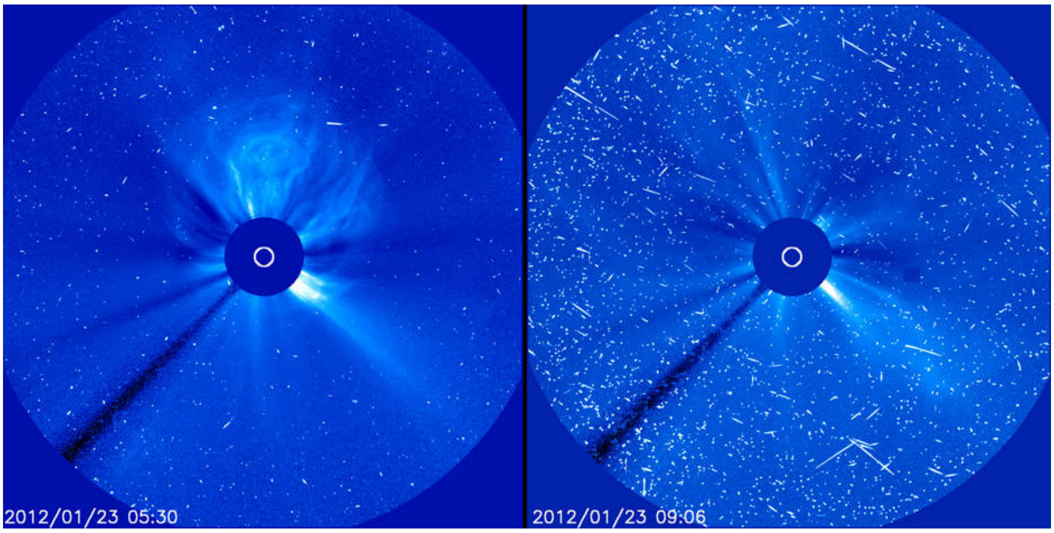


Figure 3.3: The blue pictures show the space around the Sun, the corona and are taken by the chronograph LASCO onboard of the spacecraft SOHO

In this picture, the sun is hidden behind the occulture, in the center. LASCO has taken this picture in late May 2013, in which a clear view of white plasma cloud (CME) has been captured. The plasma is being ejected into space, creating a particle storm. The energetic particles are then scattered around the space, hitting satellites and other object such as planets. These are Solar Energetic Particles (SEPs) that are occur due to solar events and the dose of radiation that risks human health may vary according to the magnitude of these events.

These solar energetic particles do not cause harm on the Earth as the Magnetosphere can direct them to the poles. However, in the case of Mars, due to the weak, almost non-existent dipolar magnetic field, the surface is not shielded against the SEPs.

Solar particle events (SPEs) are the main source of solar energetic particles, and occur when a substantial number of particles, protons with energies from a few MeV (million electron volts) to few hundred MeV move from sun's surface to the space. These events happen simultaneously with the increased solar activity.

"• SPEs occur sporadically near Solar Maximum (Rapp,2006)

• Appear to correspond to large coronal mass ejections - mainly protons.

• Large solar particle events are extremely rare and last only a matter of hours or days.

• In the last 50 years, we have had only 1 or 2 large SPEs per 11-yr solar cycle.

• Largest SPEs observed in the past were the February 1956, November 1960, August 1972, and October 1989."

COMPARISON OF GCRS AND SEPS

3.1.3

The GCRs are like the background noise of the space. They are always present and hitting the surface of Mars. the bombardment of high energy GCR particles deliver a lower but a steady dose. However, SEPs are consisting of large proton events that delivers a high dose in a much shorter time. These events may last hours and sometimes days.
(Rapp,2006)

"• The constant bombardment of high-energy GCR particles delivers a lower steady dose rate compared with large solar particle events that can deliver a very high dose in a short period of time (in the order of hours to days).

• The GCR contribution to dose becomes more significant as the mission duration increases.

• For long duration missions, the GCR dose can become career-limiting or annual-limiting.

• The main threat of SPEs is against the 30-day exposure limit.

• SPE energies are far lower than GCR and are more amenable to mitigation by shielding.

• The amount of shielding required to protect the astronauts will depend on the time and duration of the mission."

RADIATION UNITS REGARDING THE EFFECTS ON HUMAN HEALTH

3.2

It's been more than 40 years astronauts ventured beyond low Earth orbit. They have been out of the protective magnetic shield of the earth and have been exposed to space radiation. The short duration of the missions has minimized the risk until today, however, the crew that will be sent to Mars will be exposed to space radiation for a much longer period. Their exposure will be approximately for 8.5 months, only one way. This journey exposes the crew to certain risks such as: (Seedhouse, 2009)

Synergetic effects from exposure to radiation and microgravity.

- Damage on central nervous system
- Early or acute effects resulting in increased risk of cancer
- Radiation effects on fertility and heredity

The crew will be exposed to two types of radiation; GCRs that are heavy ions and SEPs, as mentioned earlier in detail. The impact of these two on human body is measured by the "dose equivalent" (Seedhouse, 2009)

Dose equivalent = Absorbed Dose x Quality Factor

The effect of radiation on tissue is calculated by the multiplication of absorbed dose by the quality factor. The absorbed dose is deposited energy in one kilogram of matter and quality factor is a measure that considers the relative effectiveness of the radiation in inducing biological effects (Seedhouse, 2009).

The biological effects are divided into two;

1)Stochastic Effects: Radiation effects that lead to higher chance of acquiring cancer due to the DNA related changes. Doses that lead to cancer can not be well determined, and prolonged exposure to low radiation dose may increase the probabilities of having cancer (Seedhouse, 2009).

2) Deterministic effects: These effects occur within a couple of hours after exposure of the whole body with the absorbed dose of 1.5 to 2.0 grays (Seedhouse, 2009). The effects are mostly nausea and vomiting, while some may experience the same effects by the exposure of only 0.5 to 1.0 grays. For doses between 2.5 to 3.0 grays almost everyone experiences nausea and vomiting. In the range of 3.0 to 4.0 grays, with minimal support, death may be a risk. Other problems caused by deterministic effects are organ dysfunction and risk of infertility.

Table 3. Summary of Definitions and Units.

Phenomena	Units
Fluence of particles in space	Number of particles per cm^2 per MeV/AMU per year
Absorbed dose	gray = absorption of 1 J of energy per kg of material
Dose Equivalent	Sievert = grays x weighting factors
Effective dose	Sieverts

Figure 3.4:Definition of units (Rapp,2006)

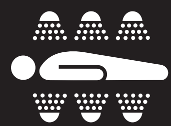
BIOLOGICAL EFFECTS OF SPACE RADIATION

Stochastic Effects:

radiation effects that leads to higher chance of acquiring cancer due to the DNA related changes

Deterministic effects:

effects that occur within a couple of hours after exposure to whole body with the absorbed dose of 1.5 to 2.0 garys



Synergetic effects from exposure to radiation and microgravity

Damage to central nervous system

Early or acute effects resulting in increased risk of cancer

Radiation effects on fertility and heredity

HOW MUCH RISK IS APPROPRIATE?

3.2.1

In the free field of decision-making on the allowable exposure in deep space, the common assumption is to use the low Earth orbit (LEO) guidelines. These guidelines follow the standards set by the National Council on Radiation Protection and Measurement (NCRP) and are based on point estimates. According to NCRP, the maximum allowable exposure should not exceed the 3% chance of getting fatal cancer, which is defined as the career limit (Scoles, 2017)

NCRP recommendations on organ dose equivalent limits for radiation exposure are presented in Table 1 and Table 2.

If one would like to design a mission to deep space, it's conventional to calculate the point estimates and compare it to estimates of radiation doses. However, the uncertainty regarding biological effects still remains, and it is discovered that protons and x-rays have significantly differing effects on DNA.

In-depth literature review revealed that different organizations have varying allowable doses and there are mixed conclusions on the efficiency of shielding. For instance, after GCRs are passed through Martian atmosphere, low-energy component of this specific kind of radiation are removed (Rapp,2006) The studies concluding that extra shielding is needed in the habitat to block the low-energy radiation of GCRs adds confusion and these may be considered futile efforts that have limited proven efficiency. Similarly, there are mixed reviews and conclusions around the use of aluminum as a shielding material, and there is a potential that this material might not be the best to be used for shielding on Martian surface.

Table 1. Recommended organ dose equivalent limits for all ages from NCRP-98 (1989) and repeated by NCRP-132 (2001). "BFO" = blood-forming organs.

Exposure Interval	BFO Dose Equivalent (cSv)	Ocular Lens Dose Equivalent (cSv)	Skin Dose Equivalent (cSv)
30-day	25	100	150
Annual	50	200	300
Career	See Table 2	400	600

Table 2. LEO career whole body effective dose limits (Sv) from NCRP-132 (2001).

Age	25	35	45	55
Male	0.7	1.0	1.5	2.9
Female	0.4	0.6	0.9	1.6

Figure 3.4: Recommended doses (Rapp,2006)

ALARA CONCEPT BY NASA

3.2.2

ALARA (as low as reasonably achievable) concept for space radiation is an accepted policy by NASA in efforts to protect astronauts that are assigned for space missions. The policy aims to minimize the exposure of astronauts allowing only 3% of increased cancer chance for a lifetime career. For instance, the exposure to space radiation of the astronauts in International Space Station are much higher comparing to typical ground based radiation workers and this is an accepted fact by NASA (iws.gsfc.nasa.gov) Thus, legal and moral reasons require NASA to limit the exposure to minimize the long term health risks. In order to attain this goal, NASA's regulation on astronauts is in compliance with the ALARA concept that is introduced by U.S Occupational Safety and Health Administration. Moreover, NASA takes an active role for protecting the astronauts with the NASA Mission Support Team which has a specific department called Space Radiation Analysis Group (SRAG).

SRAG is in charge of providing:
-Preflight crew exposure protection
-Real-time astronaut radiation protection support
-Radiation monitoring to meet medical and legal requirements

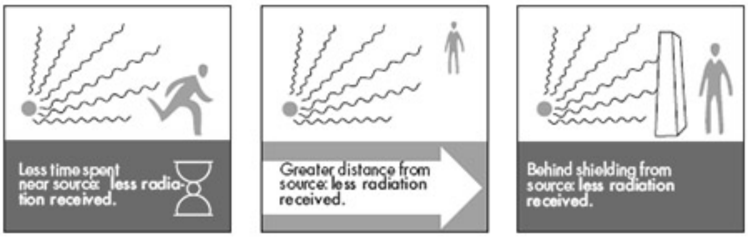


Figure 3.4: Three possible procedures to reduce the dose equivalent.

CONCLUSION: WATER FOR RADIATION SHIELDING

3.2.3

In order to mitigate the risk of getting fatal cancer and other illness caused by space radiation, appropriate shielding materials should be used. However, on Mars, range of materials to be employed in the construction is limited. One of the commonly used materials in the space industry is aluminum and surface of Mars is vastly covered in martian soil, regolith. These two materials can be utilized in order to build the habitat. Another option for the shielding material is water that can be found on Mars (NASA's approach towards missions to Mars: "follow the water")

In the graph, the shielding properties of regolith and aluminum against solar minimum GCR can be seen. Both of the materials behave very similarly during exposure to GCRs and SEPs. Water has shown to perform better in comparison to aluminum and regolith. Thus, with a slimmer shield of water (g/cm2) similar results can be attained. If the thickness of water shield increases, the dose equivalent that the crew will be receiving during their surface stay may decrease drastically. This is due to water's highly hydrogenated characteristics. Furthermore ,water can be utilized in the form of ice to give structural integrity to the habitation.

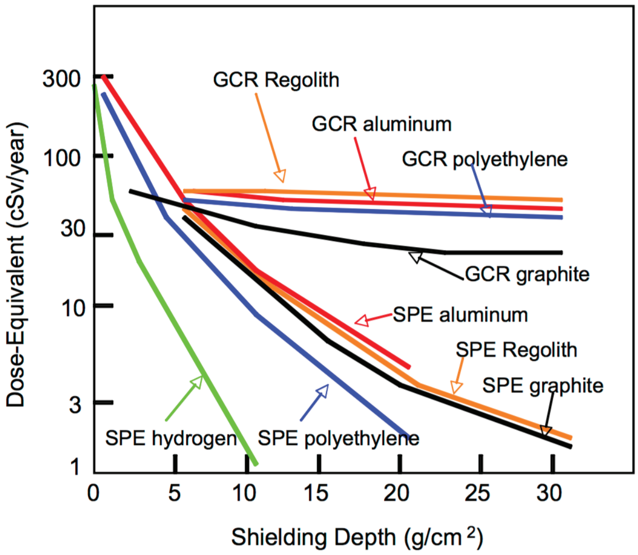


Figure 3.4: Depth of regolith and aluminum regarding their shielding properties (Rapp,2006)

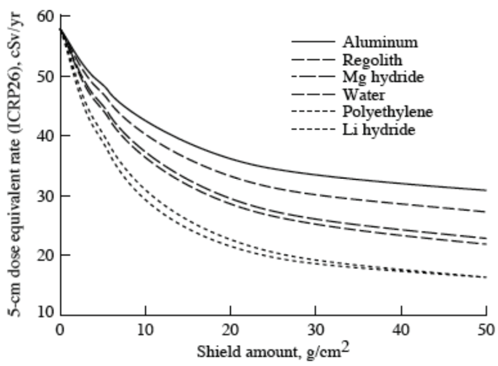
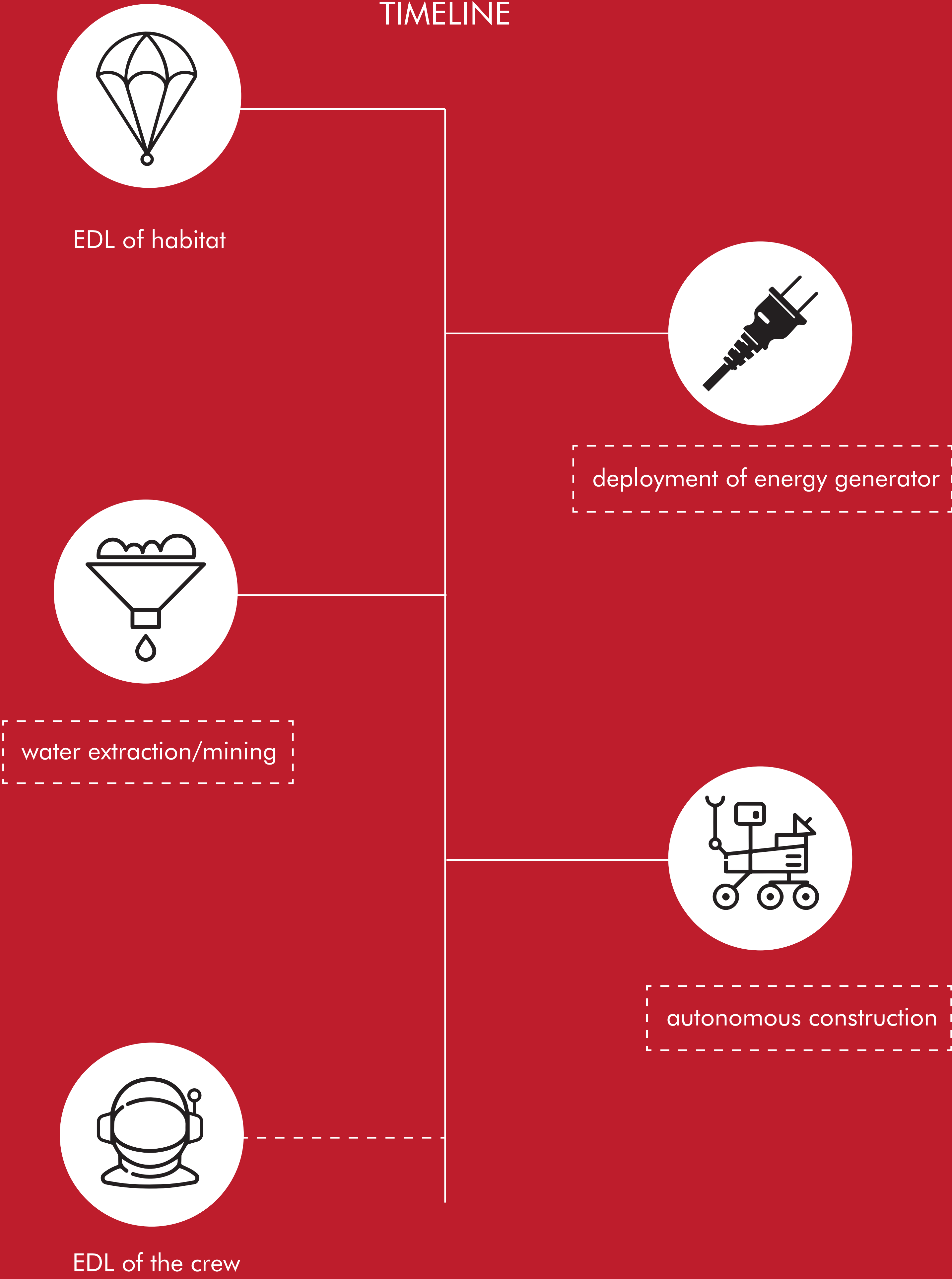


Figure 3.4: Depth of water, regolith and aluminum regarding their shielding properties (Rapp,2006)

HOW TO BUILD ON MARS?

Chapter
- 4 -

CONCEPTUAL CONSTRUCTION TIMELINE



MISSION OVERVIEW

4.1

Designing a space mission is out of the scope of “Building on Mars”. However, in order to provide credibility and feasibility to the project a planned mission had to be chosen.

NASA’s Human Exploration on Mars Design Reference Architecture 5.0 (DRA 5.0) publication serves as the main source for Mars missions with multiple mission options based on their durations, which includes outbound, short-term and long term missions.

Zubrin, who is an aerospace engineer and an advocate of manned missions to Mars, argues that human body needs to recover from the radiation exposure during transit for a certain amount of time before returning back to Earth. (Zubrin, 2011)

Under the light of Zubrin’s studies, “Building on Mars” adopted the long-term mission outlined in the DRA 5.0, which involves a stay on Mars for 539 days and this project aimed to design a habitat that will shield the crew from the space radiation during their stay, providing sufficient time to decrease the stochastic effects of exposure during the transit stages.

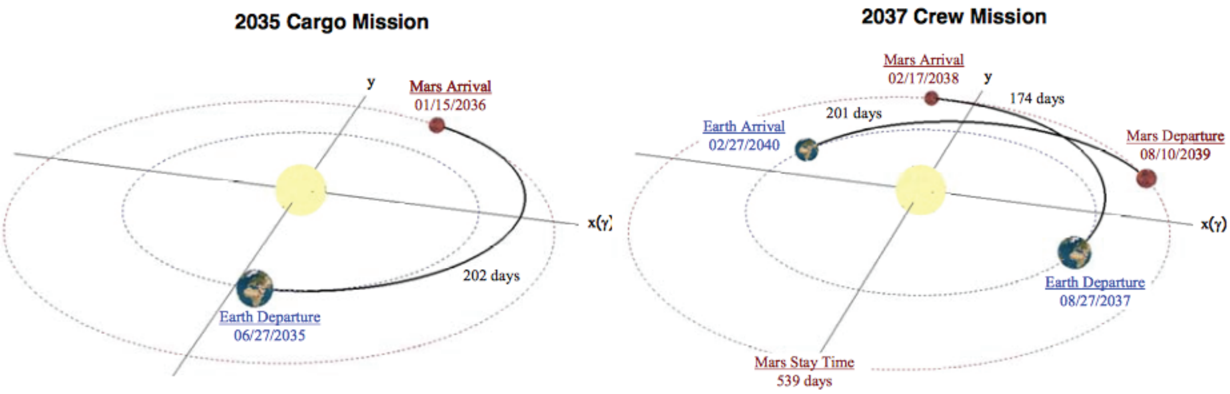


Figure 4.1: Cargo and crew trajectories for 2037 mission (DRA 5.0, NASA)

After the long-term mission has been chosen the EDL technologies, mass allocations and further details are also designed under the guidance of DRA 5.0 for this thesis. One of these details is the differentiation of the cargo mission and the crew mission. The window period between these two missions limits the construction timeline to approximately 480.

The mentioned long-term mission has been further developed in the NASA study “Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions” and this version of the mission suggests a crew of six to be a suitable number of humans to be involved (Whitmire, Leveton, Broughton, et al., 2015).Therefore, “Building on Mars” finalized the mission selection as the long-term mission with six astronauts. Further details about the mission can be viewed below in figure

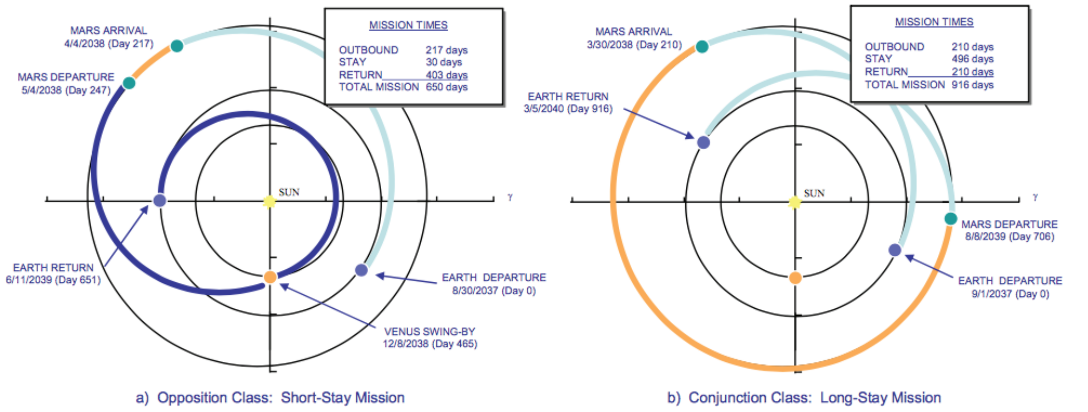


Figure 3.4: Comparison of opposition class and conjunction class mission trajectories (DRA 5.0, NASA)

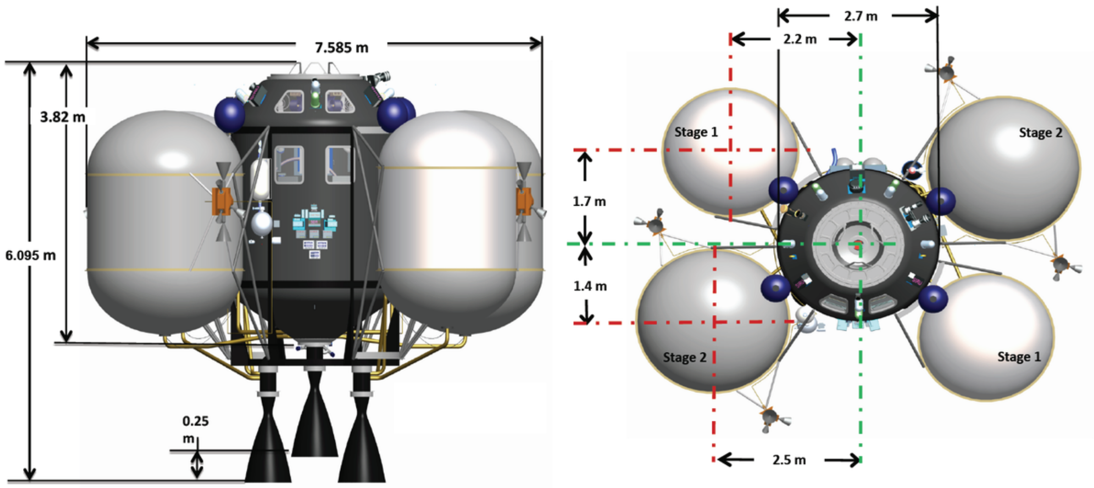


Figure 4.2: Mars Ascent Vehicle for crew of 6

Total Mission Duration	**30 Months**
- In transit to	6 months
- At target	18 months
- In transit from	6 months
Crew Size	N = 6
Crew Composition	Pilot, Physician, Geologist, Biologist, Engineer, Electrical Engineer
Gender Mix	Variable; exact mix undefined
Cultural Mix	Presumably some combination of US, Russia, Europe, Canada and Japan
Mission Tempo	Long periods of low mission tempo, interspersed with high activity times (for example, launch, jettison tanks, dock, landing)
Communication Delays	Up to 22 minutes one-way with blackout periods
Autonomy from Ground	Increasing en route to Mars, decreasing during return to Earth

Figure 4.3: Number of crew and durations (NASA)

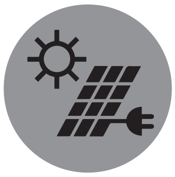
SEQUENCE FOR CONSTRUCTION WITH WATER

- 4.2 -

DEPLOYMENT OF ENERGY GENERATORS

4.2.1

WHAT OPTIONS DO WE HAVE?



solar powered systems

fission powered systems

For "Building on Mars" project, a crew of six will stay on the Mars surface for 539 days as outlined in the Mission Overview. During this time period, energy needs to be generated in order to produce liquid oxygen for the return vehicles, water extraction and construction.

NASA estimates that in order to support six crew living on Mars for 500 days, 40 kilowatts electric (kWe) will be needed. (Mason, Poston, Qualls et al. 2008)

The potential systems are nuclear and solar systems that come with advantages and disadvantages under to different circumstances.

According to the mission design, return vehicles of the crew will arrive earlier than crew's arrival to Mars and they should be landed with empty oxygen propellant tanks. The underlying reason of this arrangement is to minimize the mass. The oxygen tanks of the return vehicle will only be filled once the power is supplied and liquid oxygen (LOX) can be produced.

In case of using only one energy system, the energy plant will be first dedicated to ISRU propellent plants in order to produce the necessary amount of LOX for the crew's return vehicle. Once the crew lands on Mars, they will switch the plant over to the habitat. From the cargo mission phase to the crewed mission phase the efficiency, mass, cost and energy storage are crucial indicators to analyse.

According to NASA, the oxygen production rate for the cargo mission phase is the 1/5 of the crewed mission phase.(Rucker, 2016) This information may help in analyzing the options and guide to chose an energy generation system.

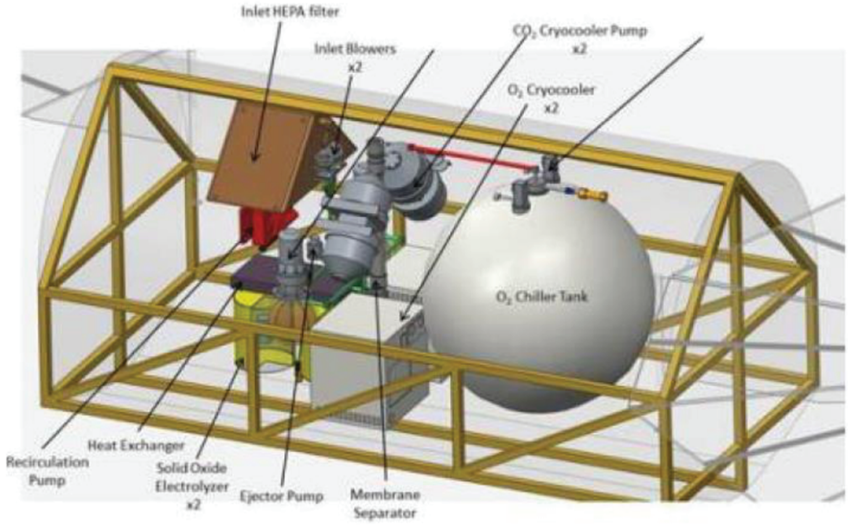


Figure 4.4: Conceptual visualisation of ISRU Plant (NASA)

According to NASA, the oxygen production rate for the cargo mission phase is the 1/5 of the crewed mission phase.(Rucker, 2016) This information may help in analyzing the options and guide to chose an energy generation system.

Solar Powered Systems

This system is sensitive to day and night cycle as well as the weather conditions such as dust storms.

Fission Powered Systems

This system may operate around the clock without any weather related disruption. However, it may risk the health of the crew by exposing them to higher doses of radiation if not placed at an appropriate distance from the habitat.

NASA's Considerations Regarding Energy Generation Systems

1) Performance, as measured by propellant production rate in kilograms per hour (kg/hr)
2) System mass
3) System robustness to the Martian environment, particularly dust
4) System design, development, test, and evaluation cost
5) System operational life

FITNESS OF ENERGY GENERATION SYSTEMS TO MARS

4.2.2

The Opportunity rover of NASA is currently on Mars. The surface temperature where Opportunity explores varies between 174K to 308K, and the sky temperature varies between 139K to 213K. (Mars Climate Database, 2016) This information can be useful as the focus Jezero Crater and the Meridiani Planum where Opportunity Rover has landed, are both located in equatorial area. The temperature variation might affect both fission powered and solar powered systems.

Dusts storms on Mars occur in different scales: occasional global storms and local storms. The local storms may last in a few days at most and have a modest influence on the optical depth. On the other hand, the global storms may last for months with a substantial increase in the optical depth. These global storms seem to occur in about every three Martian year, especially during the spring and summer on the southern hemisphere. (Mason, Poston, Qualls et al. 2008)

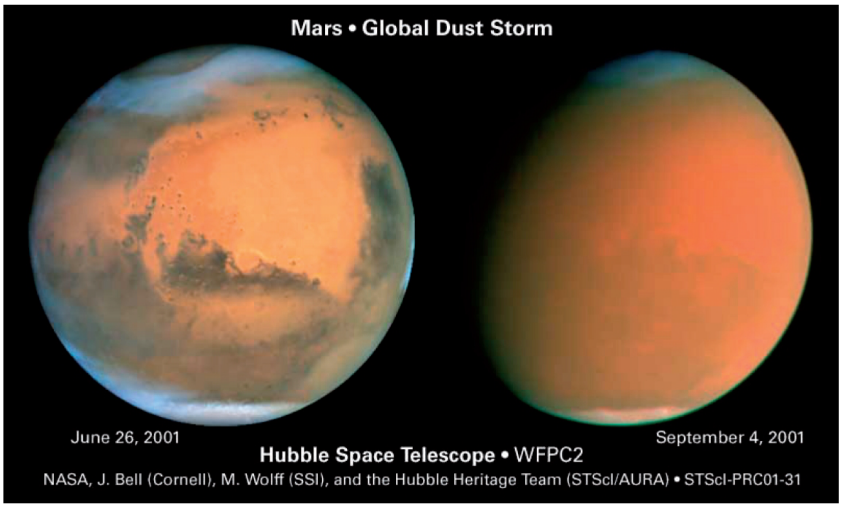


Figure 4.5: Mars global sand storms (NASA)

Figure 4.6: Optical depth conducted by Opportunity Rover (NASA)

In a NASA study on energy generation systems on Mars, a worst case scenario was chosen to analyse the solar systems (Mason, Poston, Qualls et al. 2008). A global sand storm that would last 120 days was assumed with an optical depth that varies between 1.0 (clear sky) to 5.0 (dust storm at the peak). This study was based on solar energy measurements that were collected by the Opportunity and the Spirit rover. The illustration above depicts the optical depth viewed by the Opportunity rover, during a solar storm and on a day with clear sky. As it can be seen, at the peak of the sand storm the direct sunlight was almost blocked and has become a scattered light which would decrease the amount of energy generated by the solar powered systems. The dust suspended on the very thin Martian atmosphere would induce sunlight to be scattered, only allowing 30-40% to reach to the surface compared to a clear day. Thus, solar powered systems are quite vulnerable when it comes to generating energy on Mars.

In the scope of the mission outlined in "Building on Mars", during the cargo mission phase, the energy generators would continue to work until 4,400 kg of LOX was produced.

SOLAR POWERED SYSTEMS

4.2.2.1

Solar Option A:

This option operates only for 10 hours during the daytime with a production rate of . The systems requires 0.22 kW to power the generators after post landing. The energy requirement jumps to 6.45 kW once the propellant production started. Since the system is not working during the night time, it only requires the standby energy that is 0.69 kW.
It is estimated that four solar arrays of 5.6 m diameter UltraFlex arrays would suffice to supply the energy requirement of the ISRU plant that will produce 4,400 kg LOX. The disadvantage of this option is the loss of two hours due to the warm-up of the system each sol. The total payload mass of the option A is 1,128 kg including the growth allowance for the future uses. (Mason, Poston, Qualls et al. 2008).

Solar Option B:

This option aims to decrease the production time of the LOX, making the cargo mission phase shorter. Although it creates logistical problems due to the extra payload mass, which is 1,200 kg more in comparison to Option A. Extra payloads are mostly caused by more energy storage and larger solar arrays. The objective of providing energy to ISRU plant means storing more energy that can be supplied to the plant continuously. This results in a massive structure which is composed of four solar arrays with diameter of 7.5 meters. The total payload of this option is 2,425 kg including the growth rate. (Rucker, 2016)

Solar Option Option C:

The last solar powered option operates only during the day time for 10 hours with the production rate of 2/5 . The diameter of the solar arrays are kept the same as Option B, 7.5 meters. Total payload of Option C falls between Option A and Option B, reaching 1,531 kg. (Rucker, 2016)

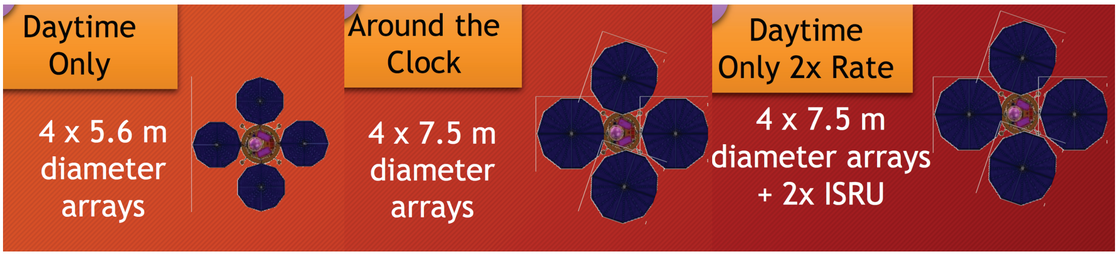


Figure 4.6: Solar power systems presented by Mars Study Capability Team, NASA

SOLAR POWERED SYSTEMS

4.2.2.2

For generating energy on Mars with fission powered system, 10 kWe radiators are suggested. Although this system might be slightly oversized, it has advantages for the crewed phase mission. A stowed 10 kWe kilo power system is approximately 4 meters tall and 1.5 meter wide (Lee, David and Louis, 2008). Once the panels are deployed the diameter reaches 5 meters providing 20 sqm surface area. This system is estimated to be 1,754 kg with an allowance of 15% of mass increase for the future use. Although the system by itself is not very heavy, third of the kilo power's mass was dedicated to the shield that is suppose to reduce the crew radiation exposure.

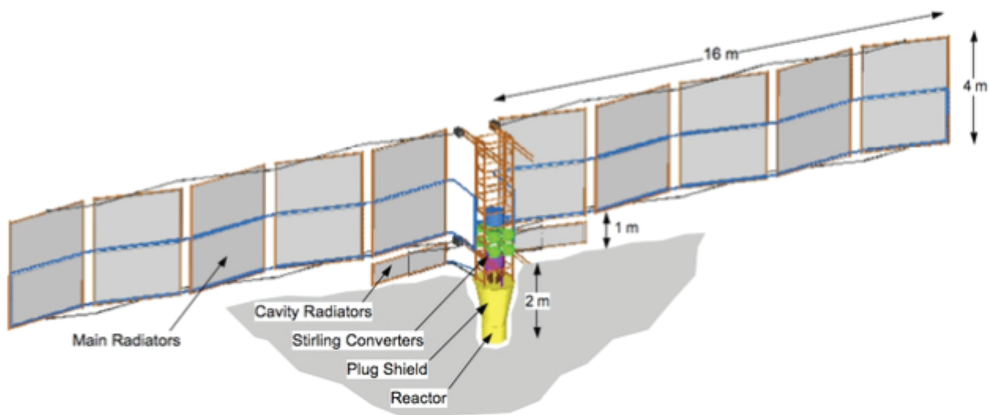


Figure 4.7: Fission powered system presented by Mars Study Capability Team, NASA

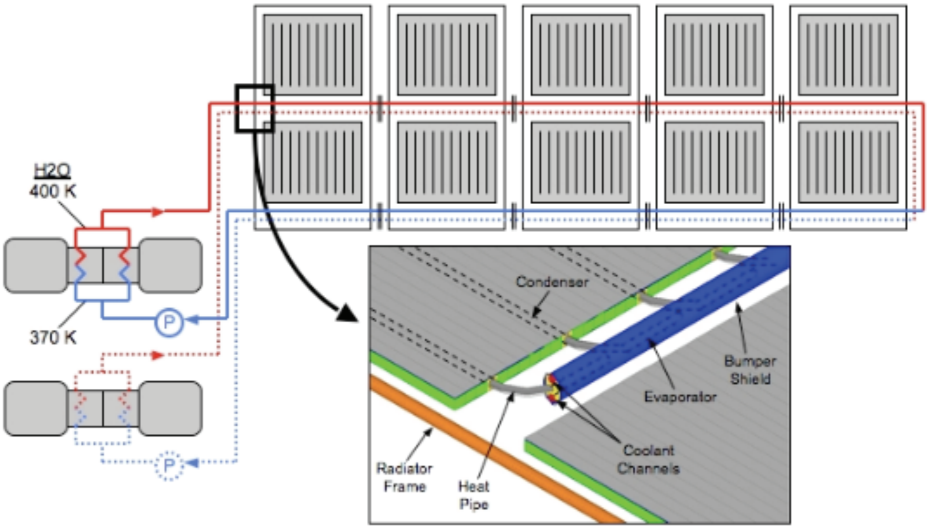


Figure 4.8: Representative, conceptual illustration of fission powered systems, NASA

Fission Option

This system operates around the clock with a production rate of . One of the advantages of the system is no deployment mechanism is needed after post landing. The system requires 106 W to start generating energy. Due to the around clock energy generation that comes with a larger electrical power system, this option's total payload mass is quite higher comparing to solar options, reaching 2,751 kg. 10-kWe kilo power unit, which is one of the major pieces of this system, comprises 1,754 kg of the total mass. (Lee, David and Louis, 2008)

CONCLUSION: MIXED GENERATION SYSTEMS

4.2.4

In terms of performance, Solar Option B can equally shorten the cargo mission phase as the Fission powered option. This indicates that the LOX production will be completed earlier, providing more time to start producing water for ice bags of the habitat's facade. In the case of a global sand storm, the solar powered systems may have a disruption up to 120 days, without providing energy to the ISRU plant. This disruption might be managed for the cargo mission phase, however, once the crew has arrived, it may have fatal consequences. One should not forget, due to the utilization of water in construction, the energy generators should also keep the water in the cryogenic conditions, in other words not letting the water freeze.

The performance of the solar powered system is very much depended on the location of the landing/habitat site. As the landing site is shifting towards the polar areas, the efficiency of the system decreases. However, for the fission powered system, location does not play a major role and it can provide similar peak powers and efficiency within the considered landing sites by NASA. On the other hand, if habitats for other locations with different latitudes were to be designed, for each location the efficiencies for both systems must be considered.

Once the mass of the each system is calculated, it is rather easy to see the lightest system is the Solar Option A. However, this system takes twice longer to produce the same amount of propellant comparing to Solar Option B.

System robustness is another concern due to the atmospheric changes on Mars. Dust accumulation on the solar arrays may drastically decrease the efficiency of the solar powered systems. Thus Solar options A, B and C are quite vulnerable in this sense. In order to tackle this problem, gimbals are included to the solar arrays, providing a rotational move to remove the accumulated dust. However, every movable mechanical piece has a potential decreasing effect on the robustness of the system.

Operational life of both of the systems are longer than the planned mission duration. However, the degradation of the solar arrays is quite possible. The fission powered system is claimed to last for 12 Earth years. (Lee, David and Louis, 2008) Both of the systems will lose their efficiency over the time due to battery performance decrement and other reasons.

Under the light of these findings, it was decided that "Building on Mars" project will require a mix of both systems. Two cargo landers will be landing on Mars surface carrying power systems. The cargo lander that carries the Mars Ascent Vehicle should be equipped with the fission power system to continuously produce LOX in order to enable crews launch back to Earth at the end of the mission. This cargo lander should be located at a kilometer distance from the cargo lander that will carry the habitat module. This distance is needed because of the fact that the fission powered generators are inducing extra radiation exposure to the crew. For the same reason, the cargo lander with the habitat will carry solar powered systems because the system has no biological harm on the crew over its operational life time.

Option	Solar 1A: 1/5 rate Daytime Only	Solar 1B: 1/5 rate Around the Clock	Solar 1C: 2/5 Rate Daytime Only	Fission 2: 1/5 Rate Around the Clock Fission Power
Total Payload Mass (including growth)	1,128 kg	2,425 kg	1,531 kg	2,751 kg
Electrical Subsystem Mass	455 kg	1,733 kg	639 kg	1,804 kg
ISRU Subsystem Mass	192 kg	192 kg	335 kg	192 kg
Power	~8 kW Daylight	~8 kW Continuous (with 16 kW of arrays)	~16 kW Daylight	~7 kW Continuous
Solar Arrays	4 each x 5.6 m diameter	4 each x 7.5 m dia.	4 each x 7.5 m diameter	None
Night Production?	No	Yes	No	Yes
LOX Production	4.5 kg/sol	10.8 kg/sol	9.0 kg/sol	10.8 kg/sol
Time to Produce 4,400 kg LOX, including 120-Day Dust Storm Outage	1,098 sols	527 sols	609 sols	407 sols
ISRU On/Off Cycles	1,098	<5	609	<5
Radiation Tolerance	100 kilorad (krad) electronics and ISRU			300 krad electronics, 10 Mega ad (Mrad) ISRU

Figure 4.8: Overview of solar and fission powered options.

TRADE-OFF CHART FOR THE ASSESSMENT OF ENERGY GENERATORS NEAR THE HABITAT MODULE

criterion / option	Mass %25	Post landing handling %5	Biological/physical effects on the crew %30	Implications on construction %20	Robustness to the environment %20
Day time only solar arrays	1,128 kg	post landing start up energy and placement	no effects	low keep alive power	sand storms
Around the clock solar arrays	2,425 kg	start up energy, placement and gimbaled structe due to the size	no effects	low keep alive power	sand storms
Day time only solar array double rate	1,531 kg	post landing start up energy and placement	no effects	low keep alive power	sand storms
Fission power	1,754 kg	may start generating energy on a lander	extra radiation exposure 1 km away from the habitat	affordable keep alive powers	high robustness to the environment

excellent, exceeds requirements — good, meets requirements — correctable deficiencies — Unacceptable

criterion / option	Mass %25	Post landing handling %5	Biological/physical effects on the crew %30	Implications on construction %20	Robustness to the environment %20	Total score
Day time only solar arrays	0,75	0,1	0,9	0	0,2	1,95
Around the clock solar arrays	0	0,05	0,9	0	0,2	1,15
Day time only solar array double rate	0,5	0,1	0,9	0	0,2	1,7
Fission power	0,5	0,15	0,3	0,4	0,6	1,5

3 excellent, exceeds requirements — 2 good, meets requirements — 1 correctable deficiencies — 0 Unacceptable

TRADE-OFF CHART FOR THE ASSESSMENT OF ENERGY GENERATORS NEAR THE MAV

criterion / option	Mass %20	Post landing handling %5	Biological/physical effects on the crew %5	Implications on construction %35	Robustness to the environment %25
Day time only solar arrays	1,128 kg	post landing start up energy and placement	no effects	low keep alive power	sand storms
Around the clock solar arrays	2,425 kg	start up energy, placement and gimbaled structe due to the size	no effects	low keep alive power	sand storms
Day time only solar array double rate	1,531 kg	post landing start up energy and placement	no effects	low keep alive power	sand storms
Fission power	1,754 kg	may start generating energy on a lander	extra radiation exposure 1 km away from the habitat	affordable keep alive powers	high robustness to the environment

excellent, exceeds requirements — good, meets requirements — correctable deficiencies — Unacceptable

criterion / option	Mass %20	Post landing handling %5	Biological/physical effects on the crew %5	Implications on construction %30	Robustness to the environment %40	Total score
Day time only solar arrays	0,6	0,1	0,15	0	0,4	1,25
Around the clock solar arrays	0	0,05	0,15	0	0,4	0,6
Day time only solar array double rate	0,4	0,1	0,15	0	0,4	1,05
Fission power	0,4	0,15	0,05	0,6	1,2	2,4

3 excellent, exceeds requirements — 2 good, meets requirements — 1 correctable deficiencies — 0 Unacceptable

WATER EXTRACTION

- 4.3 -

BACKGROUND KNOWLEDGE

4.3.1

One of the crucial research bodies of NASA for the manned mission to Mars is the research group that analyses how to produce water on Mars through in-situ resource utilization. As NASA's main approach for all the Mars missions, "follow the water", suggests, production of water has been a major study. (Hoffman, Andrews and Watts, 2016)

In order to find technologies that are capable of producing water we should first look into Martian water sources. M-WIP Study suggests a sequence to start analyzing the water sources: (Abbud-Madrid et al., 2016)

1) Formulate descriptions of hypothetical reserves on Mars,
2) Estimate the rough order-of-magnitude of the engineered system needed to produce each of the reference cases,
3) Prepare a first draft analysis of the sensitivity of the production system to the known or potential geological variation
4) Prepare an initial description of the preliminary implications for exploration.

There are several sources on Mars which may potentially lead us to produce water. According to M-WIP Study, these are:

Case 1: Glacial ice
Case 2: Natural concentration of poly-hydrated sulfate minerals
Case 3: Natural concentration of phyllosilicate minerals
Case 4: Regolith

All of these potential sources come with advantages and disadvantages, and they require special treatments and different ISRU engineering. Also, the systems that are produced for one case may not work for the other, as expected. Thus, it is important to take all of the parameters into account beforehand. These parameters are stated below:

Water Production Plant Parameters: mass/power/complexity of the ISRU engineered system

Parameters for the Potential Source: mining/acquisition, extraction, transportation, processing and storage

In order to provide these informations, one should explore the landing site and come up with the technologies that are appropriate to extract water with the source that is present in the site. This was the main concern of the research group that worked on the exploration zones.
This research group was asked to identify, along with the exploration zones, one or more candidate water sources, which have potential of producing 5 metric tons of water per year. (Abbud-Madrid et al., 2016)

GROUND RULES OF WATER PRODUCTION

4.3.2

"Building on Mars" considers to utilize water as a construction material in order to create an ice habitat on Jezero Crater. The water that will be used for the construction is planned to be produced with ISRU systems. However, these systems are subject certain rules, and the M-WIP study group has defined mission specifications for producing water through ISRU systems. "Building on Mars" aimed to comply with these specifications while designing methodologies for water production on Jezero Crater

M-WIP Mission Ground Rules for water production through ISRU systems (Abbud-Madrid et al., 2016:

-A single surface location will be visited and explored by several crews

-The site must be within the +/- 50 latitude (due to the current EDL technologies' allowance.

-The water and propellant production window is only 480 days. The ISRU system would arrive on Mars, one mission ahead of the crew to produce the propellant

-The ISRU system must be co-located with the Mars Ascent Vehicle and the habitat so that ISRU products can be stored in the systems that will use water.

-A nomial of 16 metric tons of water should be provided per crew, in order to meet the requirements of fully fueled Mars Ascent Vehicle and to provide enough oxygen to support crew's life.

Although the M-WIP study is able to provide clear guidance on the utilization of ISRU systems, construction with water has not been taken into account as there is no accepted finalized design of a Mars habitat in the literature. In the case of "Building on Mars", construction of the habitat will require much more water then what is required in the ground rules defined in the M-WIP study.

Classifying the reserves is of utmost importance to the missions as one cannot speak about water production and construction without discovering the right sources of water. Without the appropriate classification of such reserves, the exploration cannot take place and manned mission would not be possible. The reserves hold such importance for the missions not only due to human dependency on water and oxygen in order to live, but also the need for propellant production for the Mars Ascent vehicle to take the crew back to Earth.

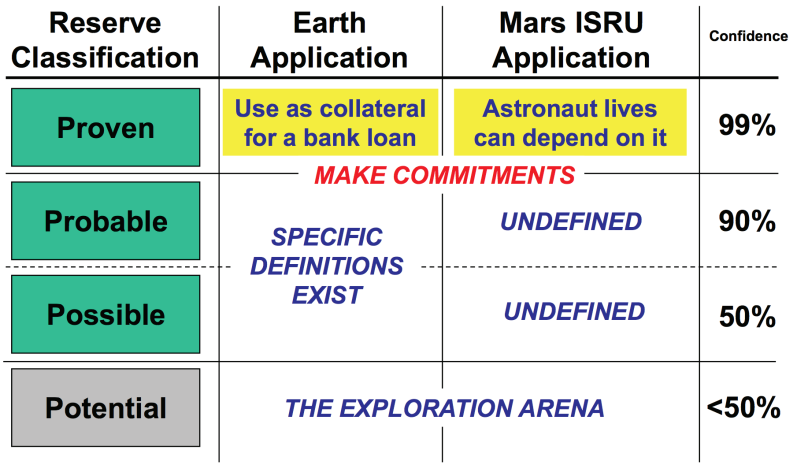


Figure 4.9: Reserve classification vs confidence of mission (M-WIP)

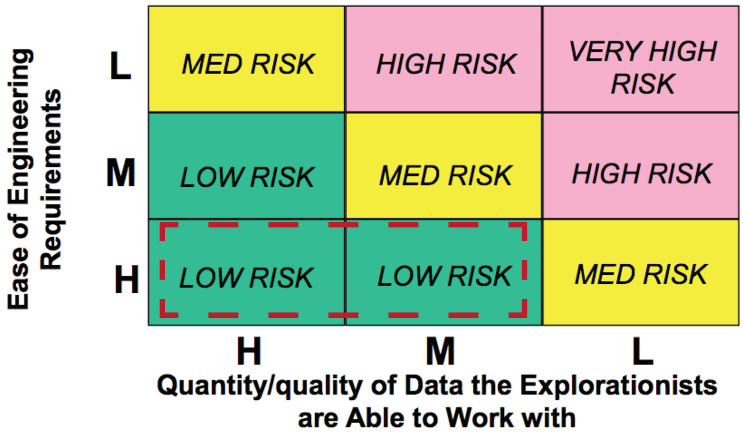


Figure 4.10: Current risks without identifying the source (M-WIP)

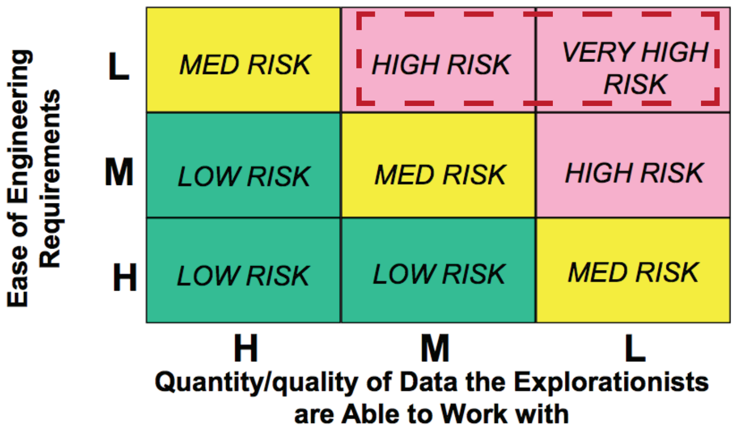


Figure 4.11: The risks after and orbiter and a rover present on site (M-WIP)

In the figure 4.9, one can see that without a proven source, the confidence of a manned mission is very low, thus, risky. Reserves show in which form the material is present in the selected exploration zone. Proven doesn't not only stand for the presence of the material itself, but also it means that the presence of the material is known and modeled. There are still lacking informations regarding the water sources considered by M-WIP study. This is due to the limited number of completed surface exploration missions, and without proving the mentioned sources, the risk of sending humans to Mars is very high.

In the figures 4.10 and 4.11, the overview of water production can be observed. Exploration of an exploration zone must take place in order to be fully confident about the presence of the source material. This information can lead NASA to deliver systems that can extract/mine water and process it to the end user.

Vicious Circle of Water Production:

Delineation of usable reserves requires knowledge of the production system

Design of the production system requires knowledge of the reserves

Because of this vicious circle, the systems are still very conceptual and further improvements for the system maturity requires more surface missions to Mars.

DISCOVERABILITY AND PRODUCTIBILITY

4.3.3

Discoverability of a source defines the initial step to extract water on mars. However, by itself discoverability would not be enough. After the discovering what is present on Mars for water production, the productibility of this material will be the next challenge, that is defining whether this source is useful or not.

A research group in NASA, illustrates the number of locations that might potentially have water sources in regard to their latitude (Abbud-Madrid et al., 2016). This information has been compiled by using the SHARAD measurements. Once the location has been decided, a rover must collect more data about the productability of the sources in this defined area. For this specific project the location of the habitation has been selected as the Jezero Crater, however there hasn't been any rover sent to this location yet.

ANALYSIS OF WATER SOURCES

4.3.4

Case A) Glacial Ice

On Mars, mostly the glacial ice is found at the higher latitudes. It lies beneath a sublimation lag, which
protects the ice from sublimating once exposed to the Martian atmosphere. There are two potential methods that allow the usage of glacier ice as a water source;

An ice deposit mined by open pit method
An ice deposit mined by down-hole heating/recovery method

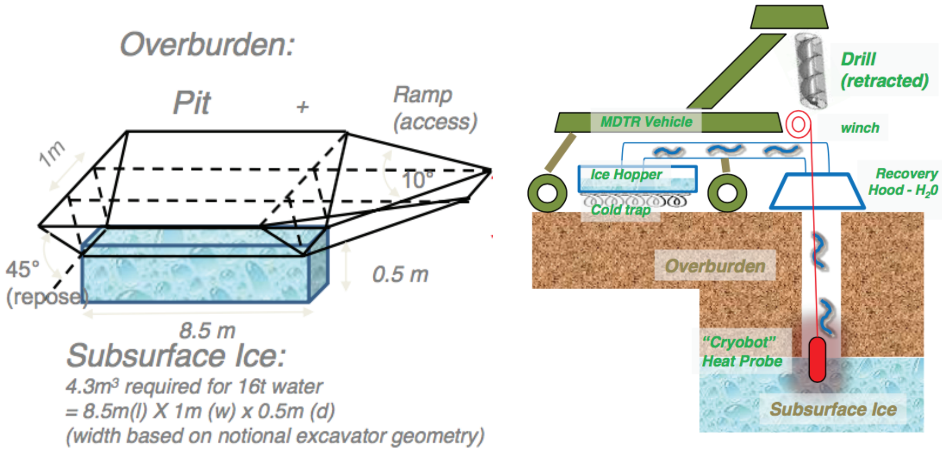


Figure 4.12: On the righ: open-pit method, on the left: down-hole heating/recovery method (M-WIP)

The thickness of the sublimation lag is yet to be discovered, and it varies from one source to another. The protector layer is assumed to be varying between 1-10 meter of thickness. (Hoffman, Andrews and Watts, 2016) This is the point where the questions are arisen. Although the glacial ice presents the highest concentration of water, the productibility and reachability of the glacial ice is a challenge by itself. This is mostly due to the removal of the overburden, the protective layer of the source. Currently, there is not much known about the mechanical characteristics of the overburden and whether it can be removed by the robots.

Surface mining of ice requires: removal of overburden and extraction of solid ice
Deep extraction of ice requires: drilling through the overburden, melting or dissolving the ice at depth and recovering it on the surface by ISRU recovery.

There is a concept developed by NASA which aims to extract water by drilling through the overburden.

Near-Surface "Mobile In Situ Water Extraction (MISWE)"

MISWE concept was developed due to the possibility of removal disturbance of the ice deposit, which may cause sublimation. The concept consists of a rover that carries a mobile drilling unit.

The concept follows the sequence below:

The water extraction vehicle localizes itself on the buried ice deposit
Mobile drilling and transport rig drills through the overburden
When the ice layer is reached, cryobot heats up to melt the ice, which is then trapped in the cold ice hopper in the vehicle
Once the ice hopper is filled, the vehicle returns back to the ISRU plant
The vehicle turns back to the ice deposit and repeat the procedure over and over until the necessary amount of water is produced

If glacial ice will be used as the water source, mentioned MISWE sequence can be followed.

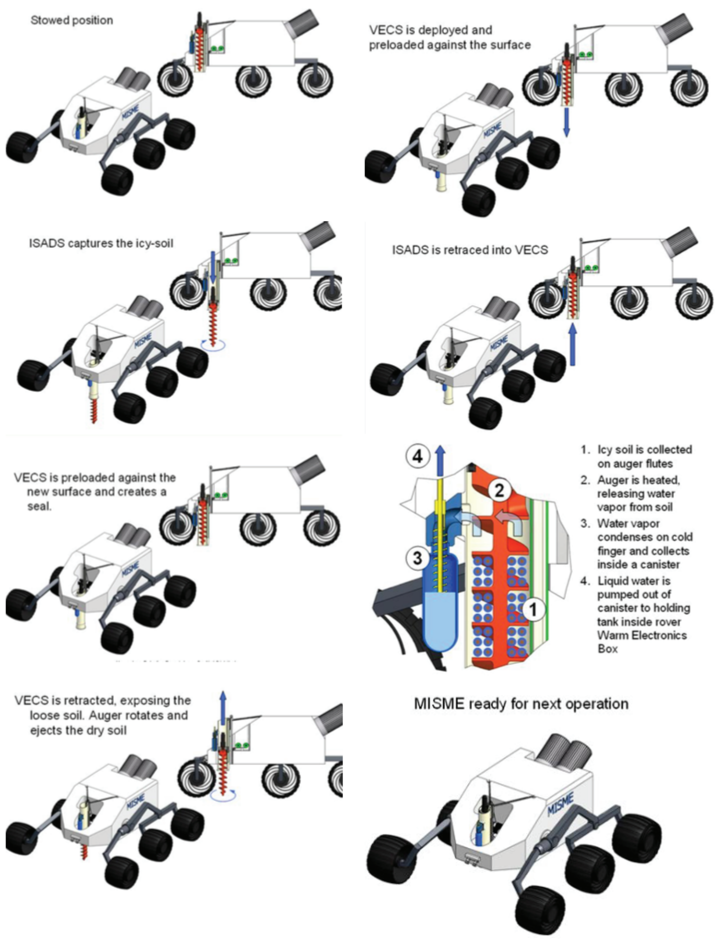


Figure 4.12: MISME method (M-WIP)

Summary for the Glacial Ice

Extracting subsurface ice by using a small open pit may require substantial amount regolith removal. The unknown mass to be removed would increase with the depth of the ice. Even if the deposit ice has reached, the removal of the hard ice can become a mechanical challenge.This would result in a higher energy demand.

Due to the lack of modelling ice in the Martian environment, researchers does not know whether ice would undergo an unstable state or not. However, there is an advantage making this source still appealing: the high concentration of water and the fairly easier processing opportunity through ISRU.

Case B and C) Poly-hydrated sulfate minerals and phyllosilicate minerals

NASA assumes that water deposits of these kinds can be present with the average of 4% of water content. This is the lower boundary for content percentage, and minerals can be found in higher concentrations. The concentration of Na-smectite has approximately 2% water content while Ca-smectite has approximately 7% content(Abbud-Madrid et al., 2016). Some exploration zones represent 6-9% of water, such as Mawrth Vallis.

For the cases of B and C, one can claim that deposits represent high concentrations. However, working with the hypothesized concentrations are providing only poor availability and workability(Abbud-Madrid et al., 2016). The advantage of using the minerally rich deposits is that no removal of overburden is needed and the higher concentrations are expected to be more localized. This is why, the treatment will be similar to finding a mine and repeatedly transporting raw material from the same location.

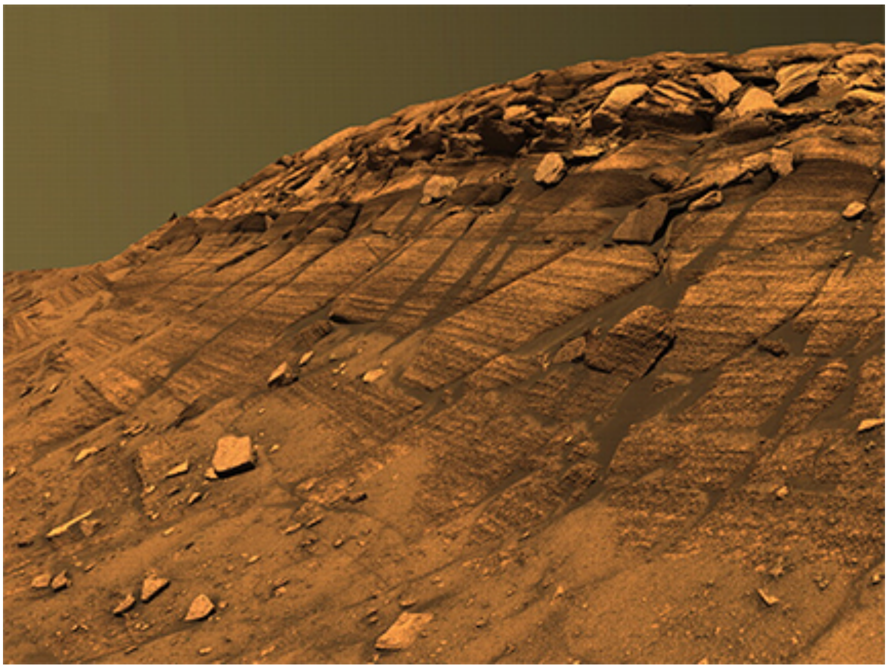


Figure 4.13:Water is known to occur on Mars in many forms, including ground and polar ice, as atmospheric water vapour, and in hydrated minerals (Baker 2001). Widespread occurrence of mono- and poly-hydrated sulfate minerals, including those discovered by the Opportunity rover at Terra Meridiani.

Regolith is the entire layer of mantle of fragmental and loose incoherent, unconsolidated rock material. covering majority of the Martian surface. REFERANS Most of the measurements in regards to mineralogy and water presence in Martian regolith are conducted by Mars Science Laboratory (MSL) that is placed on the Curiosity Rover, which is currently on Mars. MSL's instrument DAN can not directly measure H02 but it can detect Hydrogen.The H could be present in hydrous minerals or as HO(Abbud-Madrid et al., 2016). This indicates that the found material is not liquid water, however, it can be still used as a source. Water percentage in regolith varies over the depth as can be seen from table 4.1 (3).

One of the advantages of using regolith to extract water is its presence in every exploration zone (EZ). Meaning, wherever the landing would take place the ISRU plants will have enough regolith to process. Although the percentage of the hydrous minerals may vary from one EZ to another, this will only result in processing either less or more regolith to meet the necessary water volume for the propellant production, and construction.

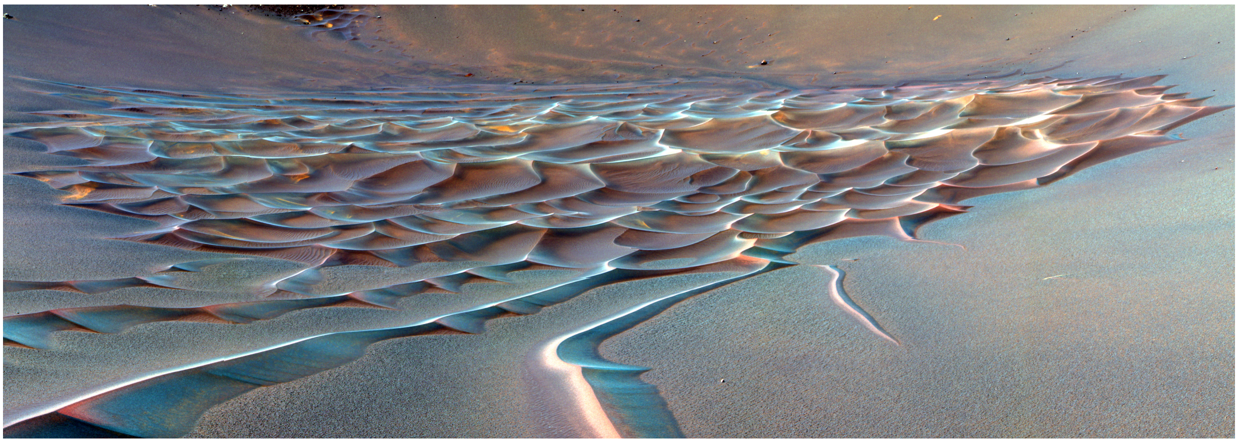


Figure 4.14: The nature of the surface hydration of the Martian low latitudes is not adsorbed water but rather more tightly bound water molecules and hydroxyl groups in the structure of the materials of the near-top surface of regolith.

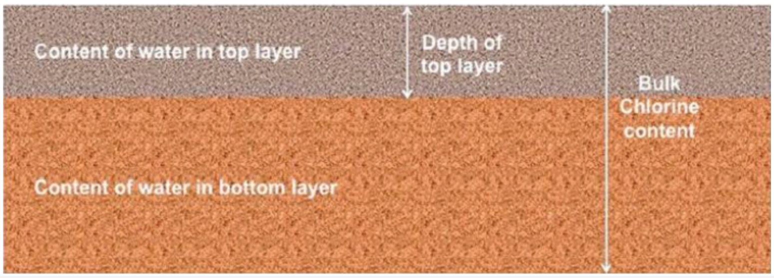


Table 3. Average Parameters of Soil for Four Different Ranges of the Curiosity Odometry

Odometry Ranges	0–455 m	455–638 m	638–876 m	876–1900 m
(1)	(2)	(3)	(4)	(5)
Top water (wt %)	1.68 ± 0.08	2.17 ± 0.12	1.50 ± 0.04	1.48 ± 0.03
Bottom water (wt %)	2.23 ± 0.08	1.41 ± 0.04	2.64 ± 0.06	3.33 ± 0.07
Vertical-average water (wt %)	2.07 ± 0.05	1.47 ± 0.03	2.31 ± 0.04	2.65 ± 0.04
Thickness of thetop layer (cm)	13 ± 1	6 ± 2	16 ± 1	22 ± 1
Content of absorption equivalent chlorine (wt %)	1.07 ± 0.02	1.14 ± 0.02	1.19 ± 0.01	1.17 ± 0.01

Table 4.1 (3) : Water content of regolith.

CONCLUSION: REGOLITH

4.3.5

Water is one of necessities to sustain human life on Mars. When it comes to water, Earth-dependency is impossible to achieve and it must be produced on Mars through in-situ material utilization processes. NASA has detected 4 main sources that can can be used for producing water on Mars including glacial ice, poly-hydrated sulfate minerals, phyllosilicate minerals, and regolith.

However, all these optional sources has their own advantages and shortfalls, and it is possible to compare them in terms of their processing efficiency. This comparison is very much influenced by the choice of location, the exploration zone. NASA sets the limits for EDL to +/- 50 latitude, this is why the deposits that are present within this region should be considered(DRA 5.0, 2009).

In the case of "Building on Mars", the location has been decided as Jezero Crater. This is an exploration zone where no rover has ever touched on the ground, thus, the mineralogy of the regolith has not been thoroughly analysed. The only information was provided by the orbiters, which are not in the form of on-site analyses. This is why the poly-hydrated sulfate minerals, and phyllosilicate minerals seem less appealing. The current data is not adequate to rely on producing water through these two sources. On the other hand, space exploration is ever evolving and NASA seems very eager to send a rover to Jezero Crater by 2020, after requiring more and on-site data from this rover, these two sources can be reconsidered for water production.

Case	Mass of Ore Required (metric tons)	# RASSOR-class loads (@80 kg/load)	Distance from Ore to Plant, typical	# RASSOR – class Excavators used (@ 60% On-Duty)	Duration Required (sols, <480 available)
D1 – Regolith @425K	~2,050 mt	>25,000	~100 m	**3** excavators	382 sols
D2 – Regolith @ 575K	~1,270 mt	>15,800	~100 m	**2** excavators	350 sols
C – Smectite (proximity)	~580 mt	>7,000	~100 m	**1** excavator	318 sols
B - Gypsum	~185 mt	>2,000	**~100 m**	**1** excavator	88 sols
B - Gypsum	(same)	(same)	**~1,200 m**	**1** excavator	480 sols
B - Gypsum	(same)	(same)	**~3,000 m**	**2** excavators	453 sols

Figure 4.15: Transportation time for each source.

Reconsideration of the minerals are important because as seen in the figure 4.15, these sources may provide water with lower transportation needs and with lower energy consumption. As seen in the second illustration, table 4.2, Smectite rich clay and gypsum rich sources may require much less transportation times to produce the water that is needed for propellant production and thus, construction.

The handling requirements of the glacial ice is quite difficult. The very first reason is the removal of overburden which possibly be high energy demanding. The other reason is that there is no modelling of the Martian ice. At this moment, we are still not sure whether the ice will sublimate or remain at its stable state. However, glacier ice option contains the highest amount of concentrated water and ISRU plants can easily process this source compared to others. The main concern with the glacial ice is the very probable absence of it in the equatorial regions of Mars, creating geographical limitations for building an ice habitat. Thus construction, propellant production as well as human life can not rely on this option.

In the case of using regolith, the risk of having a very low deposit concentration emerges. This low concentration causes in substantially higher amount of regolith to be processed. A deposit area, where hydrous percentage is abnormally low could be considered as a very high risk to the mission, resulting in an elongated cargo phase mission and even malfunctioning of the ISRU plant. However, NASA's "follow the water" approach and choice of location for the 2020 rover is promising enough to claim that Jezero Crater potentially has adequate deposits. As regolith covers the entire Martian surface, and therefore easily accessible, it becomes the best candidate for water production. Additional reasons include the short distance opportunities between ISRU plant and the deposit areas, implying great energy savings.

Deposit	Strategy	Landing Proximity	Excavation/Extraction Approach	Ore/Tailings Mass per Mission	Transport to Refinery/Retort	Refinery / Retort	Transport to Fuel Plant	Fuel Processing	Total Power Estimate[1] (Summary)
Regolith	Surface Mining, Central Processing (higher temp, lower mass)	Land on	Batch Excavation Rovers	~1,300 tons (@1.25%)	Not Required /Minimal	300 C / Continuous or Batch (8 kW)	Not required	Common (~20 kW)	~28 kW[1]
Regolith	Surface Mining, Central Processing (lower temp, higher mass)	Land on	Batch Excavation Rovers	~2,000 tons (@0.75%)	Not Required /Minimal	150 C / Continuous or Batch (8 kW)	Not required	Common (~20 kW)	~28 kW[1]
Clays	Surface Mining, Central Processing	~several km from base	Batch Excavation Rovers	~600 tons (@3%)	Ore Transport Rover (~600 tons)	300 C / Continuous or Batch (5 kW)	Not required	Common (~20 kW)	~25 kW[1]
Hydrated Sulfates	Surface Mining, Central Processing	~several km from base	Batch Excavation Rovers	~200 tons (@9%)	Ore Transport Rover (~200 tons)	150 C / Continuous or Batch (2 kW)	Not required	Common (~20 kW)	~22 kW[1]
[FUTURE WORK]: Subsurface Ice	Surface Mining	~several km from base	Prohibitive beyond TBD meters?	Not required	Not required	Not required	Ice Transport Rover (16 tons)	Common (~20 kW)	TBD (field) + ~20 kW
[FUTURE WORK]: Subsurface Ice	Down-hole heat probe + In Situ Recovery	~several km from base	Drill / Kerf only, Downhole "Cryobot" heat probe	Not required	Not required	Subsurface heating, Gas-phase Recovery with cold trap (TBD kW)	Ice Transport Rover (16 tons)	Common (~20 kW)	TBD (field) + ~20 kW

Table 4.2

TRADE-OFF CHART FOR THE ASSESSMENT OF WATER SOURCES REGARDING THE CONSTRUCTION

criterion / option	Handling (amount of materials to be carried) %20	Availablity and processibility of the source %10	Ore concentration %10	Current risk without explorations %30	Duration required for the necessary amount of water %30
glacial (sub-surface) ice	less transport due to high concentration	mechanical characteristics of the overburden	Subsurface, high concentration	current risk: high risk	fast processibility
poly hydrated sulfate minerals	583mt of the source per extracting 16 mt water	found in heterogenous ore forms	High concentration	current risk: high risk	fast processibility
phyllosilicate minerals	186mt of the source per extracting 16 mt water	found in heterogenous ore forms	High concentration	current risk: high risk	fast processibility
regolith	2000 mt of the source per extracting 16 mt water	Vast majority of the surface	Assumed 4% water content	current risk: med risk	amount of source transportation and time required for that

excellent, exceeds requirements — good, meets requirements — correctable deficiencies — Unacceptable

criterion / option	Handling (amount of materials to be carried) %20	Availablity and processibility of the source %10	Ore concentration %10	Current risk without explorations %35	Duration required for the necessary amount of water %25	Total score
glacial (sub-surface) ice	0,6	0,1	0,3	0	0,5	1,5
poly hydrated sulfate minerals	0,4	0,2	0,2	0	0,6	1,4
phyllosilicate minerals	0,4	0,2	0,2	0	0,6	1,4
regolith	0,2	0,3	0,1	0,7	0,25	1,55

3 excellent, exceeds requirements — 2 good, meets requirements — 1 correctable deficiencies — 0 Unacceptable

PROCESSING REGOLITH FOR WATER EXTRACTION

- 4.4 -

PROCESSING TECHNIQUES FOR REGOLITH

4.4.1

In the future it is projected that there will be continuous missions to Mars, and therefore there is a possibility that population will grow on the Red Planet. To sustain this growth a massive quantity of water will be necessary to supply human needs and to enable further construction.

As reported by NASA, the requirement for the water extraction system for Mars should be;

Capable of removing water from the soil
Must be capable of operating reliably
Operating maintenance free for at least 500 hours
Able to store the water
Must be powered by solar energy

Current research determined that the water within the martian regolith may be recovered once it's heated up to 200C - 500C (Bibring et al., 2005). A design team from Colorado School of Mines worked on designing a system which uses soil to extract water.

"This soil is placed on a conveyor belt that runs into a pressurized casing. A small motor attached to a sprocket on the belt's bearing, and placed at a downward angle in order to maximize gravitational assistance will automate the belt. The sand is transported into the casing where it is exposed to microwaves. These microwaves are emitted from two magnetrons attached to the roof of the casing. Microwaves are used to most efficiently free bound water molecules from the soil. From there, the vaporized water molecules will collect and condense on the roof of the casing. Once the water condenses, it runs down the roof into a gutter system that transports the water into a metering device. After the water is metered, it is siphoned into a storage unit."

Like the study from Colorado School of Mines, many other studies that assess the efficiency of the water extraction systems demonstrated that the microwave systems have the most reliable and efficient features.

Viking 1, which landed on western slope of Chryse Planitia, and Viking 2, which landed 200 km west of the crater Mie in Utopia Planitia determined that the water is present in the soil at approximately 2% by mass. Considering the landing site of the Viking missions, one can deduce that the percentage of water will be relatively higher in the higher latitudes near the northern pole cap. (Bibring et al., 2005) Due to the relatively low percentage of water presence in the Martian soil microwave based systems perform better in comparison to conventional solar heating and thermal heating systems that are deemed to be simple and effective . (Bibring et al., 2005)

Team JFEET, a group consisting of researchers and designers from Colorado School of Mines have assessed the water extraction systems and designed a system, called the Microwave Pizza Oven. (Wiens, Bommarito and Blumenstein, n.d.)

Their assessment criteria for the water extraction systems was set as following;

Feasibility of design

Durability of product

Ability to meet given design restrictions

There has been several options assessed by Team JFEET corresponding to the criteria listed above. (Wiens, Bommarito and Blumenstein, n.d.)

Inclined Pipe:

Inclined pipe technology includes an electrical heating system that heats the soil as it passes through a rotating inclined pipe. Soil is heated in order to collect the released vapor that rise from soil and travels along inside the surface of the inclined pipe. The dehydrated soil then passes out from the bottom of the pipe for the disposal.

Kettle/Pot:

This technology uses an enclosed vessel to heat the soil via conventional electrical heating. Soil is placed in a pot where the temperature of the soil is increased that causes the release of water vapor from the soil. This vapor is then collected and condensed into liquid water and stored for later use, after its amount is measured.

Sifter:

The sifter system includes a combination of a sieve and a heating element. A bin above a sifting screen collects and holds the soil. As the soil passes through the sifting screen, which is electrically heated, the soil temperature is increased to the point where water vapor is released.

Funnel:

Funnel technology follows a similar concept to that of the sifter method. A funnel design meters the flow of soil onto a conveyor belt. Conventional heating elements within the belt then heat the soil to release the water.

Conveyor Belt (Pizza Oven):

Used in conjunction with a soil metering system, similar to the funnel system, that carries the soil near the heating elements, which then heat the soil to release water vapor.

Focused Light:

Incorporates focused sunlight to concentrate the application of energy. The idea focused light would heat a portion of the soil to release water vapor.

Microwaves:

This design, unlike the other designs, does not rely upon the use of conventional thermal heating or the concentration of sunlight to heat the soil. High power radio waves (microwave energy) are used to apply sufficient energy to the soil to increase the temperature of the water, and thus generate
water vapor. This method heats the water contained within a uniformly distributed flow of soil. The microwaves apply energy to the water directly, without directly heating of the soil like the conventional heating methods.

CONCLUSION: MICROWAVE

4.4.2

For "Building on Mars", these regolith processing techniques for water extractions are evaluated.

Inclined Pipe and Kettle/Pot:

Two systems that incorporates pipe and the pot are disqualified due to projected number of moving parts and their total mass. Moving parts create potential for mechanical failures and they propose high demand of maintenance requirements.

Sifter and Funnel:

These two systems are disqualified due to the high energy demand of the conventional thermal heating of soil. Most importantly, due to the sifter and the funnel, the risk of blockage increases. This may lead to malfunction, cutting the water production until its fixed and may require extensive maintenance. The possibility of adorning the systems with an additional subsystem that can remove the blockage is not considered as it adds high complexity to the overall design, which is not desired.

Focused Light:

Focused light system is a comparatively new technology and it requires further research and development. Especially research is needed in the field of deployment of solar collector that can continuously adjust the position of the collector to produce water. The adjustability of the system is introduced through movement of the collector, which, as mentioned earlier, is not desired due to excessive number of moving parts.

Microwaves:

Due to the greater efficiency of microwave systems than the conventional thermal sources, the microwave systems are chosen as the best candidates for "Building on Mars". The efficiencies come from the fact that microwave systems are not wasting energy on heating the regolith, instead the energy is spent on extracting the water content. This system does not require a warm up period, thus it can be used instantly when regolith is loaded in the machine, and adds additional reliability to the water extraction processes.

In the light of these findings microwave systems were chosen in order to extract water within the study of "Building on Mars".

HABITAT DESIGN AND CONSTRUCTION METHODS

Chapter
- 5 -

DESIGN DRIVERS

5.1

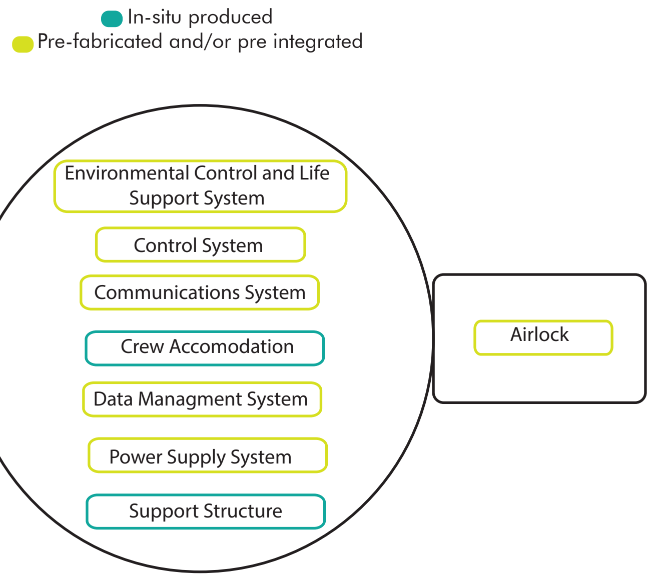


Figure 5.1: Equipments to be carried along with the habitat

outside — inside

	ice composite	multi-layer insulation	multi-layer inflatable
pressure			●
sand storm	●		
radiation	●		●
temperature	●	●	
windloads	●		
outdoor humidity	●		
indoor humidity			●
sound insulation		●	
hyper velocity impact	●		
precipitation	●		
toxication	●		●

first line of defense — second line of defense — third line of defense

Figure 5.1: Envelope's qualifications

WHAT TO WITHSTAND?

envelope design drivers

first line of defense	is the outermost layer of the facade that provides barrier against air and radiation.
second line of defense	is the protection against the small amount of water and air that can penetrate through the first line. This also provides thermal insulation.
third line of defense	is the inner most layer that cuts the access of toxic hazards to indoor and provide air tightness.

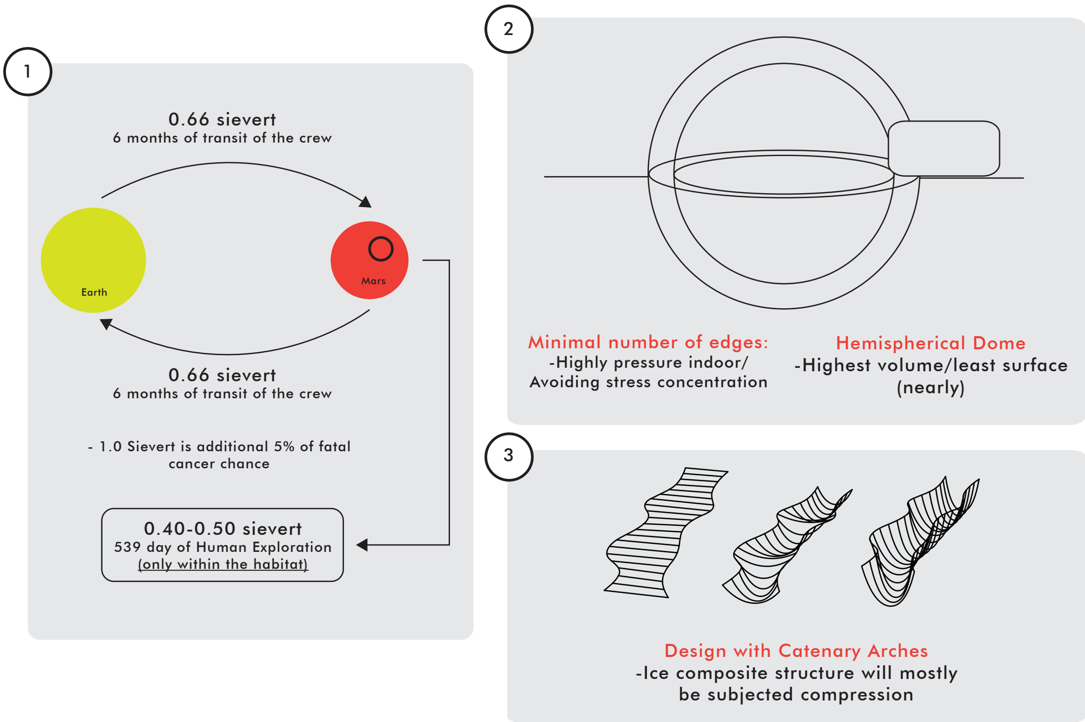


Figure 5.4 : Design decisions that have been considered.

Total Mission Duration	**30 Months**
- In transit to	6 months
- At target	18 months
- In transit from	6 months
Crew Size	N = 6
Crew Composition	Pilot, Physician, Geologist, Biologist, Engineer, Electrical Engineer
Gender Mix	Variable; exact mix undefined
Cultural Mix	Presumably some combination of US, Russia, Europe, Canada and Japan
Mission Tempo	Long periods of low mission tempo, interspersed with high activity times (for example, launch, jettison tanks, dock, landing)
Communication Delays	Up to 22 minutes one-way with blackout periods
Autonomy from Ground	Increasing en route to Mars, decreasing during return to Earth

Figure 5.4 : Crew size that is defined according to DRA 5.0 by NASA's study group

- Building on Mars -

RADIATION ASSESSMENT OF THE HABITAT

5.2

Shielding From Space Radiation

According to the mission selected for “Building on Mars” under the guidance of DRA 5.0, the transit of the crew will take place on 27/08/2037 and the crew will be launched back to earth on 10/08/2039. This leaves 539 days of stay on the Mars surface and the crew will require shielding from space radiation during this time period. The 174 days of transit will expose the crew to deep space radiation environment, however, protecting the crew during transit is out of the scope of this project.

As a reminder, there are two types of radiation on the Mars surface which are galactic cosmic rays (GCRs), and solar energetic particles (SEPs).
First, the habitat requires a sufficient radiation shielding from the GCRs. These are almost like a background noise in space, which are always present. However, the total ionizing doses caused by GCRs may change according to the solar activities. During the solar minima, contribution of GCR’s to the effective doses are at the peak. REFERENCE
The SEPs are the most acute source of exposure to the space ionizing radiation. In the case of solar flares and solar activities, the doses that the crew will be exposed to can easily exceed the career limit risking the health of the crew (Human Exploration of Mars, Design Reference Architecture 5.0, 2009). Moreover, depending on the solar activity and flare, doses may potentially result in rapid death.

There are various shielding methods to prevent damages caused by the SEPs and GCRs. Passive shieldings can be effective for protecting the crew against solar energetic particles, however, its effectiveness is limited with the GCRs (et al. Durante, Cucinotta, 2011). Another strategy to shield from ionizing space radiation is to utilize active shielding. This type of shielding includes the use of electrostatic fields, plasma shields, and confined and unconfined magnetic fields (et al. Seedhouse, 2009).

This study focuses on the passive shielding techniques that utilizes appropriate materials with adequate thickness. As previously mentioned, in-situ materials are very important to be utilized to construct the habitat on Mars. This is mostly because of minimizing the launching mass of the habitat and decreasing the dependency to the earth.

Passive Shielding

The effectiveness of a shielding material can be determined by looking into the characteristics of the material in transporting the energetic particles within the shield. This process is analyzed by the interactions of the local environmental particles with the atoms and nuclei of the shielding material.

The challenge is to find materials that have the structural integrity to be used for the habitat, which are also performing well in shielding from ionizing space radiation. Materials that have high hydrogen content are proven to protect the crew from radiation (et al. Seedhouse, 2009).The chemical composition and the mass density of the material are two important parameters that are directly associated with the radiation shielding properties.

Proceeding with Radiation shielding Assessment of the Habitat by Using Water

The scope of this research is to build a habitat on Mars that complies with the ALARA concept. A round trip to Mars, during outbound and return travel will expose the crew to 0.66 Sv (Anon, 2017) . If one way transit is considered to be approximately 180 days and the surface stay is 496 days, the aim is to shield the crew from the ionizing space radiation in such way that they are not exposed to more than 0.40-.050 Sv. during their stay on the surface of Mars. In order to attain aforementioned numbers water and other hydrogen rich materials were utilized in the habitat's envelope design.

Dose Equivalent

The impact on high radiation doses on the crew is measured by the dose equivalent. Effect on radiation on a tissue is calculated by multiplying the absorbed dose by a quality factor.

The simple formula to calculate dose equivalent is as follows:

Dose equivalent = absorbed dose x quality factor

The absorbed dose stands for the deposited energy of radiation in the energy. It is measured in grays (1 joule of energy deposited in one kilogram of matter)

The quality factor is another measure that indicates the relative effectiveness of the radiation in introducing biological effects, such as cancer or cell deformation. Highly damaging radiations have a greater relative biological effectiveness (RBE) than 1.0.

This reduces the point estimate of the blood forming organ dose equivalent, at solar minimum, from about 57 cSv/yr to about 32 cSv/yr. At Solar maximum, this drops down from 22 cSv/yr to 15 cSv/yr (Rapp et al. 2006).

Background information about Spenvis

In order to calculate the ionizing dose equivalent, a software needs to be employed. As a result of fast learning possibilities and user friendliness provided, Spenvis was selected to be used. Spenvis is a web-based operational software introduced by ESA, which was developed by Belgian Institute for Space Aeronomy (Wikipedia, 2015).

ASSESSMENT

Option A: Procedure of Switching the Planets

Spenvis offers a "step by step" procedure where the user inputs information concerning the mission. The very first step is to determine the location or trajectory of the mission. The location can be set by switching the planet and user-defined set of geographical points.

Step 1: Definition of Mission and Planetary Position

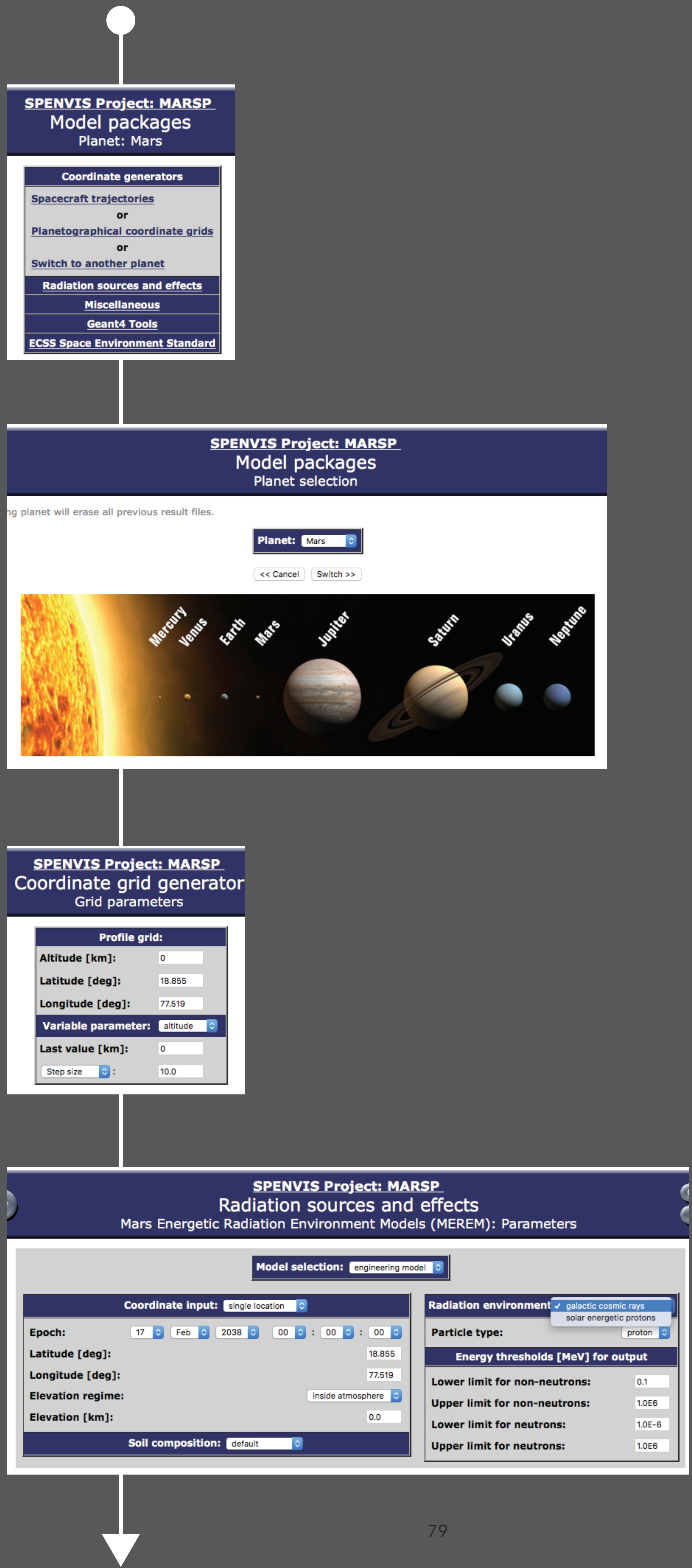
The first step is switching planet to Mars, that will lead Spenvis to take the planetary environment into account. The CO2 atmosphere of Mars has quite an impact in shielding from radiation. Mars atmosphere is 16 g/cm2 (Simonsen 1997, Cucinotta et al. 2005). This reduces the point estimate of the blood forming organ dose equivalent, at solar minimum, from about 57 cSv/yr to about 32 cSv/yr. At Solar maximum, this drops down from 22 cSv/yr to 15 cSv/yr (Rapp et al. 2006).

As the selected location is Jezero Crater and the habitat is on the surface, the following information should be inserted to the software:
Altitude (km) : 0 km
Latitude (deg) : 18.855
Longitude (deg) : 77.519

Step 2: Definition of Sources

The next step is to set the radiation sources and effect. Spenvis uses the MarsREM study for defining the planetary radiation environment, which was conducted by ESA in 2007. MEREM(MarsREM) allows the users to insert mission related information that play a key role in running the simulation, which are related to the mission epoch, which are defining the solar cycle and Martian season. Here the option to run the simulation for GCR and solar energetic protons is present.

For galactic cosmic rays, protons, heavy ions (although there is a low percentage within the GCR) and alpha particles have high contribution to the dose equivalent. However, for solar energetic particles protons are very important to analyse. Once the radiation environment is defined, especially for the type of radiation that is mostly interested in to be analyzed, GEANT4 tool of Spenvis should be used.


SPENVIS Project: MARSP
Model packages
Planet: Mars
Coordinate generators
Spacecraft trajectories
or
Planetographical coordinate grids
or
Switch to another planet
Radiation sources and effects
Miscellaneous
Geant4 Tools
ECSS Space Environment Standard
SPENVIS Project: MARSP
Model packages
Planet selection
ng planet will erase all previous result files.
Planet: Mars
<< Cancel
Switch >>
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
SPENVIS Project: MARSP
Coordinate grid generator
Grid parameters
Profile grid:
Altitude [km]: 0
Latitude [deg]: 18.855
Longitude [deg]: 77.519
Variable parameter: altitude
Last value [km]: 0
Step size : 10.0
SPENVIS Project: MARSP
Radiation sources and effects
Mars Energetic Radiation Environment Models (MEREM): Parameters
Model selection: engineering model
Coordinate input: single location
Epoch: 17 Feb 2038 00 : 00 : 00
Latitude [deg]: 18.855
Longitude [deg]: 77.519
Elevation regime: inside atmosphere
Elevation [km]: 0.0
Soil composition: default
Radiation environment
galactic cosmic rays
solar energetic protons
Particle type: proton
Energy thresholds [MeV] for output
Lower limit for non-neutrons: 0.1
Upper limit for non-neutrons: 1.0E6
Lower limit for neutrons: 1.0E-6
Upper limit for neutrons: 1.0E6

Step 3: Shielding Analysis

Geant (Geometry and Tracking) was developed by CERN and first released in 1998. It provides simulations in order to help in understanding the passage of particles through matter by using Monte Carlo methods (Geant4, 2017). Geant proved to be applicable to areas of high energy physics, nuclear experiments, medical physics, accelerator physics and space physics.

Geant4 has multiple options that are serving for different purposes. In the case of Building for Mars, Multi-Layered Shielding Simulation (MULASSIS) should be used. However, this option does not allow to switch the environment to mission based, thus may create complications. Furthermore, web-based simulation Spenvis, offers a limited amount of computation time to its users, which limits the number of primary particles to simulate. However, interesting results start appearing by using a minimum of 10,000 particles.

Due to the fact that, MEREM was not maintained and updated well enough, running the simulation with this procedure may result in failures. This is why, another procedure was discussed with Alessandra Menicucci (Space Systems Engineering Department, Faculty of Aerospace engineering, TU Delft)

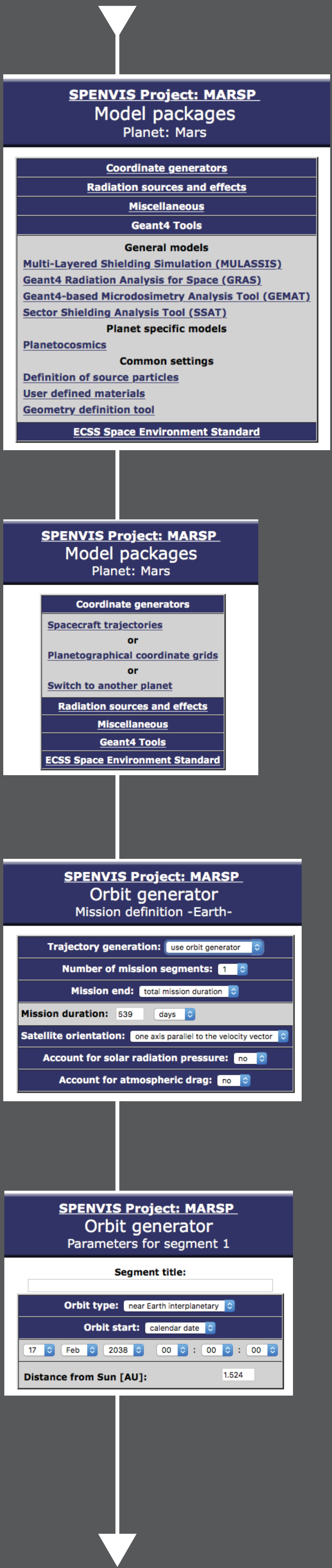
Option B: Using the Spacecraft Trajectory

The other option is to use the spacecraft trajectory to define a location at an interplanetary spot. However, if the simulation is used for an interplanetary trajectory or a fixed point, this results in being exposed to deep space radiation in the vacuum. On the other hand, Mars has an atmosphere and this has a contributing effect on reducing the equivalent dose. This was discussed with Alessandra Menicucci and a precaution were taken in order to mimic Mars atmosphere in the software by using an extra layer of aluminum with the thickness of 2.54 cm (suggested by JPL, NASA).

SPENVIS team is maintaining the spacecraft trajectory fairly better than the “switch to another planet” option. This is why this procedure was followed to run the simulation which had the potential to process and results may

Step 1: Definition of the Mission

Here, the distance from the sun in astronomical units should be inserted to Spenvis. Distance of Mars from the sun is approximately 1.524 AU (NASA, 2009). The duration of the mission should also be inserted to calculate the dose regarding the time spent behind the shields of the habitat. According to DRA 5.0, manned mission will take approximately 496 days as mentioned earlier. Furthermore, the orbit start date is set to 17/02/2038 which is the defined date of crew’s arrival to Mars. The simulation starts counting the surface mission duration of 539 days from this date on and calculates the dose equivalent accordingly.


SPENVIS Project: MARSP
Model packages
Planet: Mars
Coordinate generators
Radiation sources and effects
Miscellaneous
Geant4 Tools
General models
Multi-Layered Shielding Simulation (MULASSIS)
Geant4 Radiation Analysis for Space (GRAS)
Geant4-based Microdosimetry Analysis Tool (GEMAT)
Sector Shielding Analysis Tool (SSAT)
Planet specific models
Planetocosmics
Common settings
Definition of source particles
User defined materials
Geometry definition tool
ECSS Space Environment Standard
SPENVIS Project: MARSP
Model packages
Planet: Mars
Coordinate generators
Spacecraft trajectories
or
Planetographical coordinate grids
or
Switch to another planet
Radiation sources and effects
Miscellaneous
Geant4 Tools
ECSS Space Environment Standard
SPENVIS Project: MARSP
Orbit generator
Mission definition -Earth-
Trajectory generation: use orbit generator
Number of mission segments: 1
Mission end: total mission duration
Mission duration: 539 days
Satellite orientation: one axis parallel to the velocity vector
Account for solar radiation pressure: no
Account for atmospheric drag: no
SPENVIS Project: MARSP
Orbit generator
Parameters for segment 1
Segment title:
Orbit type: near Earth interplanetary
Orbit start: calendar date
17 Feb 2038 00 : 00 : 00
Distance from Sun [AU]: 1.524

Step 2.1 (analysis for GCR): Definition of Radiation Source

The next step is fairly similar to what has been previously done with option A. Radiation sources and effect should be determined and the particles that interest the user should be selected. In the case of "Building on Mars", GCRs were the main consideration. This is why, long term solar particle fluences and galactic cosmic ray fluxes were looked into.

Long term solar particle fluences: ion range from H to Ni and solar particle model was set to EPS-PSYCHIC (Total Fluence)

GCR Spectra: ion range from H to Ni, GCR model ISO 15390 were used, at solar minimum condition from May 1996. Using solar minimum is very important because GCR's contribution to the dose equivalent is the highest at these conditions. This approach secures the design by the means of designing for the worst case scenario.

Step 2.2 (analysis for SEP): Definition of the Source

The procedure was repeated by changing the solar activity to solar maximum, in which the activities on the solar surface at the highest, thus the number released particles are higher comparing to solar minimum conditions. The results may cause adjustments in the envelope design in terms of thickness (g/cm2) of shielding materials. On the other hand, major solar activities are not occurring very often. In the last 50 years, there has been one or two major SPE(solar particle events) within the solar cycle of 11 years (Rapp, 2006).

Step 3: Shielding Analysis

Once the mentioned parameters are set and ran correctly, the Geant4 tools are ready to be used. At this point, it is important to define the source particle macro. For this reason, initially the parameters should be inserted in the MULASSIS (multilayered shielding simulation). Since the earlier parameters for solar activities were set to solar minimum, the simulation should be used for GCR to better apprehend the shielding properties of the habitat's envelope against ions (H1, H1) and irons with atomic number of 26 (Fe56 to Fe58).

SPENVIS Project: MARSP

Model packages

Planet: Earth

Coordinate generators

Radiation sources and effects

Radiation sources

Trapped proton and electron fluxes [Standard models]

Trapped proton flux anisotropy

Short-term solar particle fluxes (only for SEU)

Long-term solar particle fluences

Galactic cosmic ray fluxes

Shielded flux

Solar cell radiation damage

Damage equivalent fluences for solar cells (EQFLUX)

NIEL based damage equivalent fluences for solar cells (MC-SCREAM)

Long-term radiation doses

Ionizing dose for simple geometries

Non-ionizing energy loss for simple geometries

Effective dose and ambient dose equivalent

Single event effects

Short-term SEU rates and LET spectra

Long-term SEU rates and LET spectra

Spacecraft charging

Atmosphere and ionosphere

Magnetic field

Meteoroids and debris

Miscellaneous

Geant4 Tools

ECSS Space Environment Standard

SPENVIS Project: MARSP

Radiation sources and effects

GCR spectra: Input parameters

Ion range: H to Ni

GCR model at 1 AU: ISO 15390

ISO-15390 standard model

solar activity data: Solar Minimum (May 1996)

Magnetic shielding: no

Model developed by

Lomonosov Moscow State University

Skobeltsyn Institute of Nuclear Physics

BIRA-IASB

Reset | Run | Combined Run

SPENVIS Project: MARSP

Radiation sources and effects

ong-term solar particle fluences: Parameters

Solar particle model: ESP-PSYCHIC (total fluence)

ion range: H to Ni

Prediction period: automatic

Offset in solar cycle: automatic

Confidence level [%]: 95.0

Magnetic shielding: no

SPENVIS Project: MARSP

Geant4 tools

Multi-Layered Shielding Simulation (MULASSIS)

vides a general one-dimensional space radiation analysis for a multi-laye
g it. The current version of MULASSIS is v1.23.

Status	Settings	Remarks
defined	Source particle macro	Solar, ion, GPS macro file
defined	Geometry	Planar slab, 7 layers
defined	Analysis parameters	Total ionizing dose
Advanced settings		
defined	Material definition	7 material defined
defined	Cuts-in-range	No cuts-in-range

Create macro

Step 4: Defining the Shield Geometry

With MULASSIS, the geometry of the habitat can be defined by the user. This is why shape of the habitat was set to sphere. Here number of layers should be inserted according to how many layer that the envelope is consisting of. For, “Building on Mars” a simplified version of the building envelope according to their thickness and their materials was used as the following:

G4_Al: 2.54cm (to mimic the Mars atmosphere)
G4_Polyethelene: 20mm (to mimic 20mm of ETFE)
G4_Water: 800mm (as the main radiation protective shield)
G4_Polyethelene: 20mm (to mimic 20mm of ETFE)
G4_Air: 60 mm (to mimic Aerogel for insulation purposes)
G4_Carbondioxide: 200mm (to mimic the CO2 bags for insulation purposes)
G4_Mylar: 10 mm (used for insulation purposes)

These materials that are shown above have been selected from the material library that spenvis offers. There also is an option to add user defined materials by inserting their chemical formula and density (g/cm3).

Step 5: Radiation Analysis for Space (GRAS) for the assessment of Dose Equivalent Analysis

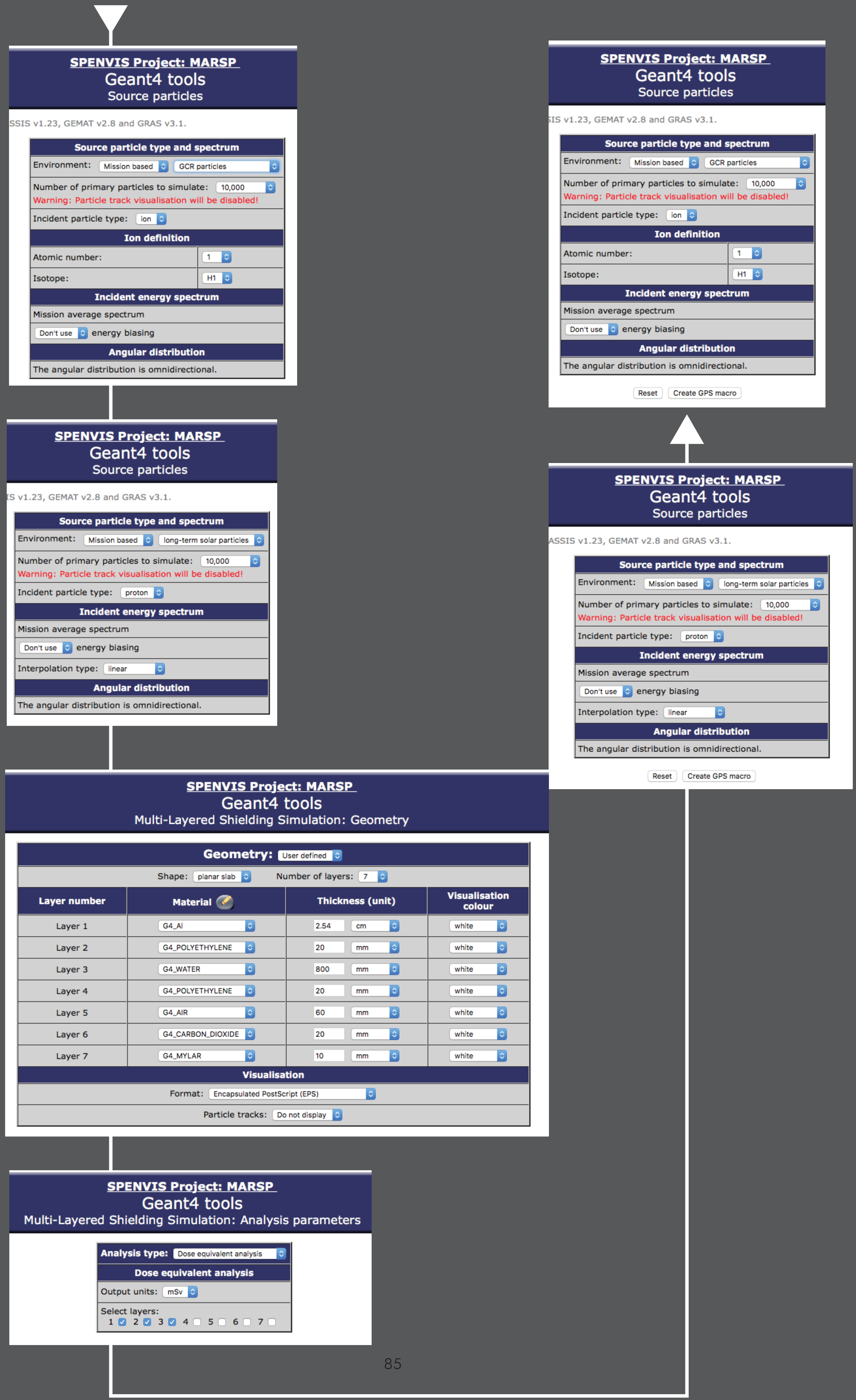
After defining the geometry of the habitat's envelope, dose equivalent analysis can be used. In order to do that, the GRAS execution mode should be switched to MULASSIS from GDML.

Step 6: Defining the source particles for GCR

This is the final step before creating the macro file. This file will be executed afterwards to generate results, where equivalent doses can be seen. In order to do that environment should be set to mission based, GCR particles and number of primary particles should be at least 10,000. Ion definition can be made according to ions' atomic number. For Galactic cosmic rays, H1,H2, Fe56 to Fe58

Step 6: Defining the source particles for SEP

This last step should be performed two times. After macro files are created and results have been taken for GCR, similar procedure should be followed for SEP. In order to do that, solar maximum should be selected from the earlier steps. Source particles should be set by switching the environment to mission based and using long term solar particles.
Number of primary particles to simulate should be at least 10,000, so that the results can be reliable. Once these variables are selected, macro file can be created and results can be generated afterwards by pressing on run.


SPENVIS Project: MARSP
Geant4 tools
Source particles
SSIS v1.23, GEMAT v2.8 and GRAS v3.1.
Source particle type and spectrum
Environment: Mission based GCR particles
Number of primary particles to simulate: 10,000
Warning: Particle track visualisation will be disabled!
Incident particle type: ion
Ion definition
Atomic number: 1
Isotope: H1
Incident energy spectrum
Mission average spectrum
Don't use energy biasing
Angular distribution
The angular distribution is omnidirectional.
SPENVIS Project: MARSP
Geant4 tools
Source particles
IS v1.23, GEMAT v2.8 and GRAS v3.1.
Source particle type and spectrum
Environment: Mission based GCR particles
Number of primary particles to simulate: 10,000
Warning: Particle track visualisation will be disabled!
Incident particle type: ion
Ion definition
Atomic number: 1
Isotope: H1
Incident energy spectrum
Mission average spectrum
Don't use energy biasing
Angular distribution
The angular distribution is omnidirectional.
Reset
Create GPS macro
SPENVIS Project: MARSP
Geant4 tools
Source particles
S v1.23, GEMAT v2.8 and GRAS v3.1.
Source particle type and spectrum
Environment: Mission based long-term solar particles
Number of primary particles to simulate: 10,000
Warning: Particle track visualisation will be disabled!
Incident particle type: proton
Incident energy spectrum
Mission average spectrum
Don't use energy biasing
Interpolation type: linear
Angular distribution
The angular distribution is omnidirectional.
SPENVIS Project: MARSP
Geant4 tools
Source particles
ASSIS v1.23, GEMAT v2.8 and GRAS v3.1.
Source particle type and spectrum
Environment: Mission based long-term solar particles
Number of primary particles to simulate: 10,000
Warning: Particle track visualisation will be disabled!
Incident particle type: proton
Incident energy spectrum
Mission average spectrum
Don't use energy biasing
Interpolation type: linear
Angular distribution
The angular distribution is omnidirectional.
Reset
Create GPS macro
SPENVIS Project: MARSP
Geant4 tools
Multi-Layered Shielding Simulation: Geometry
Geometry: User defined
Shape: planar slab
Number of layers: 7
Layer number
Material
Thickness (unit)
Visualisation colour
Layer 1 G4_Al 2.54 cm white
Layer 2 G4_POLYETHYLENE 20 mm white
Layer 3 G4_WATER 800 mm white
Layer 4 G4_POLYETHYLENE 20 mm white
Layer 5 G4_AIR 60 mm white
Layer 6 G4_CARBON_DIOXIDE 20 mm white
Layer 7 G4_MYLAR 10 mm white
Visualisation
Format: Encapsulated PostScript (EPS)
Particle tracks: Do not display
SPENVIS Project: MARSP
Geant4 tools
Multi-Layered Shielding Simulation: Analysis parameters
Analysis type: Dose equivalent analysis
Dose equivalent analysis
Output units: mSv
Select layers:
1 2 3 4 5 6 7

Conclusion: Shielding Features of the Habitat's Envelope

The scope of this study was to attain satisfying numbers by the means of dose equivalent at a mission based period of 496 days. Within this amount of time, the crew should not receive more than 0.40-.050 Sv of total equivalent dose.

By introducing minimum of 80 g/cm2 of water as a shielding material the numbers are assumed to be reached. As it can be seen from the graph, 50 gr/cm2 water shielding drops the annual GCR dose equivalent to 0.39 cSv and 100 gr/cm2 of water shielding drops the dose equivalent to 0.33 cSv.

Materials and thicknesses of the shielding envelope is as follows:

G4_Al (aluminum): 2.54cm (to mimic the Mars atmosphere)
G4_Polyethelene: 20mm (to mimic 20mm of ETFE)
G4_Water: 800mm (as the main radiation protective shield, that will be formed in ice)
G4_Polyethelene: 20mm (to mimic 20mm of ETFE)
G4_Air: 60 mm (to mimic Aerogel for insulation purposes)
G4_Carbondioxide: 200mm (to mimic the CO2 bags for insulation purposes)
G4_Mylar: 10 mm (used for insulation purposes)

With the aforementioned envelope design the annual GCR dose equivalent is assumed to be almost as low as utilizing 100 g/cm2 water as shielding. This results in as an annual GCR dose equivalent of 0.33 cSv. However, it should not be forgotten that the mission based period will be longer than a year. This is why the GCR dose equivalent will be higher than 0.33 cSv. Furthermore, there will be a contribution to the total dose equivalent by the SEP as well, which requires further investigations.

Table 6. Point estimates of GCR annual dose equivalent within habitat vs. water shielding (g/cm^2) for a fixed Mars atmosphere of 16 g/cm^2 (Anderson et al. 2005).

Water shielding (g/cm^2)	Annual Dose Equivalent (cSv)
0.3	78
2.0	69
5.0	63
10.0	54
15.0	49
20.0	46
30.0	43
50.0	39
100.0	33

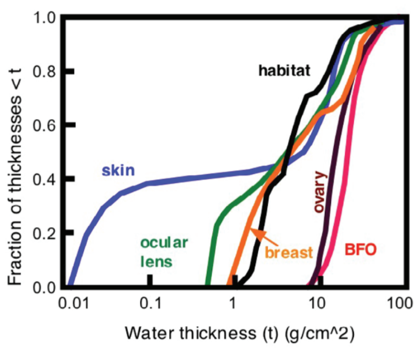


Figure 9. Cumulative thickness distributions for habitat targetpoint and body target points used by Anderson et al. (2005) (figure9.jpg).

Table 5. Point estimates of integrated BFO Dose (cSv) on the surface of Mars at two elevations. (Simonsen 1997)

Radiation Source	BFO Dose at 0 km elevation	BFO Dose at 4 km elevation
GCR at Solar Minimum (annual)	10.5 – 11.9	12.0 – 13.8
GCR at Solar Maximum (annual)	5.7 – 6.1	6.2 – 6.8
Feb. 1956 SPE	8.5 – 9.9	10.0 – 11.8
Nov. 1960 SPE	5.0 – 7.3	7.5 – 10.8
Aug. 1972 SPE	2.2 – 4.6	4.8 – 9.9
Aug. 1989 SPE	0.1 – 0.3	0.3 – 0.6
Sept. 1989 SPE	1.0 – 2.0	2.0 – 3.8
Oct. 1989 SPE	1.2 – 2.7	2.8 – 5.9

Figure 4.14 - 14.15: Tables and graphs implemented for the conclusion (Drapp)

NET HABITABLE VOLUME & ICE VOLUME OF THE HABITAT

5.3

In this part of the study, net habitable volume (NHV) of the habitat was calculated. The required space was assumed to be nearly 100 m3 per crew. The study was continued by calculating the ice volume which covers the habitat as a shield. The calculations are as follows:

1 metric tonne (mT) = 1 cubic meter
20 metric tonne (mT) per crew to use for propellant, EVA (extravehicular activity) and ECLSS

Crew of 4 = 4 x 20 = 80 mT
Crew of 5 = 5 x 20 = 100 mT
Crew of 6 = 6 x 20 = 120 mT

Each exploration zone should have the potential to provide at least 100 mT water. This suggestion does not comply with the requirements in case of that the number of crew number is higher than 5. Not only concerning the crew number, if the construction of habitat involves usage of water, the numbers are subjected to a high increment.

Volume of an ellipsoid: $V= 4/3\pi$ abc

Inner ellipsoid measures:
a = 5 m, b = 5.51 m, c = 5 m
Volume= 575.95 m3 (cubic meters)
Surface= 335.30 m2 (square meters)

Outer ellipsoid measures:

a = 5.8 m, b = 7.17 m, c = 5.8 m
Volume = 1010.33 m3 (cubic meters)
Surface = 490.68 m2 (square meters)

Water Volume Needed for Construction
(in case of minimal ice thickness of 80 cm)

volume (outer) - volume (inner) = water volume (needed)
(the increment of volume of the water solidification is neglected)

1010.33 m3 - 575.95 m3 = 434.38 m3

The thickness of the minimal ice depth must be optimized once the radiation analysis are conducted.

Volume per activity

Total volume = ground floor volume + first floor volume

Ground floor volume = total volume - first floor volume

Total volume = 575.95 m3
First floor volume = 193, 55 m3
Ground floor volume = 382,40 m3

Distribution percentile (corridors, walls, spaces that are not necessarily assigned to a function): %20

Functional Ground floor volume: 382,40 - 76,48 = 305,92 m3
Functional First floor volume: 193,55 - 38,71 = 154,84 m3

Functions:
(GF)Medical and exercise : 3/14 x 305,92 = 65,55 m3
(GF)Gathering : 2/14 x 305,92 = 43,70 m3
(GF)Science lab : 2/14 x 305,92 = 43,70 m3
(GF)Eating unit : 2/14 x 305,92 = 43,70 m3
(GF)Maintenance unit : 2/14 x 305,92 = 43,70 m3
(GF)Hygiene unit : 1/14 x 305,92 = 21,85 m3
(GF)Relax zone : 2/14 x 305,92 = 43,70 m3
(FF)Sleeping units : 154,84 m3

GF: ground floor
FF: first floor

ARCHITECTURAL LAYOUT

5.4

Ground floor is designed to accommodate functions that matter to everyone in the crew. Exercising area, gathering area with a table for six, relaxation zone adorned with inflatable furnitures, a scheduling area right at the entrance of the staircase, a hygiene unit, pop-up medical room with curtains, maintenance unit, and a science lab are the offered areas on the ground floor.

Due to the crew cohesion some of the areas are kept closer to each other without separation walls. This design aimed to stimulate the visual connection between the crew. The floor plans have been assessed with Angelo Vermeulen (Delft University of Technology) who was the crew-commander of HI-SEAS, a Mars study simulation funded by NASA (Siceloff, 2015).
He pointed out several issues that he encountered during 8 months of isolation with a crew of six and emphasised that:

Unity of the crew is of utmost importance. The feeling of togetherness motivates everyone, thus visual connection should be attained especially in the common areas.

The hygiene unit must be positioned at a farther distance from the eating areas and kitchen in order to decrease chances of food contamination with airborne pathogens

During his stay medical area was one of the most unused areas of the habitat. Because of that he suggested a pop-up medical room, which can be folded while it is not needed.

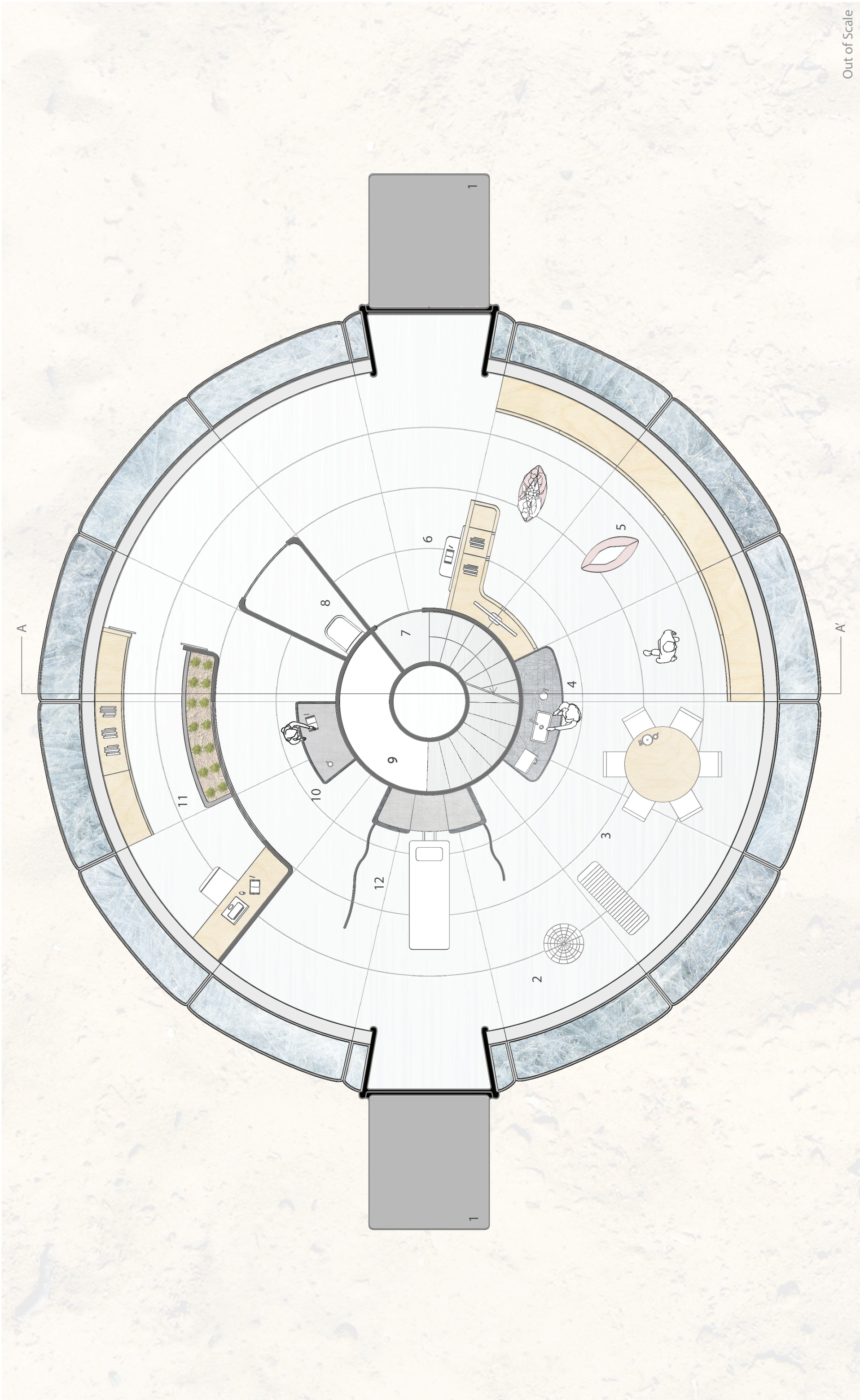
The science lab may require a controlled environment. That is the reason behind the enclosed unit design, with individual systems that can provide the necessary conditions.

On the first floor, there are 6 individual units. This floor is the sleeping quarter of the crew. The rooms are almost 5 sqm each and have a fixed bed. The rest of the furnitures are movable to give the crew autonomy to arrange their rooms according to their own preferences.

The sleeping quarters are detached from the core where the systems are installed. The reason to detach the sleeping quarters is to improve the acoustic qualities of the sleeping quarters where continuous noise is expected. As Orla Punch (Architectural Designer, European Space Agency, 2016) mentioned on a skype meeting in February 2017; the noise is one of the challenges that must be well taken care of, for the crew's wellbeing. Literature review revealed that noise problems due to working systems were encountered in the International Space Station as well (Trimarchi, Fuller, 2017).

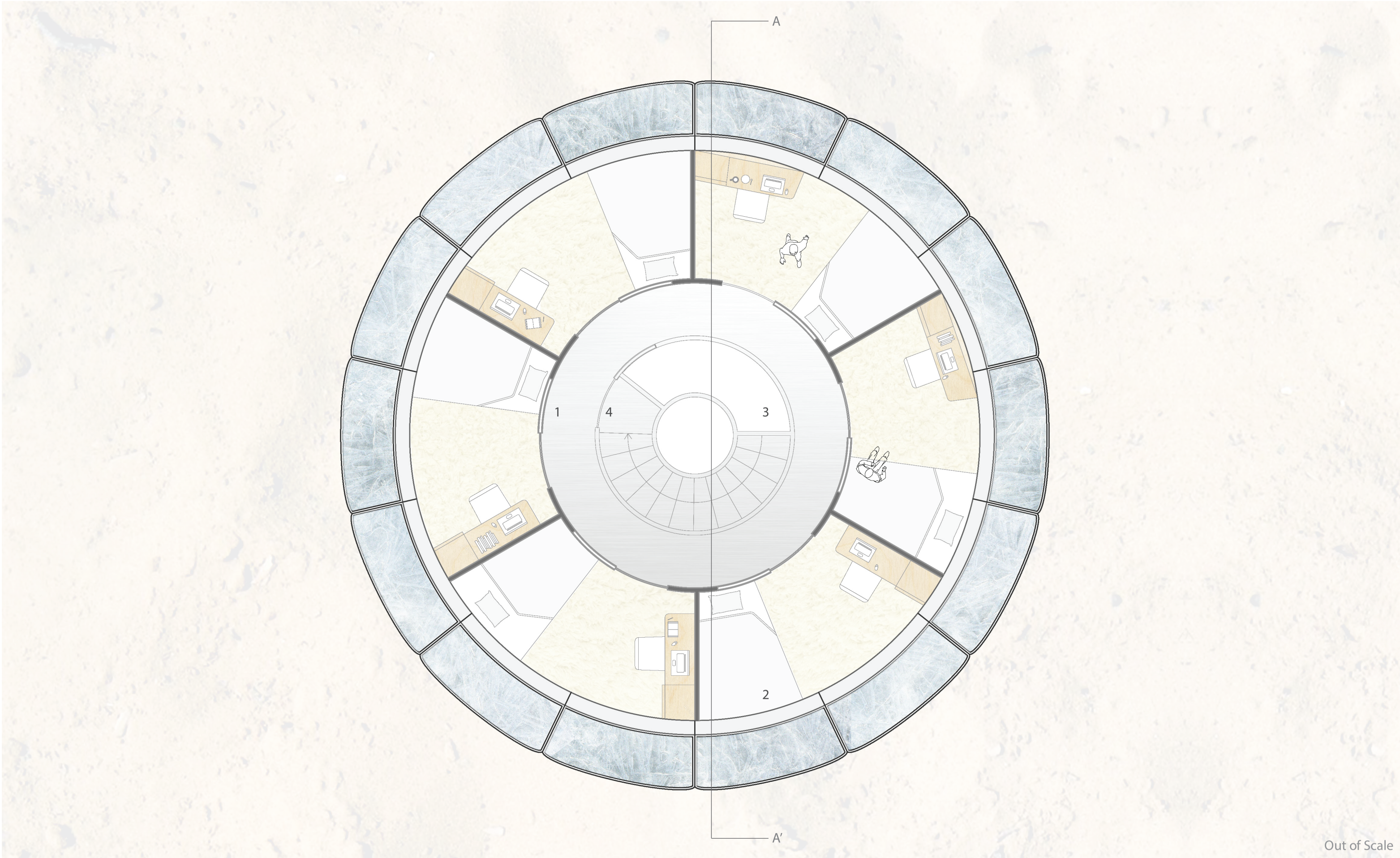
Limitations of the layout

The separation walls can be integrated to the core, however, the furnitures, accessories and equipments should be carried to attain an internal organization as shown above. This results in extra mass to carry and should be studied in a different manner.



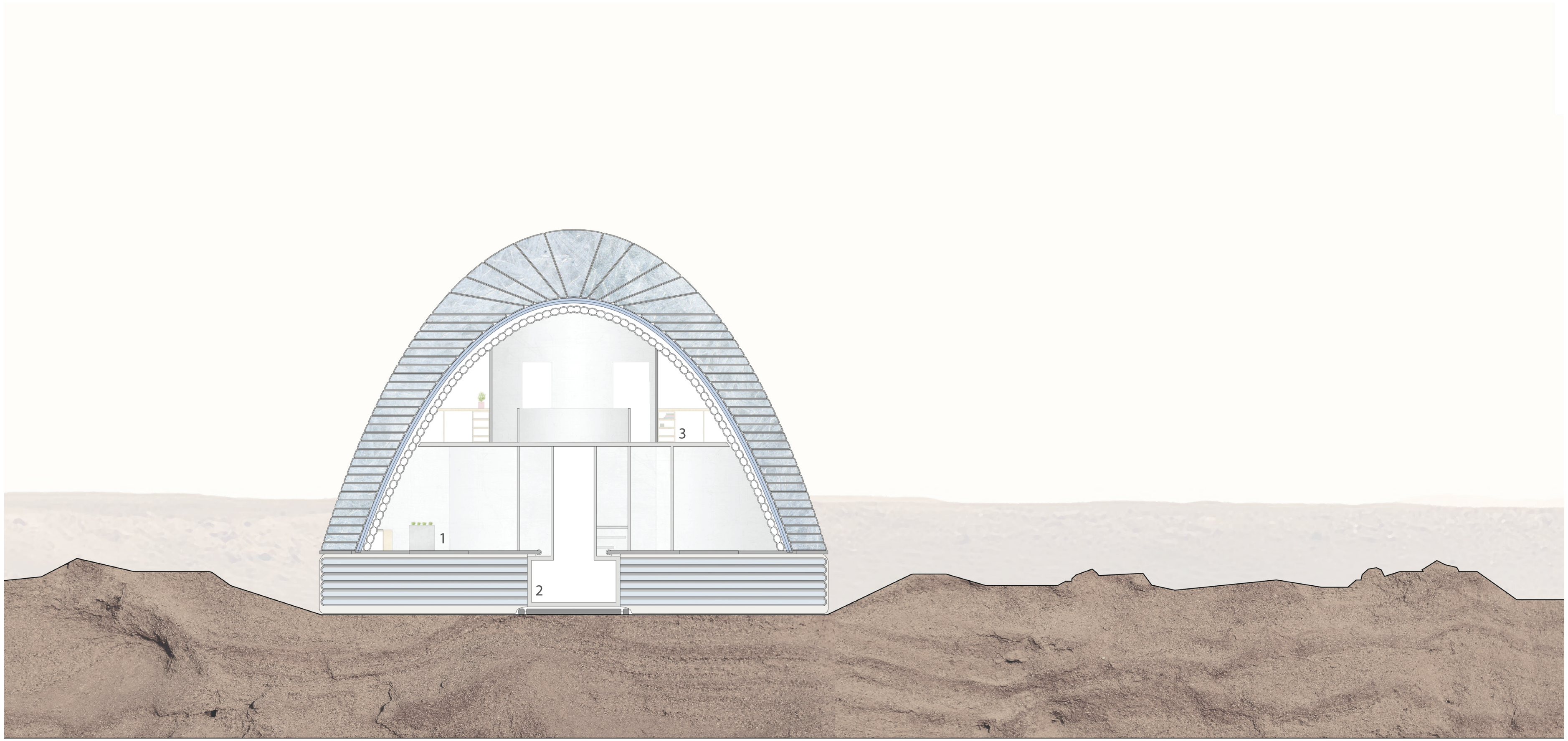
GROUND FLOOR PLAN

1. Airlock 2. Excercise Area 3. Gathering 4. Eating Unit 5. Relaxation Zone 6. Scheduling Area 7. Staircase 8. Hygeine U nit 9. Installations and ECLSS 10. Maintenance Unit 11. Science Lab 12. Pop-up Medical Room



FIRST FLOOR PLAN

1. Corridor 2. Crew Unit 3. Installations and ECLSS 4. Staircase

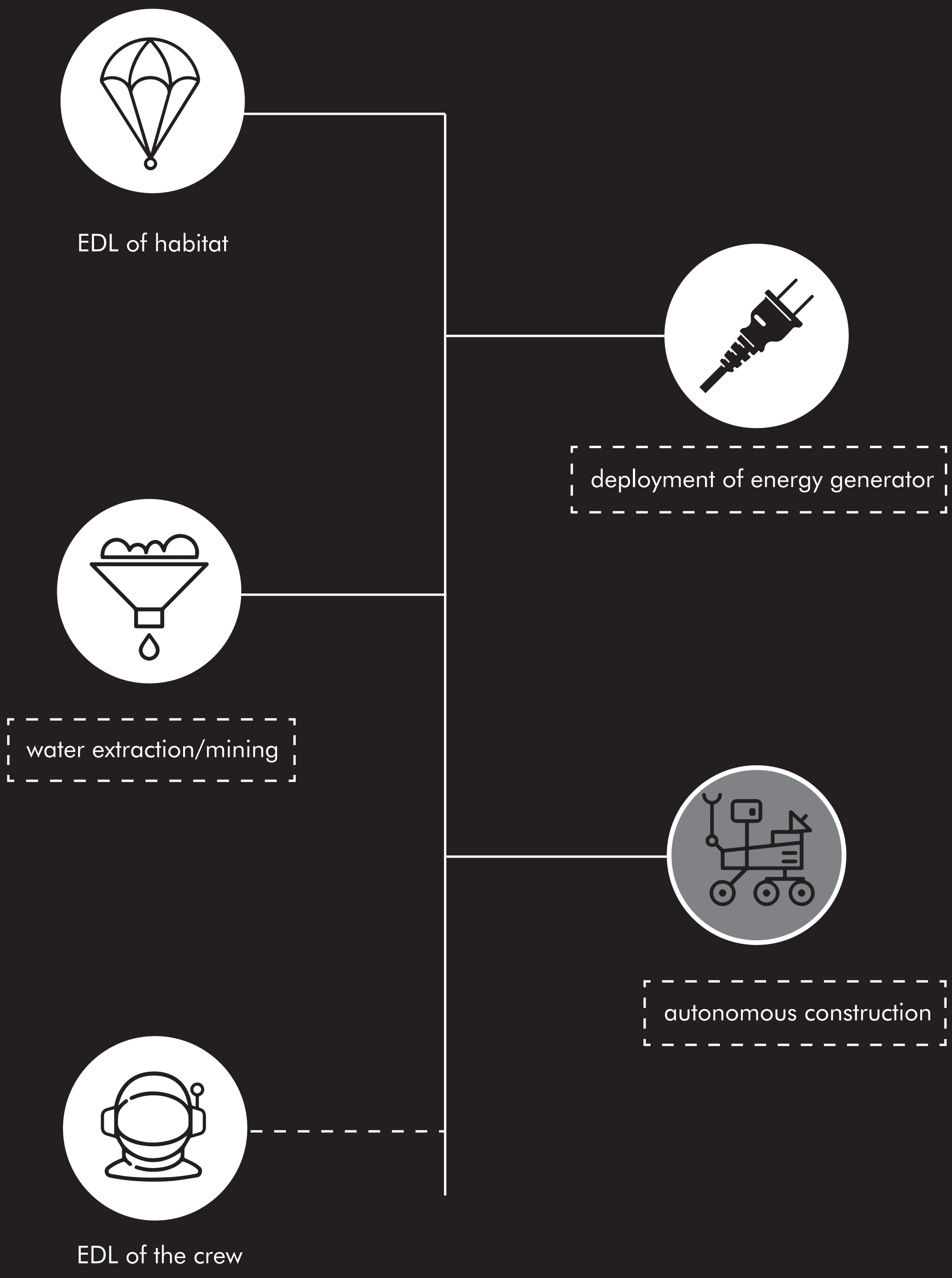


SECTION AA’

1. Science Lab 2. Installations and ECLSS 3. Crew Unit

AUTONOMOUS CONSTRUCTION OF THE HABITAT

5.5



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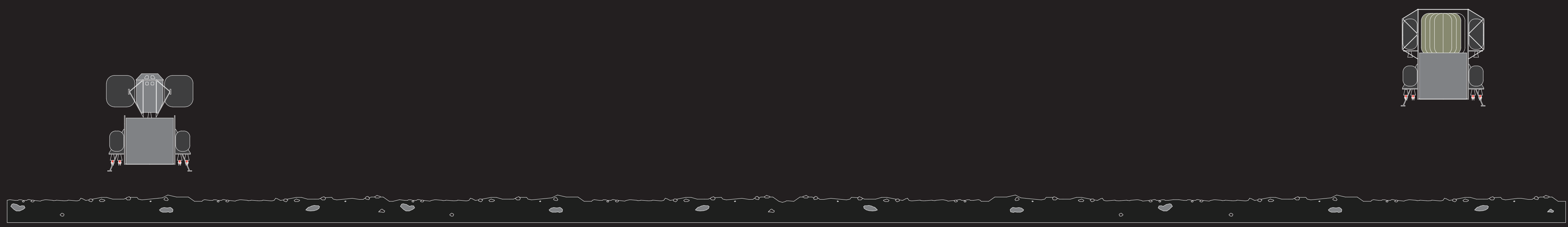
EDL OF THE CARGO LANDERS



00

In this chapter, a conceptual construction methodology will be presented accompanied by numerous of illustrations. These illustrations are basically showing the construction step by step. The technologies that have been integrated were mostly influenced by the developments by space agencies and other architectural firms that has been working on space architecture projects.

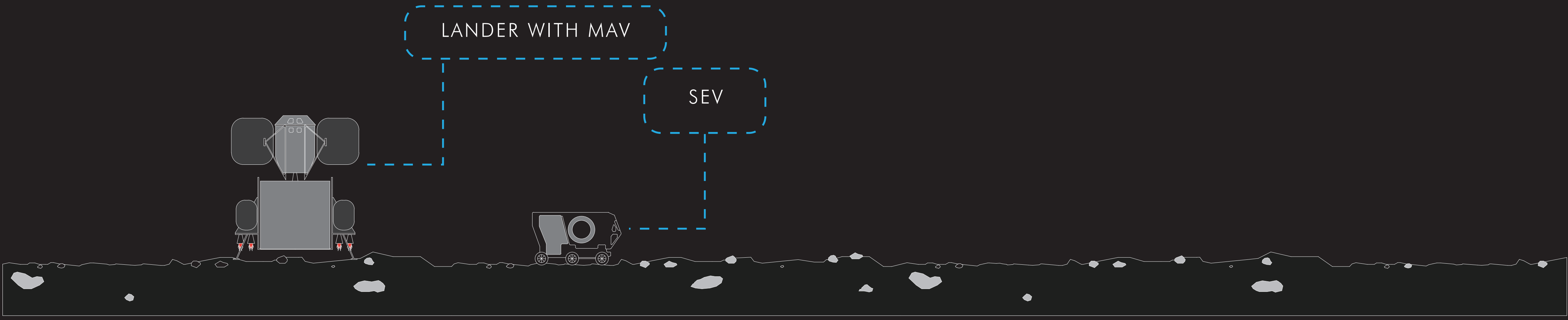
Although the construction methodology might seem interesting and promising, the limitations are very overruling due to low technology readiness level of certain technologies. However, base assumptions were made in order to produce this work. This base assumptions have certain implications on the amount of water that can be extracted, operating rassors that are currently under development by NASAi landing accuracy and such.

The construction should autonomously proceed due to the time delay between Mars and Earth. This delay may go up to 24 minutes (Ormston, 2012) and may result in slowing down the construction drastically if proceeded Earth dependently.

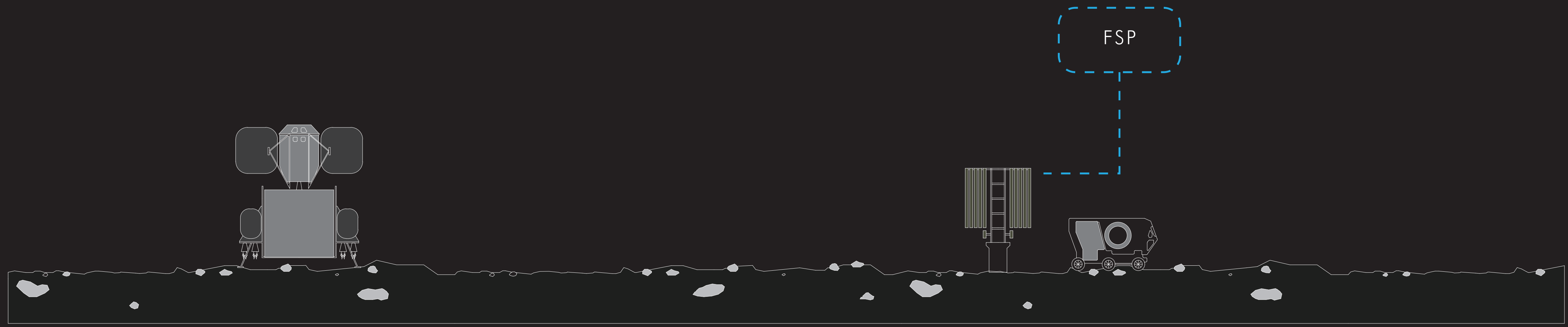
This chapter only touches upon the steps that are suppose to be followed. The mathematical and engineering work still has to be performed to attain an autonomously constructed martian habitat, where every robot and mechanical body works in an harmony and aware of each others' current work. Thus, they may individually make choices according to other robot's current work state.

These two cargo landers will arrive before the crews lands and the construction must be completed before their arrival. (480 days)

01 DEPLOYMENT OF MULTI MISSION EXPLORATION VEHICLE



02 POSITIONING THE FISSION POWER GENERATOR



01A

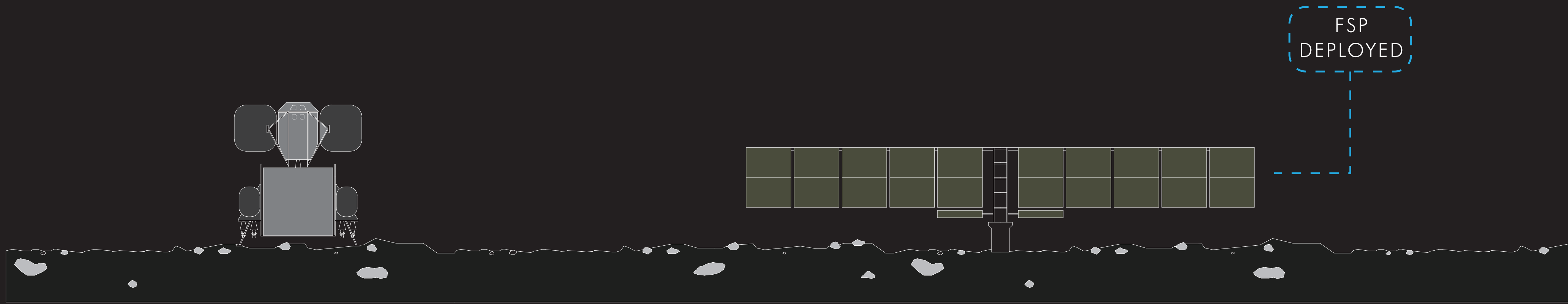
Two cargo landers that are carrying the necessary equipments for the manned mission to Mars are landing on the surface. One of the technologies that NASA currently works on is Terrain Relative Navigation (D.Way, S.Dutta, 2016) that will significantly increase the accuracy of the landing site. The EDL technology that is used for this construction methodology takes advantage of this increased accuracy. These cargos are complying with NASA 40 metric tons cargo landers and they are carrying similar equipments(Mission to Mars, NASA, 2017). The cargo lander on the left side is carrying the MAV (Mars Ascent Vehicle) that is needed for astronauts to go back to Earth, the SEV (multi-mission space exploration vehicle), a science kit, two fetch rovers, a fission power unit of 40 kW and an ISRU plant.

The cargo lander on the right side, however, is carrying instruments that do not entirely follow suggestions of NASA, as water is the main construction material and it has specific handling requirements.The cargo lander will carry the inflatable habitat module, 4 solar arrays, 4 rassors, 1 ISRU plant equipped with microwave technology to be used in water extraction through Martian regolith, and one SEV.

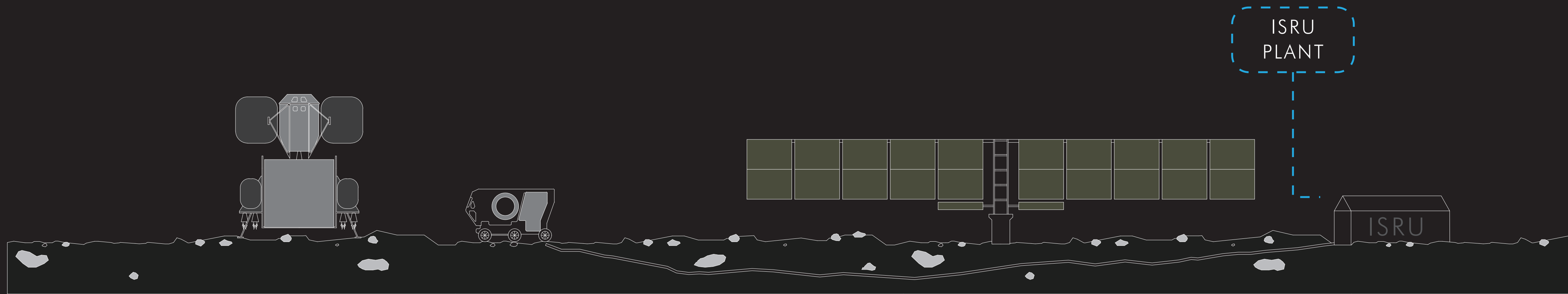
02A

The multi-mission space exploration vehicle is one of the crucial elements that catalyze and facilitate the manned mission to Mars. In this case, the very first task of the SEV is to carry the base fission power generator and to position it on a location where it may deploy. This generator must be at least a kilometer away from the habitat because it causes extra radiation exposure to the crew (Rucker, 2015). Therefore, the other lander that carries the inflatable habitat module will land according to where this lander locates itself, and fission power generator must be positioned accordingly.

03 DEPLOYMENT OF THE FISSION POWER GENERATOR



04 CONNECTION BETWEEN ISRU, FSP, MAC



03A

The fission power generator horizontally expands almost 34 meters with 7 meters height. It is composed of five radiators on the each side attached to a truss pole held by the reactor at the base (2NASA/TM, 2010). The proposed FSP system uses a low temperature, uranium dioxide-fueled, liquid metal-cooled fission reactor coupled with free-piston Stirling converters (Mason, Poston, Qualls, 2008).

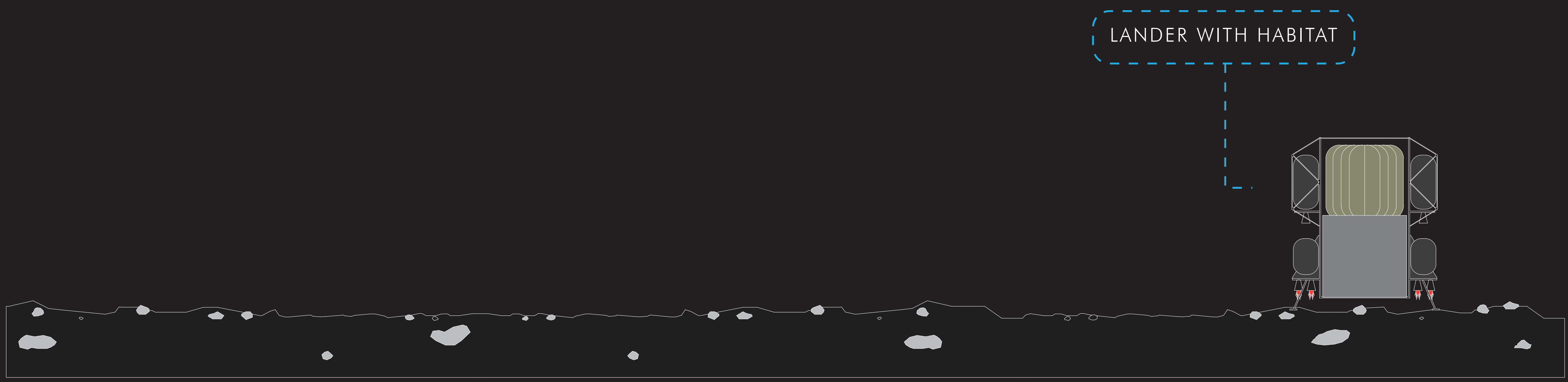
04A

Once the generator is positioned and deployed it will start generating energy for the ISRU plant. This is a very crucial step of the mission as it secures the crew to take off from the Martian surface in case of any malfunction or mission abortion.In order to achieve this security this lander, as previously mentioned, carries the Mars Ascent Vehicle. However the fuel tanks of MAV is not filled with the necessary amount of propellant at this point and first task of ISRU is to produce propellant with the energy provided by the energy generator.

In this stage, the responsibility of the SEV is to collect the pre-integrated pipes (to the ISRU plant) and connect these pipes with the propellant tanks of the MAV. This pipeline will help distribute the propellant among the tanks of the MAV equally.

The ISRU plant will use 16 mT of water (per crew) in the propellant production (Abbud-Madrid,Beaty, 2016)

01 EDL OF THE CARGO LANDER WITH HABITAT



02 SEV COMES OUT OF THE LANDER

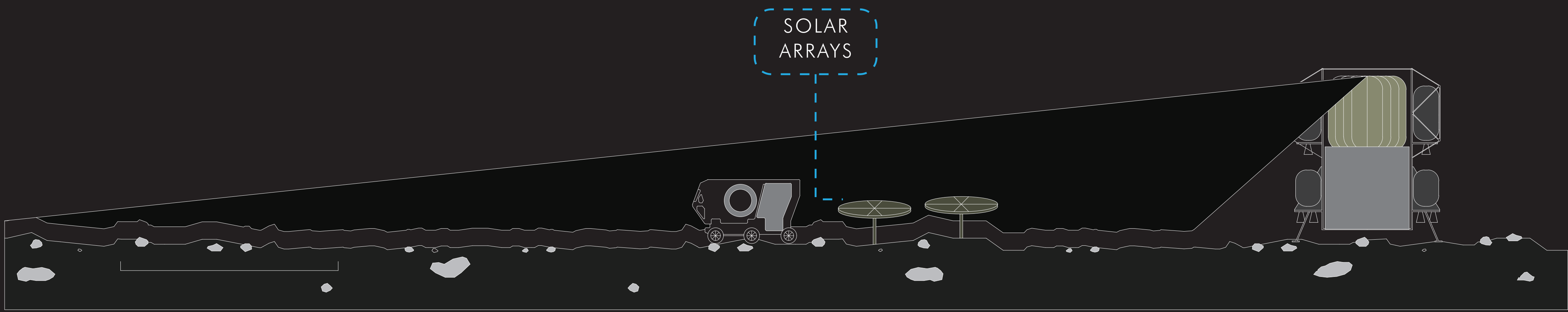
01B

The cargo lander with the inflatable habitat carries four solar arrays, four rassors, one ISRU plant equipped with microwave technology that will be used in water extraction through martian regolith, and one SEV. This lander has the inflatable habitat module that has its own pre-integrated propulsion system. The decision on whether tanks of the habitat module should be pre-filled with propellant or not, must be performed on a later stage. For this decision, certain studies ought to be completed regarding the mass constraints and loss of propellant during the cargo phase of the mission.

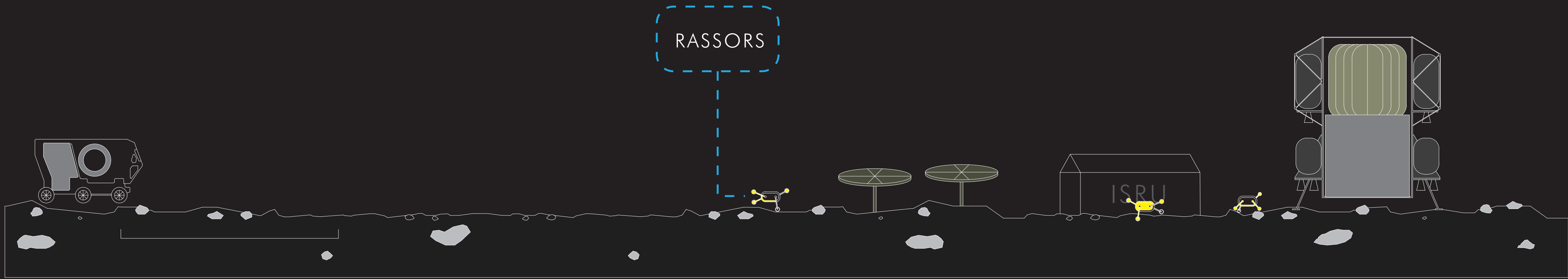
02B

The multi-mission space exploration vehicle (SEV) plays a crucial role in this phase of the construction. It is the very first equipment to be deployed because the construction starts only after the solar arrays start producing energy for the rassors. Thus, the first task of the SEV is to carry the solar arrays and position them at an adequate distance from the lander.

03 DEPLOYMENT OF THE SOLAR ARRAYS & TERRAIN SCANNING



04 ERECTING THE ISRU PLANTS



03B

The solar arrays are positioned with the help of the SEV. Their distance from the habitat does not influence crew's health in a negative way, therefore, there is no necessity to erect them at a long distance as the fission power systems.

Before this procedure starts the terrain recognizing cameras should scan the terrain and find appropriate places for the ISRU plant, solar arrays and most importantly for the habitat to be placed. Once the flattest location is detected the construction may start

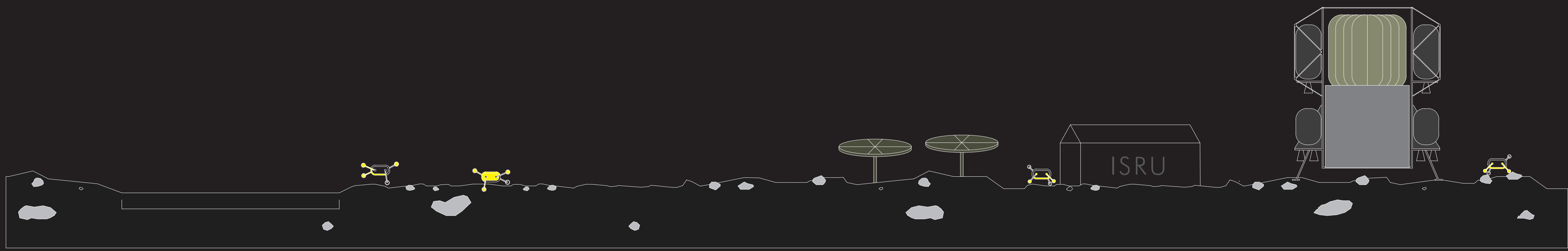
04B

Once the terrain scanning is complete, the locations are determined for each equipment to be placed in. The ISRU plant is only then deployed and connected with solar arrays to start producing water for the construction. The solar arrays will also be connected to the lander, where rassors are in stand by position waiting to be charged for carrying out the site flattening task, where the habitat will then be located.

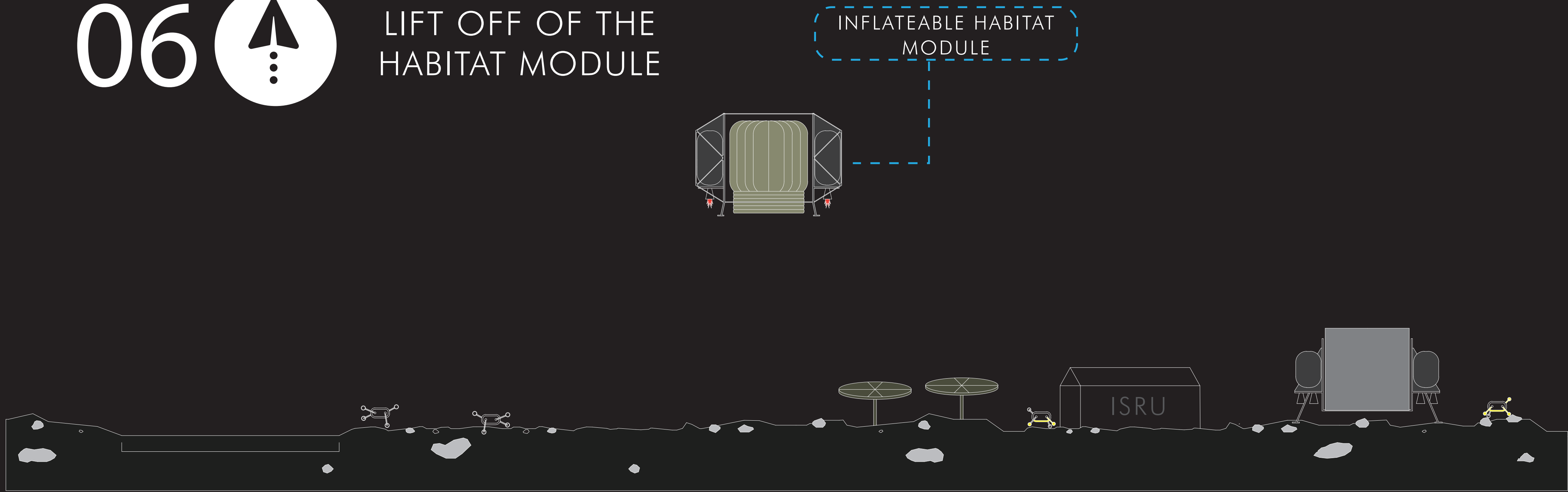
However, it shouldn't be forgotten that the chronological sequence must be as the following:

1) Deployment of solar arrays
2) Providing energy to the rassors
3) Rassors provide regolith to the ISRU plant
4) ISRU Plant starts extracting water with the provided regolith

05 FLATTENING THE HABITAT SITE



06 LIFT OFF OF THE HABITAT MODULE



05

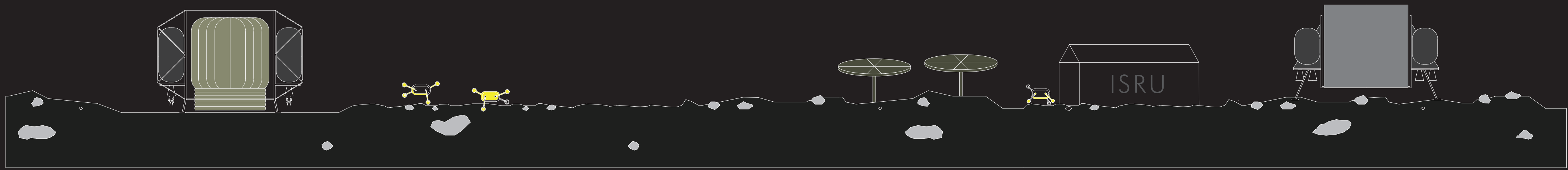
After rassors are charged and ready to operate, they can simply leave the lander and go to the location that is assigned for the habitat. Two rassors will be working on flattening the site while the other two will provide regolith to the ISRU plant. A very fast flattening procedure is not desired because the fine regolith can be suspended in the atmosphere and accumulate around the already flattened site before the inflatable habitat arrives in the correct position.

06

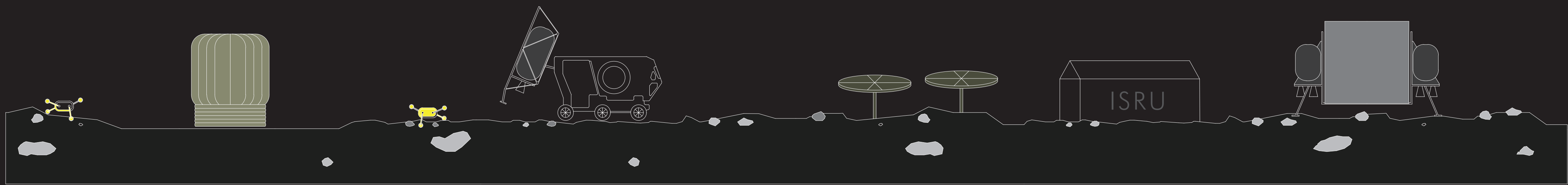
When the habitat site is flattened, and ready to accommodate the inflatable habitat module, the module that is located within the top part of the lander will take off to its assigned location. In order to come up with the right methodology, certain studies should be performed in regards to necessary amount of propellant, mass of the module, its ballistic coefficient and the retropropulsion technology which needs to have enough thrust to lift off the module.

However, conceptually speaking, this technology can be utilized for this project as it has been employed for NASA's Mars Science Laboratory Curiosity Rover during EDL. One argument against the feasibility of this method is the fact that Curiosity was only 900 kilograms(NASA, Entry, Descent, and Landing) and the habitat module will be a lot heavier than this.

07 HABITAT MODULE TOUCHES DOWN ON THE SURFACE



08 DETACHMENT OF THE TANKS AND RETRO-ROCKETS



07

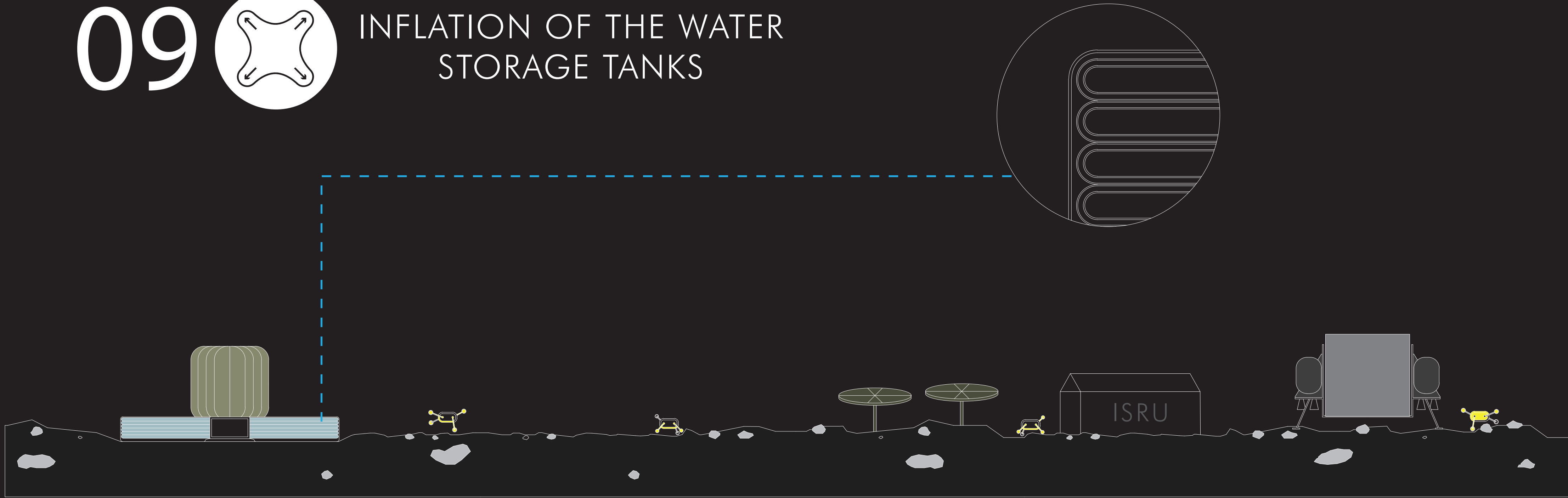
After the lift-off of the habitat module, it smoothly touches down the flattened site with the help of retro-rockets

08

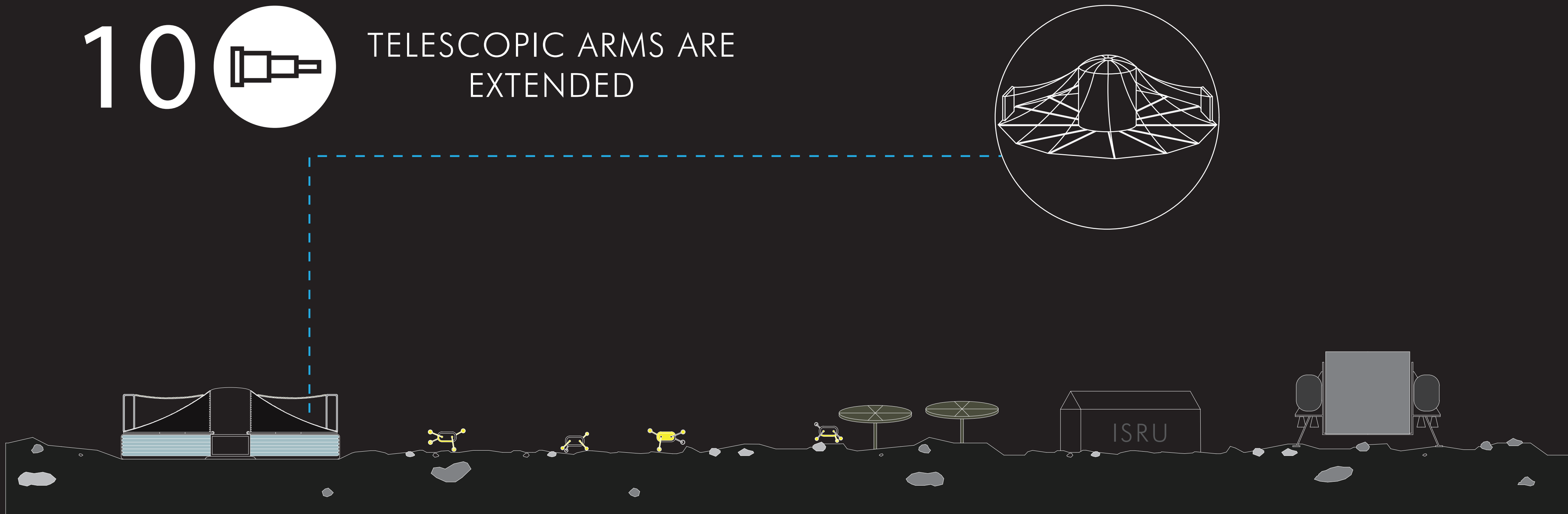
The propellant tanks, retro-rockets and the engine are attached to the habitat module with a truss frame. With the help of SEV the aforementioned objects will be detached from the inflatable habitat module, leaving all the sides empty, creating space for the inflatable water storages to expand.

SEV will carry the detached objects to a safe zone where the engine parts or the truss elements might be reused at a later stage in case of any mechanical malfunction. Space environment and earth independency requires circularity at a very level. None of the materials or engine parts should be abandoned and everything must be well kept for future use in case they are needed.

09 INFLATION OF THE WATER STORAGE TANKS



10 TELESCOPIC ARMS ARE EXTENDED



09

These water storage tanks are made out of water impermeable cloth-like materials, very possibly combination of several different layers, including nextel or kevlar. This is because it will be in contact with regolith at the basis. There must be aerogel layers which can be poured as an insulation layer, between the inner storage tanks and the outermost layer. This is very important because the water should be kept liquid during the construction as well as after crew's arrival.

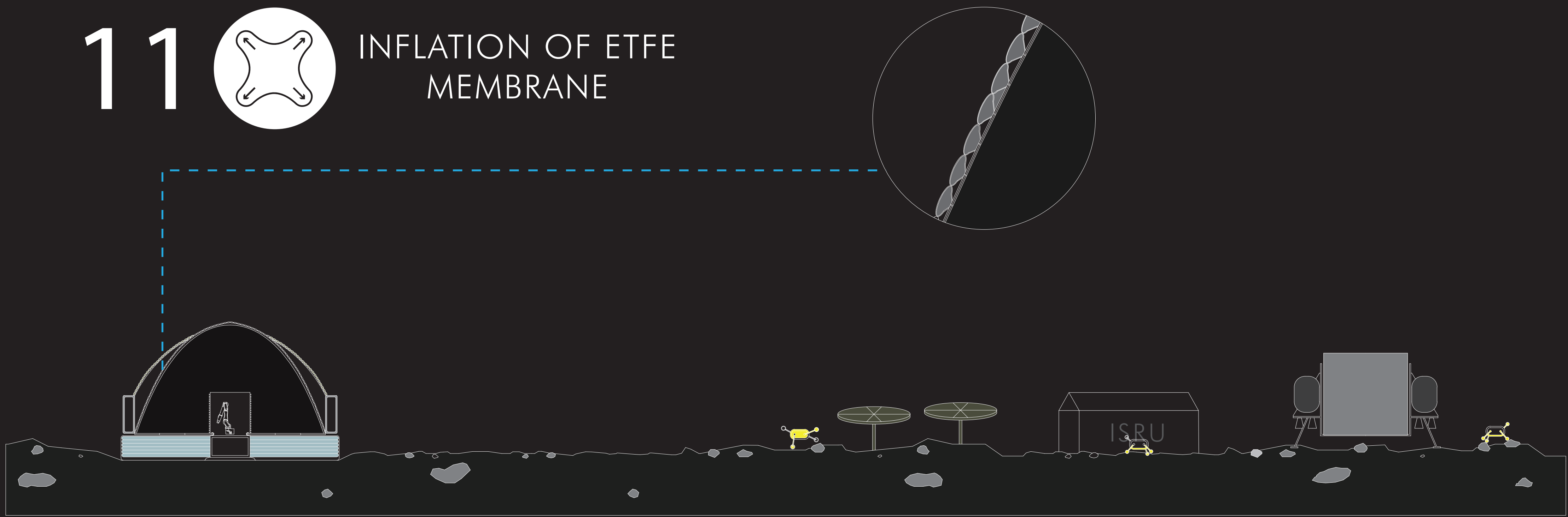
The water storage tanks have a cavity wall structure. These cavities are filled with air, giving the structure the required stiffness. And the inner cavity leaves enough space for 20 mT of water to be filled in each level. This is the suggested limit for supporting crew's life, which is determined per crew (M-WIP, 2016).

10

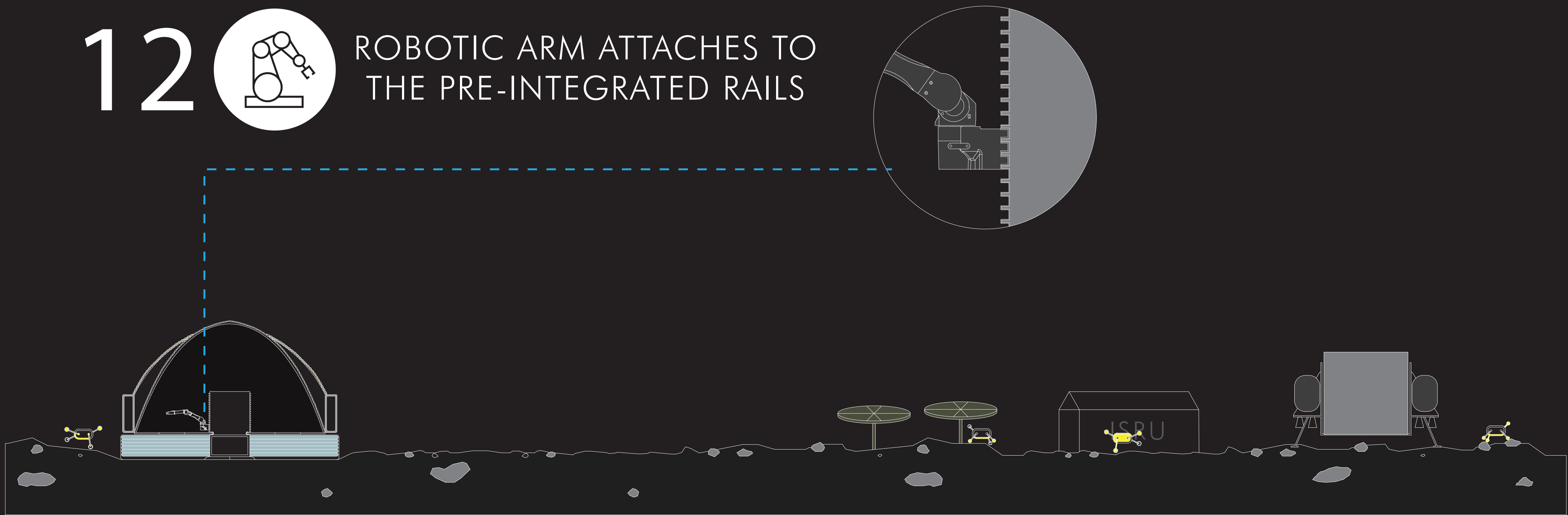
There are 14 telescopic arms that are pre-integrated into the core. The core is surrounded by the multi-layer inflatable which expands to the sides once the telescopic arms are activated. The multi-layer inflatable is attached to the core from the very bottom, where telescopic arms are located at a slightly higher position with smoothened tips. The motive behind smoothing the tips of the arms is to protect the multi-layer inflatable from damages during the extension of the arms from the core to the perimeter that is pre-defined by the water storage tanks. Positioning of the telescopic arms creates constraints to the multi-layer inflatable, keeps it in position without letting the inflatable take a balloon shape.

There are two airlock bulkheads integrated previously to the inflatable, which are then extended to the parameters by the help of the telescopic arms. Similar concept can be seen in the Bigelow inflatable modules that are already used in the space industry (Ingham, Haakonstad, 2012).

11 INFLATION OF ETFE MEMBRANE



12 ROBOTIC ARM ATTACHES TO THE PRE-INTEGRATED RAILS



11

The multi-layer inflatable is consisting of ETFE layers that are strengthened with Dyneema tensile cords. Once telescopic arms are extended to the sides, the inner pressure can be increased to 70,000 pascals. This helps the inflatable to tighten up and have a certain shape that's defined by the telescopic arms. At this very stage, overpressuring the internal environment may cause in ripping or damaging the membrane which is the main reason that pressure is kept low.

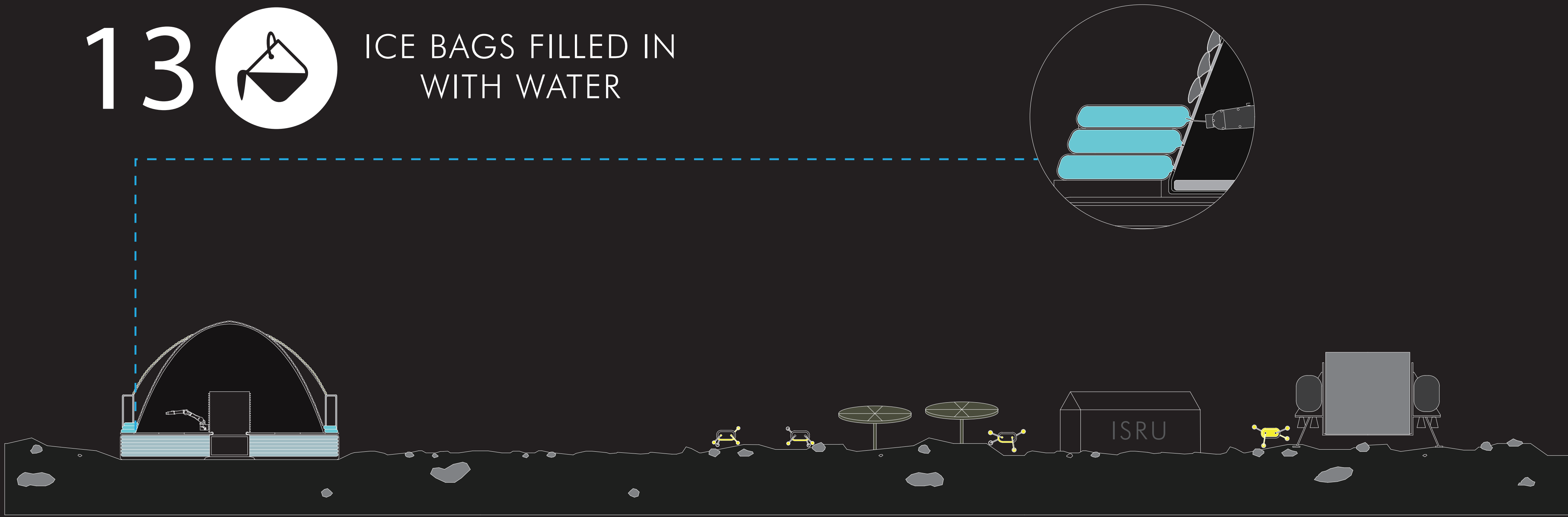
All of the water/ice bags are distributed along the membrane by pressurizing the internal environment. These bags have individual pre-integrated water inlets that are detectable by the robotic arm equipped with cameras.

12

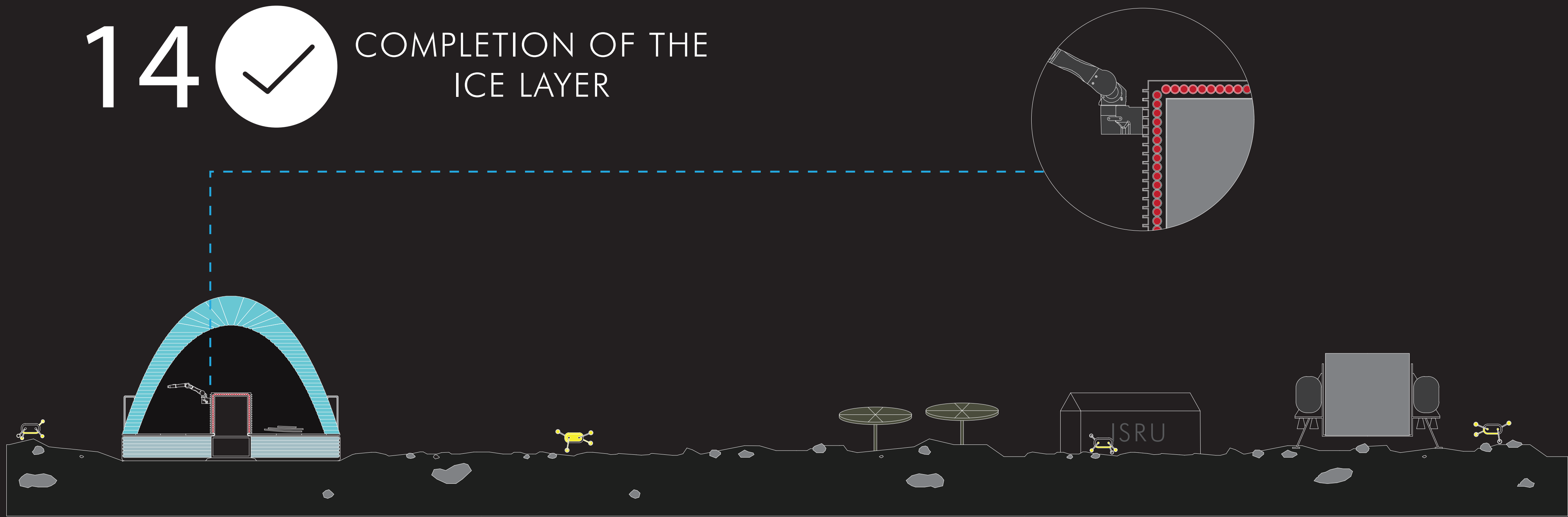
There is a robotic arm that has been pre-positioned inside the core. This robotic arm plays a very crucial role for the construction, thus it may need extra protection due to launch vibrations which may have destructive impacts on the systems and the robotic arm (NASA, Vibration Testing),

The outermost layer of the core has integrated rails where the robotic arm should autonomously attach itself, go around and start spraying water inside the deflated water/ice bags.

13 ICE BAGS FILLED IN WITH WATER



14 COMPLETION OF THE ICE LAYER



13

This is one of the considerably important steps in which previously vacuumed water/ice bags are filled with water. Due to very low temperatures (lowest -83 degrees celsius, highest -31 degrees celsius according to Mars Climate Database) these bags are exposed to, the water which is sprayed inside is preheated. This suggestion was given by an expert, Paulo Cruz (Structural Engineering Department,University of Minho, Guimarães) who has been working on ice structures extensively.

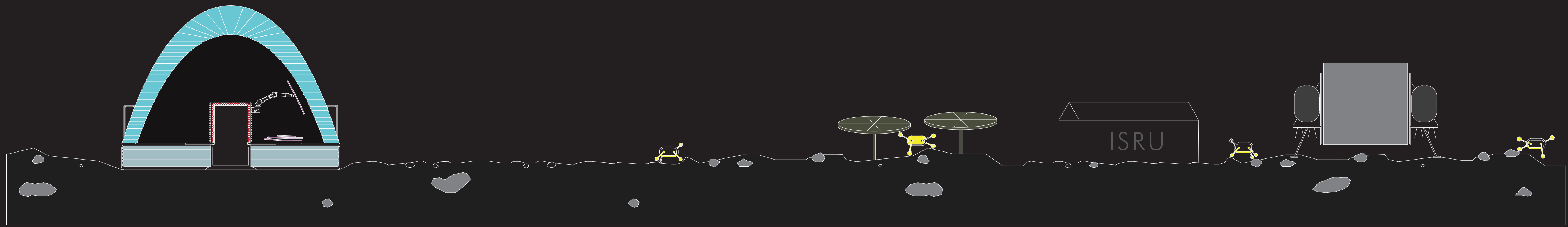
The water used in the construction is extracted in the ISRU plant. Rassors are continuously carrying regolith to this plant, where regolith is subjected to microwave beams and hydrous content of regolith is removed to produce water (for further information, see the water extraction chapter)

It should be clarified that the water/ice bags will be filled level by level. Once the very bottom layer is filled and solidifies, the upper lever can be filled with water. This has to do with the uniformity of the structure. Without letting the lower level freeze, the upper levels' weight may result creating a nonuniform structural shape.

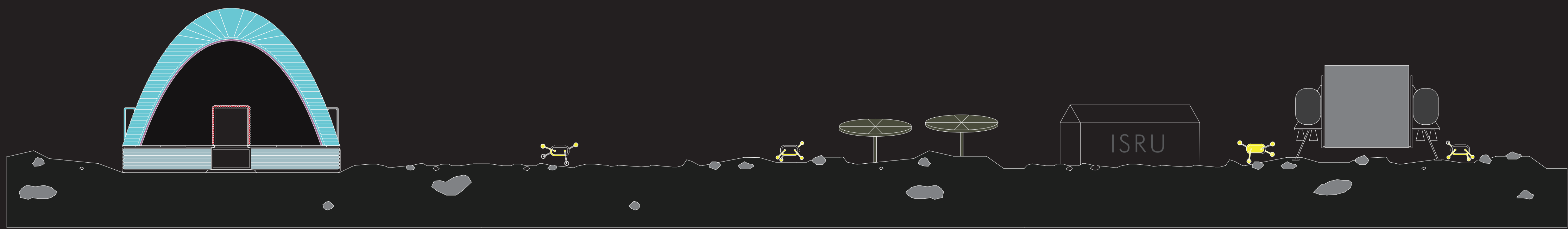
14

The top crown (key stone) water/ice bag is the most difficult one to be filled with water due to its higher volume and its position. Once the nozzle of the robotic arm starts spraying water, there is a chance of blockage if the water is freezes too fast..

15 ASSAMBLY OF THE AEROGEL PANELS BY ROBOTIC ARM



16 RELEASING THE CO2 BAGS BY TEARING OFF THE PRE-INTEGRATED RAILS



15

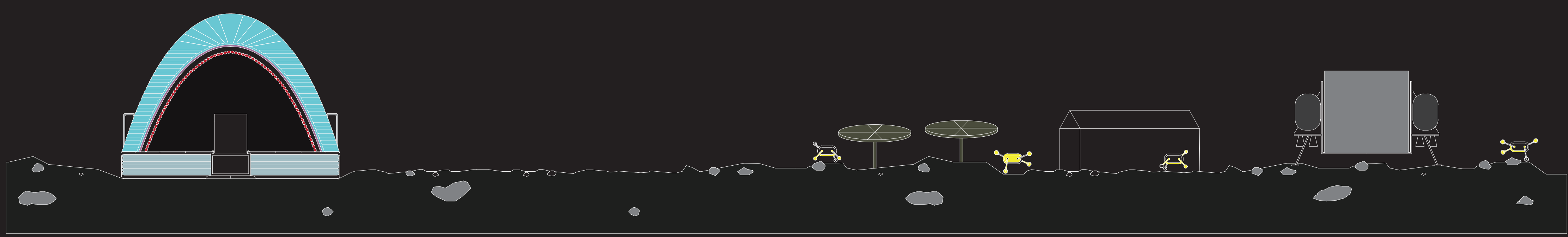
Along with the robotic arm there are pre-manufactured aerogel panels placed inside the core. These panels should be attached to the ETFE layer where joints are previously added. Aerogel panels can be connected to these. However there can be different strategies to use aerogel. One of them is to pour the liquid form inside a preformed cavity.

The aerogel layer is very crucial for insulation purposes as well as the protection of the ice layer. The indoor temperature that is set to 21-24 celsius degrees, without adequate insulation, may melt the ice layer from inside. This must be secured with a material that has a very low thermal transmission coefficient which is also light in weight. Therefore aerogel is used.

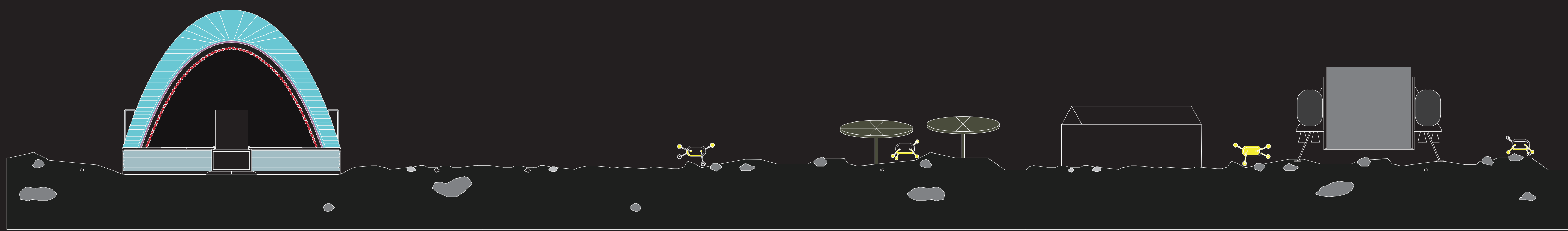
16

The core where all of the systems and mechanical installations are placed has multiple layers. The outermost layer where rails are introduced, as previously mentioned, wrapped by the inflatable membrane. In the intermediate cavity, there is deflated CO2 bags. Once the operations of the robotic arm is completed, the outermost layer will be torn off and CO2 bags will be ready to be inflated. This is an extra layer of insulation which will assumingly lower the heat transmission coefficient of the total envelope.

17 INFLATION OF THE CO2 BAGS



18 PRESSURIZING TO 100,000 PASCALS



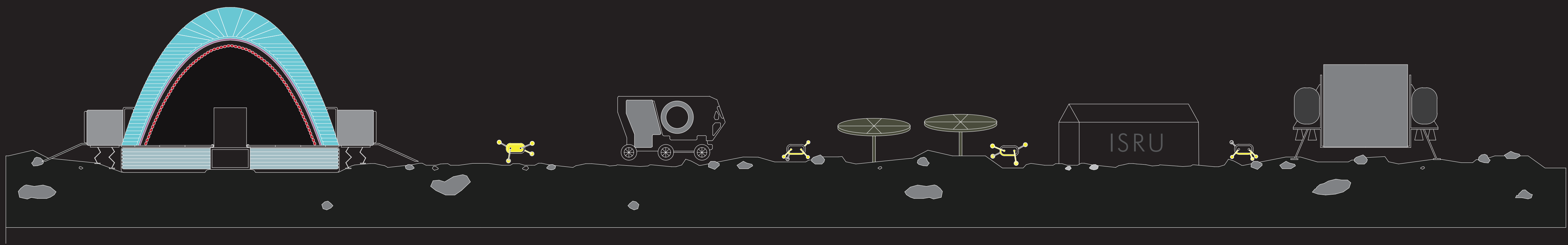
17

The systems inside the core will suck air from the atmosphere of mars and inflate the bags. Once the bags are inflated, the air inside should be kept still otherwise, due to the air movement, convection may happen. In case of convection the heat transmission coefficient of the overall wall will decrease, this is why the movement should be avoided as much as possible.

18

After all the layers are appropriately inflated and built, the internal pressure is now increased to 100,000 Pascals. This is almost the same atmospheric pressure that is observed at the sea level on Earth. This is very important to the crew regarding their habitability on Mars.

19 ATTACHING THE AIRLOCKS BY THE HELP OF SEV



19

Ultimately, two airlocks that are previously manufactured and carried from Earth will be taken from the cargo lander by the SEV. It will position them in front of the pre-positioned and pre-integrated airlock hatches which are attached to the habitat's membrane. This attachment should occur in a synchronized and autonomous manner between the hatch and the airlocks.

The airlocks are integrated with hydraulic footings that can alter their height according to the position of the hatches to lock themselves. Once this procedure is completed the habitat is ready to accommodate the crew.

CONCLUSION

Autonomous construction of a habitat on mars is a challenge, however it's very crucial to minimize the dependency on earth. This is mostly because launching to space is very expensive and the communication delay between earth and mars is almost 22 minutes (Ormston, 2012).

However, architects, architectural engineers and other engineers in this field should work in a very close collaboration to delve into the construction methodologies in order to optimize the building sequence. Although the construction of this habitat, conceptually does not involve human work force, the habitat will be accommodating humans at the end. This is why, engineers should not forget the human involvement in this mission and should not dictate architects' and architectural engineers' input.

In the construction methodology above, a conceptual idea of an autonomous construction can be observed step by step. There are 25 crucial steps that should be taken to build the habitat which will need further improvements. On the other hand, this document aims to create a basis for building a habitat that can accommodate a crew of 6 people with minimized effects of space radiation on the crew. It shows the overall picture of an autonomous construction.

LIMITATIONS

-Unknown behavior of the ETFE membrane at a very low temperature (neyden asagisi)
-Unknown behaviour of the water, once it is sprayed at -70/-90 degrees celsius inside the water/ice bags
-Retropropulsion flight capabilities of the habitat module due to its mass
-Redundancy of the robotic arm
-Robotic arm deterioration in the free space radiation environment during deep space flight
Attachment of the aerogel panels to the ETFE membrane

SUGGESTIONS FOR ARCHITECTURAL ENGINEERS

-Thermal comfort of the crew within the habitat should be well analyzed
-The insulation properties of the envelope should be well analyzed
- Acoustic comfort of the crew might be disturbed by the systems (such as ECLSS) due to the structure borne acoustic transmission through the walls

RECCOMENFATIONS

The folded version of the inflatable habitat module is unknown due to the materialistic characteristics of ETFE. The main reasons to use ETFE are its high chemical resistance and polythene characteris that provides a very good radiation protection, even better than of water. However it’s fairly a rigid material and difficult to fold. There are several other materials that can be replaced with ETFE but necessitates further investigations. These are:

-PCTFE: high chemical resistance, high dimensional stability, wide temperature resistance range.

-PETG: low brittleness, high chemical resistance.

-Surlyn: flexible, translucent

.

EVALUATION

Chapter
- 6 -

CONCLUSION

6.1

Mars was very similar to Earth once: warmer and wetter. However, the planet has been subjected to drastic changes over time. Many scientists find the exploration of Mars very crucial as it opens the doors to better understanding what our planet may go through in the future. However, sending humans to another planet necessitates an extremely sustainable habitat, advancement of new technologies and many other improvements in different fields that may possibly have great impacts and benefits even to our daily life on Earth.

Mars, except for the Earth, is the only planet within our solar system that is orbiting the Sun within the circumstellar habitable zone, which indicates that the planetary surface may support liquid water, and thus, life. This complies with NASA's follow the water approach (Mars.nasa.gov, 2017).

However, harsh environment on Mars creates lots of challenges to sustain human life on its planetary surface. The nearly non-existent magnetic field and very thin atmosphere makes the planetary surface very vulnerable to GCRs and SEPs, two major types of ionizing space radiation. This is why a habitat design with an adequate envelope that provides enough shielding characteristics is a necessity. This habitat should be designed in a way that it keeps the crew's exposure to radiation within allowable career limits. 1 sievert is the assumed radiation exposure of the crew for mission to Mars and is associated with 5% chance of acquiring a fatal cancer (Howell, 2017). The carrier limit in NASA guidelines is mentioned as 3% chance of getting fatal cancer. For this project, a long-stay mission that will make the crew stay for 539 days on surface has been chosen. Knowing that the crew will acquire 0.66 sievert during their transits, the habitat was designed to shield them from radiation for 539 and the projected exposure is 0.40 to 0.50 sievert total dose equivalent. Because of its shielding properties water was chosen as the main construction material as well as the main radiation shielding material. 800 mm of water has been used together with other materials for the envelope design outlined in the earlier sections.

After this decision, construction techniques were analysed, which led to a research on generating energy to supply construction needs. 40 kWe fission power and three other solar powered systems were considered. A method that uses fission and solar power generating systems simultaneously was chosen. Fission powered systems were located at a kilometer distance from the habitation zone near the Mars Ascent Vehicle, that is the return vehicle. Solar powered systems were employed for supplying energy to ISRU plants that are extracting water to be used in the construction of the habitat. The underlying reason for this arrangement is that fission power systems propose negative health impacts on the crew and they need to be placed farther apart from the habitation zone.

Because the water is used as the main building material, possible water sources were researched. Glacial ice, phyllosilicate rich minerals, poly-hydrated sulfate minerals and regolith are the known water sources on Mars (Mepag.jpl.nasa.gov, 2017). Due to current exploration risks without having a rover in the selected habitation location, that is the Jezero Crater, regolith is chosen as the main source of water extraction. Afterwards, processing techniques of regolith was analysed and microwave technology was selected due to its higher efficiency in extracting water from regolith, in comparison to other options.

From this point on, a methodology of an autonomous construction for an inflatable habitat was developed. The design included 25 crucial construction steps that needs to be followed without earth-dependent controlling systems due to the data transmission delay of 22 minutes between Mars and Earth. The construction methodology generated for this study is at a conceptual stage and requires further investigations in the fields of aerospace engineering. However, it sets the foundations for an autonomous construction of a radiation shielding habitat on Mars, including water extraction techniques to supply the necessary amount of water for the construction, as well as the energy generator systems to support the demand of the construction.

DISCUSSION & FUTURE RECOMMENDATIONS

6.1

Concerning the space radiation exposure: The shielding assessment of the habitat should be well studied with another simulation rather than spenvis. There should be a continuous information flow between the architect and space radiation experts to optimize the habitat regarding its shielding properties.
Concerning the energy generation techniques:Energy demand of the sufficient water extraction for the habitat’s water/ice shield should be well studied
Concerning the water extraction techniques:After 2020 Rover by NASA lands on Mars, other water sources apart from regolith should be re-considered depending on their presence within the set habitation zone
The total duration needed for water extraction would answer the questions of whether the construction might be completed in 480 days
Concerning the construction methodology:The total mass of the inflatable module is unknown and needs further study to understand if it complies with NASA’s 40 mT cargo landers.Once the mass of the inflatable habitat module is defined, retropropulsion technology for lifting of the habitat can be developed. Behaviour of ETFE at a low temperature such as -70 degrees celsius and low atmospheric pressure should be analyzed.Redundancy of the central robotic arm that sprays water inside the water/ice bags should be well analyzed..A correlation research can be made in order to assess the radiation shielding properties of different compositions of regolith analogues and water. Optimally performing composite, providing enough protection to crew from space radiation, may be selected for the construction, in regards to its mechanical strength and in-situ material utilization possibilities on Mars.

REFERENCES & APPENDIX

Chapter
- 7 -

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COMMENTS

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